University of Alberta

Patterns of River Breakup Timing and Sequencing,
Hay River, NWT

by

Nadia Kovachis

A thesis submitted to the Faculty of Graduate Studies and Research
in partial fulfillment of the requirements for the degree of

Master of Science

in

Water Resources Engineering

Department of Civil and Environmental Engineering

Spring 2011
Edmonton, Alberta

Examining Committee

Dr. Faye Hicks, Civil and Environmental Engineering

Dr. Mark Loewen, Civil and Environmental Engineering

Dr. Suzanne Kresta, Chemical and Materials Engineering

Abstract

River ice breakup and associated flooding are realities for many northern communities. This is certainly the case in Hay River, NWT, which is located at the junction of the Hay River and Great Slave Lake. Hay River experiences a wide range of spring river ice scenarios; from docile thermal melt outs, to severe ice jams resulting in life-threatening, disastrous flooding.

This study involved the analysis of five seasons of aerial and time-lapse photographs (over 90,000), water level measurements and hydrometeorologic data. This work also compiled an extended historical record of breakup in the Hay River delta, which was compared against the field data gathered for this study; combining local, experiential knowledge with scientific observation into a cohesive description of breakup. This will be used to advise the non-technical flood watch community on the patterns of timing and sequencing of breakup, which is critical for evacuation planning.

Acknowledgements

This research project was a collaboration between the University of Alberta (UA), Canada's Department of Indian Affairs and Northern Development (DIAND) and the Town of Hay River. Many other people and agencies also contributed data, resources and heuristic knowledge to this study. All of these contributions are most gratefully acknowledged. Thanks to Dr. David Harrison for locating and providing past reports on breakup, as well as his own notes used to extend the available historical record. Thanks also to Water Survey of Canada personnel, who provided unpublished water level records for gauges in the Hay River basin.

Major funding for this research was provided by the Natural Sciences and Engineering Research Council of Canada (NSERC) through the Strategic Grants (Safety and Security) Program. This funding, which provided graduate student stipends and funds for the field monitoring program, is much appreciated.

The author would like to thank Dr. Faye Hicks for her guidance and encouragement. For all of their help with the field monitoring programs, many thanks to the Hay River team for their long hours and hard work: Michael Brayall, Chris Krath, Joshua Maxwell, Janelle Morley, Jennifer Nafziger, David Watson, Liming Zhao and to research partners at the Department of Indian Affairs and Northern Development (DIAND): Shawne Kokelj and Meg McCluskie. Thanks to Drs. Hicks, Loewen and Kresta for being a part of the final oral examination committee.

The author is grateful for the love, support and encouragement of family and friends throughout this process. It was a pleasure to be part this river ice breakup research; many friendships and fond memories were made during time spent in Hay River.

Table of Contents

List of Tables

List of Figures

List of Appendices

Chapter 1: Introduction

The Hay River is a tributary in the Mackenzie River system (Wedel 1985) that flows in a in northeasterly direction out of British Columbia (BC) and Alberta (AB) and into the Northwest Territories (NWT), ultimately discharging into Great Slave Lake (Figure 1.1). The Town of Hay River is located at the mouth of the Hay River, where it splits into the East and West Channels to form a small delta. As is common with many north-flowing rivers, spring arrives first in the upper basin and this generates snowmelt and consequent increased river discharge in the headwaters. The snowmelt wave lifts and breaks the ice cover in the upper basin and carries it downstream into the river ice further north, where conditions are still cold and the ice is strong. The ice runs jam up against the intact ice, obstructing the flow, and water backs up behind them until eventually they release under the pressure. The resulting wave of ice and water runs downstream until it again encounters intact, competent ice, or some other obstructing influences such as a tight bend or an island. Then the process of ice jam formation and release is repeated. In this way, breakup progresses northwards in a very dynamic fashion. On the Hay River, the breakup can progress from the headwaters right down to the Town of Hay River on Great Slave Lake in as little as two days, or it can take more than a week. However, the result is generally the same: the ice runs eventually encounter intact ice in the delta or on Great Slave Lake, forming ice jams that often lead to flooding in the community.

There are four key developments in and around the Hay River delta that experience ice jam flooding.

- The Kátl`odeeche First Nation Reserve is located on the east side of the East Channel. The Old Village, located at the north end of the reserve near Great Slave Lake, is particularly prone to ice jam flooding when ice jams form in the mouth of the East Channel.
- The West Point Fishing Village on Vale Island is located on the east side of the West Channel at Great Slave Lake. It is quite prone to flooding when ice jams form in the mouth of the West Channel.
- The Town of Hay River's "Old Town", also on Vale Island is quite prone to flooding when ice jams form in the East Channel.
- The Hay River Airport, located on the west side of Vale Island, is prone to flooding when ice jams form in the West Channel.

Following the extreme ice jam flooding event in the Hay River delta in 1963, a new community (New Town) was established on higher ground upstream of the Forks (UMA 1979, Harrison 1984). Nevertheless, many people still live and work in the flood prone areas. Consequently, monitoring of the progression of breakup is an annual endeavor of the community's Flood Watch committee, and a number of residents have developed considerable expertise in terms of understanding the evolution and nature of breakup. This expertise, combined with the comprehensive monitoring efforts of the volunteers on the Flood Watch committee has proven valuable for ensuring the safety of residents living in and around the Hay River delta.

Considerable efforts have also been undertaken in the past to conduct scientific and engineering studies of the Hay River breakup (Stanley *et. al* (1959), Stanley *et. al* (1963), UMA (1978), Jasper (1983), GWNT/IWD (1984), Gerard and Stanley (1988a and b), Wedel (1988), Gerard and Jasek (1990), Gerard *et. al* (1990), Jasek *et. al* (1993) and Jasek (1993)). Most recently (2004 to 2010) this site has again been the subject of intense scientific study by researchers from the University of Alberta.

In addition to these studies, there is substantial local knowledge residing in a handful of residents who have been watching breakup for decades. There is a need to ensure the continuity of information by consolidating knowledge from local experts as well as scientific and engineering studies. This knowledge will then be quantified using information gathered in five years of intensive breakup field study. As such, the objectives of this study are four-fold:

1.) Ensure the continuity of knowledge of the key sequence and nature of breakup on the Hay River at Hay River by integrating the heuristic knowledge of local residents, academic researchers, government experts and the Town of Hay River flood watch committee.

2.) Consolidate that knowledge with quantitative hydrometeorological data to facilitate some predictive capabilities, primarily in terms of the timing of various stages of breakup.

3.) To contribute knowledge towards a flood forecasting expert system which would be of practical use to the local Flood Watch Committee.

4.) To determine the critical monitoring data required in the long term to support future (more robust) forecast model development.

The following sections detail how the objectives of this study were achieved. Chapter 2 describes the synthesis of available data, including: river basin and study reach details, historical breakup descriptions on the Hay River and available hydrometeorological and water level information. Chapter 3 explains the interpretation of this data through analysis of the progression of breakup based on timing, degree-days and water levels and also delineates the most consistent and useful indicators and predictors of breakup and identifies the most critical monitoring data required for future forecast model development. Chapter 4 summarizes the most valuable findings in this study and makes recommendations for future breakup monitoring and study.

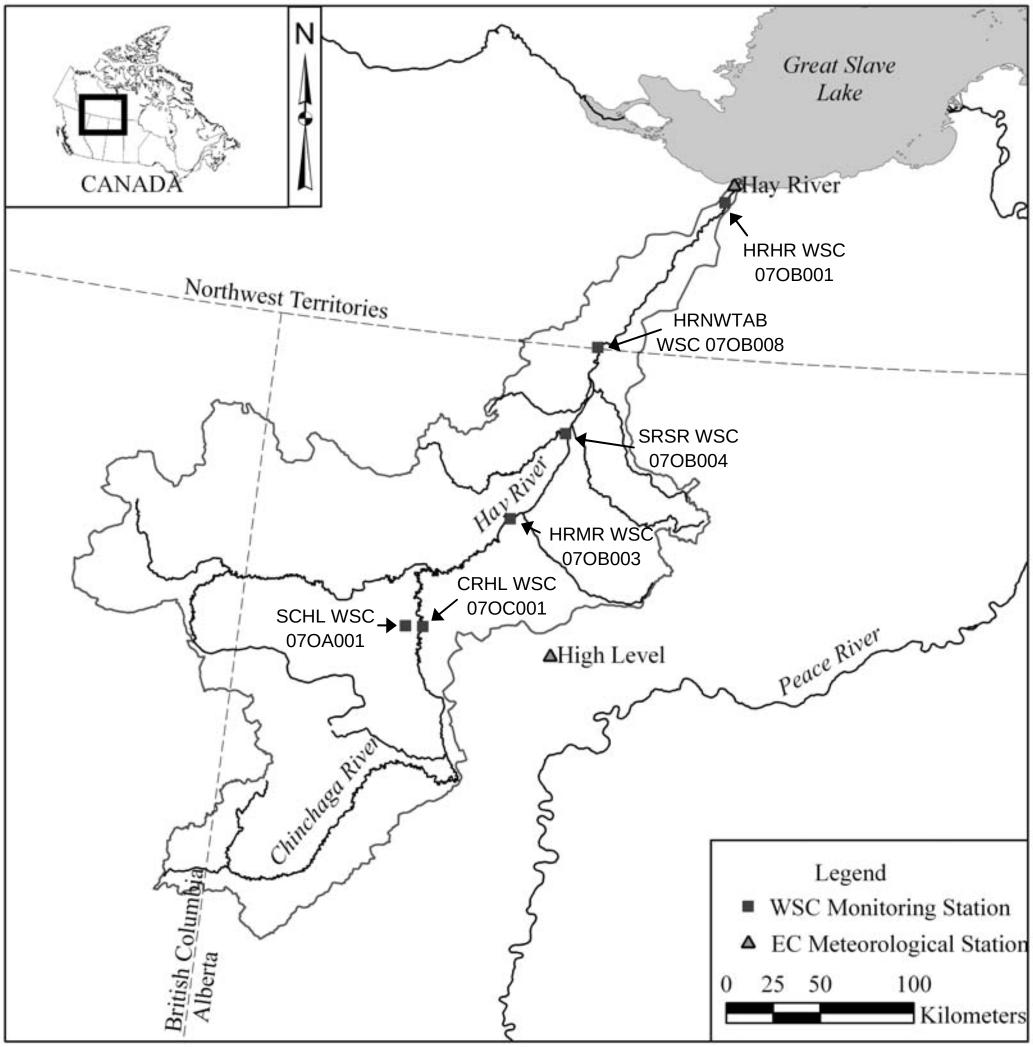


Figure 1.1: Map of the Hay River basin, including the EC meteorological stations and WSC water level monitoring stations.

Chapter 2: Synthesis of Available Data

A variety of information on breakup on the Hay River was available from a number of sources. This chapter details the Hay River basin characteristics and topographic features, as well as the study reach and its 10 individual study sites. The known record of breakup and the studies surrounding it are discussed, while the historical dates and sequencing of breakup stages are analyzed. Water level data was provided for Water Survey of Canada (WSC) gauge stations by WSC staff and for EMO gauges by the Town of Hay River. Hydrometeorological data for both Hay River and High Level was obtained from the Environment Canada website, found at *http://climate.weatheroffice.gc.ca/climateData/canada_e.html*. The data collected by the University of Alberta and DIAND's breakup field program as part of this study (2005 to 2010, excluding 2006) includes manual water level measurement in the Hay River delta and both aerial and ground photography of the river. In this chapter, both the provided and collected data are described and synthesized with the historical record.

2.1 Physical Features of the Hay River Basin

The Hay River has a total length of 1114 km, and its drainage basin covers 48,000 km^2 (GNWT/IWD 1984). Based on topographic features, the Hay River basin can be subdivided into three distinct sub-basins: the Chinchaga River basin and the upper and lower Hay River basins (UMA 1979, Harrison 1984). The Chinchaga River, which originates in the foothills of the Rocky Mountains, is the primary tributary to the Hay River, draining 23% of the basin (UMA 1979). The Chinchaga River basin topography is rugged and its stream channel decreases more than 700 m in elevation by the time it emerges from these hills to the plains of northern Alberta (UMA 1979). The upper Hay River drains the remainder of the Hay River basin south of the NWT/AB Border (Gerard and Stanley 1988) and covers 42% of the area of the Hay River basin (UMA 1979). It is composed primarily of marshlands and low relief plains (Harrison 1984 and Gerard and Stanley 1988a and b) and the river elevation drops 400 m from the basin headwaters to the NWT/AB Border (UMA 1979). The lower Hay River extends 165 km from the NWT/AB Border to Great Slave Lake and drops by 150 m (UMA 1979).

A profile of the Hay River water surface was determined by Hicks *et al.* (1992) by analyzing the contour intersections on 1:50,000 scale National Topographic Series (NTS) maps, supplemented with surveyed river cross section data at selected locations. River stationing for this profile was taken as the distance, in km, along the channel centerline from the river source at coordinates UTM N11 6379670 311280 (58˚43’18”N/117˚15’49”E), as defined in Gerard and Stanley (1988a and b). Figure 2.1 shows the lower portion of the profile, extending from *km 900* down to Great Slave Lake. Based on this profile, and other geomorphic characteristics of the river, five sub-reaches have been designated for the purposes of this study, as shown in Figure 2.2: Reach 1 extends 330 km upstream of the NWT/AB Border and has an average slope of 0.0002 (Hicks *et al.* 1992). Limited information (primarily WSC gauge data) is available to study the progression of breakup in Reach 1. The other four sub-reaches constitute the river north of the border extending downstream to Great Slave Lake, and represent the primary focus area for this study. To facilitate this study, 10 key sites were identified along the study reach. Table 2.1 lists these sites and their locations, while Figures 2.3 to 2.12 provide detailed descriptions of the extents of each site and the typical breakup patterns that occur there. These ten sites are the primary focus of this research, however other sites of interest are also discussed in the following sections.

Reach 2 extends from the NWT/AB Border (*km 945.5*) to the 33 m high Alexandra Falls (*km 1034.0*) and has an average slope of 0.0002 (Hicks *et al.* 1992). In this reach, the Hay River meanders through alluvial plains and is occasionally interspersed with islands. Reach 3, which encompasses the steep gorge section of the Hay River, extends from Alexandra Falls (*km 1034.0*) to the hamlet of Enterprise (*km 1048*) and has an average slope of 0.0058. Just downstream of Alexandra Falls (*km 1034.0*), the 75 m deep incised valley contains the 15 m high Louise Falls (*km 1037.1*) then develops into an entrenched meandering pattern (Harrison 1984).

Reach 4 begins at Enterprise (*km 1048.0*) and extends to the Hay River delta (*km 1108*) and has an average slope of 0.0005 (Hicks *et al.* 1992). The gorge height decreases gradually in the downstream direction forming entrenched meanders and by *km 1053.5*, a discontinuous floodplain is evident. This continues to *km 1083*, when the Hay River reverts again to entrenched meanders. Bank heights continue to decrease in the downstream direction, reducing to less than ~5 m by the Pine Point Bridge (*km 1098*). At the Town of Hay River (*km 1108*), on the south shore of Great Slave Lake, the river splits and forms a small delta. Reach 5 consists of this delta, extending from where the channel splits into the East and West Channel (the Forks at *km 1108*) to the shores of Great Slave Lake. The average channel bed slope in the Hay River delta is 0.0001, as per the reported ground survey of the channel beds in Gerard and Stanley (1988a and b). Figure 2.13 illustrates the Hay River delta and communities located there.

2.2 Historical Breakup Descriptions for the Hay River

The recorded history of Hay River dates back to 1868. To varying extents, breakup stages have been documented in the Town of Hay River since 1894 (Stanley et. al 1959, Diamond Jenness 1978, Jasper 1983, Gerard and Stanley 1988a and b and Wedel 1988). Appendix A contains a complete consolidated summary of the historical Hay River breakup record, detailing all of the known information on river breakup from 1894 to 2010. This includes information documented in diaries from the local Anglican and Catholic Missions, consulting engineers' reports, files from the Town of Hay River Emergency Measures Organization (EMO), academic research publications and newspaper reports.

Records covering the period up to 1950 were obtained from diaries kept at the St. Peter's Anglican and St. Anne's Roman Catholic Missions and from letters written by priests and teachers and the Mission schools (Stanley et. al 1959, Diamond Jenness 1978, Jasper 1983 and Gerard and Stanley 1988a and b). These Missions were located between *km 1113* and *km 1114* in the East Channel (Figure 2.13). The diaries provide the dates of breakup and the locations of high water marks for years in which breakup flooding occurred. There is very little documented breakup information for years where no flooding occurred, as might be expected, since these breakups would have been unremarkable to residents.

After 1950, breakup records included EMO files and engineering reports, which contained more detail. In particular, the documentation of breakup monitoring efforts expanded after the largest ice jam flood on record occurred in 1963 with the formation of the Town Flood Watch Committee, and a number of engineering and research studies followed. Among the studies conducted by engineering consulting firms, government agencies and academics, the definitive reports include Stanley *et. al* (1959), Stanley *et. al* (1963), UMA (1978), Jasper (1983), GWNT/IWD (1984), Gerard and Stanley (1988a and b), Wedel (1988), Gerard and Jasek (1990a), Gerard *et. al* (1990b), Jasek *et. al* (1993), and Jasek (1993). These reports were typically published following years in which significant flooding occurred and the subject matter and emphasis varied greatly. They can be generally grouped into the following categories:

- Characterization of the Hay River as it pertains to breakup, including:
    - general overviews of the Hay River's basin and channel characteristics;
    - river cross sections and bathymetry surveys;
    - breakup observations; and
    - studies of water temperature variation during breakup.
- The development of ice jam flood forecasting algorithms and procedures, including:
    - breakup flood elevation analyses and hydraulic model calibration;
    - ice jam release stage analyses;
    - probability analysis of flood risk; and
    - peak stage prediction during flooding events.
- Flood control mitigation studies, including:
    - channel modification options;
    - ice control structures; and
    - economic analysis of these options.

Between 1987 and 1993, following a particularly severe flood event in 1985, intensive research was instigated by the Department of Indian Affairs and Northern Development (DIAND) and Environment Canada. This initially involved sponsoring research studies and monitoring efforts by University of Alberta (UA) researchers, and later by DIAND staff directly (Gerard and Stanley

1988a and b, Gerard and Jasek 1990a, Gerard *et. al* 1990b, Jasek *et. al* 1993, Jasek 1993). This research led to the development of sophisticated ice jam flood forecasting models for the community which were implemented in a user friendly computer software program. However, personal computers were not widely available or used by the public at that time and consequently the breakup forecasting models were not implemented for operational use by the Town Flood Watch committee.

DIAND's involvement in the monitoring in the Hay River breakup ended in 1993. Although the Town Flood Watch Committee continued its annual monitoring program, their efforts were necessarily focused on ensuring public safety, not scientific documentation of the breakup. As a consequence, only sparse information on the nature and timing of breakup is available in the period from 1994 to 2003, primarily from Hay River's independent weekly newspaper, *The Hub*.

The community again experienced a major ice jam flood in 2003 and, given that the earlier ice jam forecasting models were not in use (and were also most likely outdated), DIAND commissioned the University of Alberta to investigate the available data with a view to updating the flood forecasting models for the community. This expanded into a comprehensive study funded by the Natural Sciences and Engineering Research Council of Canada, which was conducted with DIAND and the Town Flood Watch Committee as research partners. The joint efforts of these three partners between 2004 and 2010 provide the most comprehensive field data to date.

2.2.1 General Overview of the Typical Sequence of Breakup

In addition to assembling comprehensive records documenting breakup dates in the Town of Hay River, several of the earlier reports also included partial descriptions of the progression of breakup in Reaches 2, 3 and 4. Specifically, breakup descriptions were compiled for 1977 (UMA 1978), 1985, 1987 and 1988 (Gerard and Stanley 1988a and b) and 1989 (Gerard and Jasek 1990). Although full specifics of these breakup records are detailed in Appendix A, it is useful to summarize the breakup progression for those years here, to facilitate an understanding of the typical patterns experienced.

UMA (1978) documented the progression of breakup in the spring of 1977, in which no flooding occurred. By 27-Apr, Reach 2 (from the NWT/AB border (*km 945*.5) to Alexandra Falls at *km 1034.0*) had cleared and local crack and jam formation occurred at the Pine Point Bridge. The onset of breakup in the Town of Hay River (Reach 5) also occurred on 27-Apr. On 28-Apr, a small ice jam was reported in Reach 3 (i.e. in the gorge between Alexandra Falls (*km 1034.0)* and Enterprise (*km 1048*)), while ice further downstream remained intact. Over the course of the next 4 days, this jam shoved and pushed its way through Reach 4 (from Enterprise (*km 1048*) to *km 1103.5*). On 3-May, this jam arrived at the Hay

River delta (Reach 5) and caused the peak stage but no flooding. Melt out to Great Slave Lake occurred by 4-May (Gerard and Stanley 1988a and b).

Gerard and Stanley (1988a and b) provided detailed descriptions of the progression of breakup in the spring of 1985. The ice jam related flooding that occurred during this breakup is the second largest flood on record. On 1-May, a localized transverse crack and jam occurred in lower Reach 4 at Pine Point Bridge (*km 1098*) (Wedel 1985). An ice jam released at *km 935* (Reach 1) on 5-May (Wedel 1988). Breakup initiated in the Hay River delta (Reach 5) on 6-May. The peak stage occurred in Hay River during the early hours of 7-May, and caused extensive flooding (Gerard and Stanley 1988a and b). The ice jam melted clear to the lake on 9-May (Gerard and Stanley 1988a and b).

Gerard and Stanley (1988a and b) described breakup in the spring of 1987 and 1988. The river ice breakup in the spring of 1987 did not cause any flooding. The first documented breakup event in 1987 is that on 25-Apr, Reach 2 (from the NWT/AB border (*km 945.5*) to Alexandra Falls (*km 1034.0*)) had intermittent sections of small jams, open water and intact ice. Reach 3 was open from Alexandra Falls (*km 1034.0*) to Enterprise (*km 1048*), and the head of an ice jam was found at Paradise Gardens (*km 1071*). The jam extended to the Golf Course (*km 1088.5*), where intact ice was present to the Forks (*km 1108)* in the Hay River delta (Reach 5). Also on 25-Apr, the Golf Course jam released and shoved into the Hay River delta, initiating breakup. The peak breakup stage occurred on 27-Apr, but did not result in flooding. This jam melted out to the lake on 30-Apr.

During breakup 1988, some flooding occurred (Gerard and Stanley 1988). Breakup stages in Reach 2 (south of the NWT/AB border (*km 945.5*) to Alexandra Falls (*km 1034.0*)) were documented on the first reconnaissance flight, on 23-Apr. By 24-Apr, Reach 2 had cleared of ice. A small jam formed in the gorge in Reach 3, between Alexandra Falls (*km 1034.0*) and Enterprise (*km 1048*). Intact ice extended from this jam to Great Slave Lake. On 25-Apr, a small ice jam formed at the Pine Point Bridge (*km 1098* in Reach 4). The onset of breakup in town (Reach 5) occurred on 27-Apr. The peak stage and some flooding also occurred on this day. The jam melted out to the lake by 2-May.

Gerard and Jasek (1990) documented several upstream ice jam stages during 1989, when significant flooding occurred. On 1-May, a jam formed in Reach 2 at *km 996* near Grumbler Rapids. Early on 2-May this jam released, and continued to shove through Reach 2. Another jam formed in gorge in Reach 3 (between Alexandra Falls (*km 1034.0*) and Enterprise (*km 1048*). When it released, breakup began at Paradise Gardens (*km 1071*) in Reach 4, and progressed downstream until breakup initiated in the Town of Hay River (Reach 5). The peak stage jam occurred on 6-May.

Additionally, the University of Alberta and DIAND research crews recorded the progression of breakup stages in increasing detail from 2004 to 2010. Detailed accounts of the progression of breakup during these years are also included in Appendix A. In 2004, UA/DIAND noted that breakup was a thermal event. Although ice accumulations were noted in Reach 4 (between Enterprise (*km 1048.0*) and the Forks at *km 1108.0*), these were slushy accumulations of ice that grew as the ice cover deteriorated and broke apart. This slush pile up slid as far as the Chamber of Commerce Park in the Town of Hay River (*km 1103.5*), but never shoved into the delta. The peak stage in the delta occurred, with ice intact, on 1-May. This ice melted out to Great Slave Lake by 5-May.

In 2005, the UA/DIAND research team observed that the Hay River broke up essentially from upstream to downstream. Transverse cracks, sheet accumulations and mini-jams formed in Reach 2 (between the NWT/AB border (*km 945.5*) and Alexandra Falls (*km 1034.0*)), while a jam formed in the gorge (between *km 1040.5* and *1048.0* in Reach 3). On 22-Apr, this jam released and progressed in domino fashion, stalling between Paradise Gardens (*km 1071.0*) and the Golf Course (*km 945.5*). By noon the following day, the jams downstream of Alexandra Falls had shoved into the East and West Channels of the delta. The peak stage caused some flooding on 25-Apr, and melt out occurred on 28-Apr.

Breakup in 2006 did not occur from upstream to downstream. Breakup occurred first in upper Reach 4 (Paradise Gardens (*km 1071.0*) and the WSC near Hay

River gauge at *km 1095.2*) before breakup occurred in Reach 2 (the NWT/AB border (km 945.5) to Alexandra Falls at *km 1034.0*), except for a jam in Grumbler Rapids (*km 986.0*). The onset of breakup occurred on 24-Apr, as a jam pushed into the West Channel. Ice runs continued to arrive until 28-Apr, but the jam did not push into the East Channel. The University of Alberta research team was unable to stay until complete melt out due to a lack of funding for the monitoring program for this year. After their departure, the peak stage and some flooding occurred in the Hay River delta, but no detailed records were kept of this. The date of melt out was obtained from the EMO West Channel Bridge water level record (*km 1108.3*) as 29-Apr (when the ice affected water levels dropped and levelled off).

In 2007, cracking was recorded in Reach 2 (between the NWT/AB border (*km 945.5*) and Alexandra Falls at *km 1034.0*) on 23-Apr. On 24-Apr, a jam had formed in the gorge (between *km 1040.5* and *1048.0*), but there was some open water downstream of Enterprise (*km 1048.0*) and a jam between *km 1062.0* and *1065.0.* On 25-Apr, two jams had formed Reach 2; in one 10 km downstream of Grumbler Rapids (*km 986.0*) and the other upstream of Mink Creek at *km 1023.0*. A small jam formed at the Pine Point Bridge (*km 1098.0*) while thermal deterioration had melted the ice out of the Forks and West Channel. The onset of breakup occurred during the morning of 26-Apr, and the jam extended back to Paradise Gardens (*km 1071.0*) with substantial ice runs arriving from upstream. The jam shoved first down the West, and then down the East Channels. The peak stage caused some flooding on 27-Apr, and the jams melted out to the lake on 29-Apr. This date of melt out was obtained from the EMO West Channel Bridge water level record as when the ice affected water levels dropped and levelled off).

Breakup in 2008 resulted in significant flooding. On 30-Apr, the ice cracked at the EMO gauge at Alexandra Falls (*km 1032.0*). Small mini-jams had formed in Reach 2 (between the NWT/AB border (*km 945.5*) and Alexandra Falls (*km 1032.0*)) by 1-May. A jam was building in the gorge (Reach 3), while the ice in Reach 4 (Enterprise (*km 1048.0*) to *km 1108.0* at the Forks) remained intact. The onset of breakup occurred in the Hay river delta on 4-May, while ice between the gorge jam (*km 1048.0*) and the WSC near Hay River gauge (*km 1095.2*) remained intact. By that afternoon, the jam released and shoved into the Hay River delta. Significant flooding occurred on Vale Island, Old Town and in the Old Village, stranding 25 people, knocking over telephone poles and the Anglican Church off its foundations. The NTCL yards were flooded, and barges were floated out onto the lake and moved around. This jam remained in place over 6-May, while Vale Island was evacuated for 24 hours. The jam melted out to the lake on 8-May.

In 2009, breakup occurred essentially from upstream to downstream. Mini-jams were spotted in Reach 2 (between the NWT/AB border (*km 945.5*) and Alexandra Falls (*km 1034.0*)) on 26-Apr. On 30-Apr, the ice at the EMO Alexandra Falls (*km 1032.0*) gauge cracked and on 1-May, ice was spilling over the falls. By 2-May, and a jam was accumulating at Escarpment Creek (*km 1040.5* in Reach 3).

The onset of breakup occurred in the delta on 2-May, as the shoved from the WSC at Hay River gauge (*km 1095.2*) into the Hay River delta. The ice jammed in the West Channel in the mouth, and in the East Channel the toe was located at Strang's corner (~*km 1109.7*). Conditions in the delta remained essentially unchanged until 6-May, when the an upstream ice jam release precipitated the release of the gorge jam. This ice run shoved into the delta, causing the peak stage and some flooding. Melt out occurred on 7-May.

The first transverse crack in 2010 was observed at the Island at *km 974* in Reach 2 on 21-Apr. As the rest of Reach 2 broke up between *km 945.5* and *1034.0*, a jam formed at Grumbler Rapids (*km 986.0*) on 21-Apr. During the next day, transverse cracking occurred at the EMO Alexandra Falls gauge (*km 1032.0*) and the WSC gauge at Hay River (*km 1095.2*). By 23-Apr, the jams in Grumbler Rapids (*km 986.0*) and the gorge (between *km 1040.5* and *1048.0*) had become large. The onset of breakup occurred on 24-Apr, shoving to the mouth of the West Channel and to the NTCL berm (*km 1111.3*) in the East Channel. The gorge jam (*km 1048.0*) released in the early hours of 25-Apr, and it pushed its way through Reach 4 (between *km 1048.0* and *1108.0*) and into the delta. Later that day, it caused the peak stage and some flooding. The ice jam melted out to the lake on 28-Apr.

From these accounts, consistencies in the pattern of breakup progression were identified. Although the sequencing of breakup stages along the entire river can vary year to year, the general pattern between these five reaches has proven to be relatively consistent. Based on the observations of the river breakup since 2005, as well as those of earlier researchers and information provided to us by residents of Hay River, the typical breakup sequence can be described as follows:

Stage 1. ***Melting in the headwaters:*** The southern portion of the basin experiences warmer temperatures and an increase in snowmelt and subsequent discharge. This runoff wave lifts the intact ice cover (Figure 2.14 a) downstream.

Stage 2. ***Thermal deterioration:*** Intermittent warm spring weather initiates snowmelt on the ice cover and ice melt along the channel margins. Small open leads may develop, but the ice cover remains competent. Thermal deterioration of the ice also begins in areas where the river is not shaded by high banks; especially in the Hay River delta (Reach 5), as shown in Figure 2.15.

- Significant ice melt can occur in the West Channel at the Town of Hay River during this period, but elsewhere, the majority of the thermal deterioration is confined to ice melt along the channel margins and snow melt on the ice surface (Figure 2.14 b).
- The ice in the West Channel is especially prone to decay as the ice freezes to the bed of the river and is relatively dry. As spring runoff arrives in the delta, this rotty ice breaks up, creating brash ice at the downstream end of the West Channel.

Stage 3. ***Transverse cracking:*** Snowmelt runoff from the basin headwaters in the south lifts and breaks the strong, intact ice cover further north (downstream). This cracking, due to increased the water levels and velocities associated with this snowmelt runoff, primarily occurs through transverse cracking in river bends, creating large individual ice sheets (Figure 2.14 c). The sheets are shifted downstream by flow drag, causing ice ridging. Often the dynamic progression is too rapid for transverse cracks to be observed.

- When the first transverse crack forms just upstream of Alexandra Falls, the reach just upstream of the falls clears (between *km 1031.9* and km *1034.0*), and water released from storage. This creates a wave that propagates downstream, and might possibly be responsible for cracking between the WSC gauge at Hay River and the Pine Point Bridge (*km 1095.2 to 1098.0* in the lower Reach 4), where the ice is weakest (due to thermal deterioration).

Stage 4. ***Sheet accumulations:*** Once the ice is broken into discrete sheets, water levels must increase so that the ice sheets can overcome the geometric constraints of the river and move with the flow. There are two types of geometric constraints: vertical and horizontal. In a straight segment of river, water levels must increase such that the intact ice sheets clear the grounded border ice. When this happens, the ice is forced to move, as it is no longer being held at the borders. Horizontal geometric constraints are caused by the river planiform patterns. Early on, sheet movement is constrained temporarily by tight bends or islands in the channel. This creates ‘sheet ice accumulations’ (Figure 2.14 d). The stopping and starting of ice sheets as they try to work their way downstream creates small, localized fluctuations in water levels which break the ice sheets into smaller pieces (called ice floes). Being smaller, these ice floes can move through tight bends and around islands more easily.

Stage 5. ***Mini-jams:*** Variations in ice thickness, as well as river alignment, slope and velocity cause breakup to progress quicker in some areas along the river compared to others. This leads to small accumulations of broken ice (~0.5 to 2 km long) upstream of intact segments of the ice cover.

- Mini-jams tend to occur first in the reaches upstream of Alexandra Falls (i.e. in Reaches 1 and 2).
- In the lower reaches, mini-jams tend to occur first in the river gorge just downstream of Louise Falls (Reach 3) and at the Pine Point Bridge (Reach 4).

Stage 6. ***<u>Ice jams:</u>*** The creation and consolidation of mini-jams result in small, localized fluctuations in water levels that in turn break away pieces of the intact ice sheets upstream. In this way, small ice jams increase in length as breakup progresses (Figure 2.14 e). Eventually this can lead to ice accumulations about 5 to 20 km in length.

- In Reach 2, the most significant ice jams tend to occur at Grumbler Rapids.

- In Reach 3, this stage generally involves lengthening of the ice jam in the gorge downstream of Louise Falls (between Escarpment Creek and Enterprise). Breakup of the ice cover just upstream of Alexandra Falls typically precipitates a brief, but dramatic ice run over the falls. As these ice runs pass over Alexandra and Louise Falls, the ice floes are pulverized into small pieces, and pack tightly into the gorge. This gorge jam accumulates ice runs from upstream until it can overcome its physical constraints and shove forward.

- In Reach 4, this generally results in the formation of an ice jam extending down the East Channel to the NTCL berm and along most, or all, of the West Channel.

Stage 7. ***<u>Ice jam release and ice runs:</u>*** The water and ice impounded in an ice jam exert a tremendous driving force, and some ice jams will consolidate (shove and thicken) under the pressure. In some cases, the ice jam itself will let go, releasing a steep fronted water wave which travels downstream at high speed. Beltaos (2008) refers to these ice <u>ja</u>m release wa<u>ves</u> as "javes". Violent ice runs associated with javes have been documented moving at speed of up to 5 m/s (18 km/h). They can push through an intact ice cover or alternatively, they may lose momentum and stall to form a new ice jam.

Although the jave and the ice run initially travel together, the jave eventually moves out ahead of the ice run. When the water wave and ice run reach a downstream ice jam, the water wave first lifts and destabilizes the ice jam, then the ice run impacts on the ice jam, consolidating it. The combined effect of the water wave and ice run are often sufficient to cause the release of the downstream ice jam. This is especially likely if the ice jam is held in place by a segment of intact ice that is lifted free of geometric constraints by the precursor water wave. If the ice jam does not release, or if an ice jam reforms somewhere downstream, some of the water wave will travel underneath this ice and continue downstream.

- The release of the gorge jam that forms every year in Reach 3 should be monitored. There are two scenarios of ice conditions between the jam formed in Reach 3 and the Town of Hay River (Reach 5). The first is that the backwater waves from the onset of breakup in the delta chip away at all remaining ice in Reach 4 (from *km 1048* at Enterprise to *km 1098* at the Pine Point Bridge).

This results in an unimpeded ice run situation when the jam in the gorge in Reach 3 does release. In this second case, the jam in Reach 3 releases while there is still intact ice present in Reach 4. This creates an impeded ice run scenario, when the ice run encounters this intact ice and either ploughs through it, or jams again only to release later (re-jamming).

Stage 8. ***Re-jamming:*** Ice jam release events sometimes progress down the Hay River in domino fashion, with the ice runs from upstream ice jam release events instigating the release of the next downstream ice jam. In this case, the ice runs increase in size as they progress downstream. Alternatively, ice runs tends to stall at tight bends and islands. This temporarily re-jams the ice, causing water and ice pressures to build up and then release with renewed speed and magnitude.

- Common stalling points in Reaches 3 and 4 include: the gorge at Escarpment Creek, the island just downstream of Enterprise, the tight bend at Paradise Gardens, and the right angled bend at the Golf Course.

Stage 9. ***Jam formation in the Hay River delta*:** There are typically two stages in the ice jam formation in the Hay River delta: the onset of breakup which creates small ice accumulations and the arrival of ice runs from upstream which cause large ice jams and the peak stage.

- Before the onset of breakup, the ice in the West Channel typically thermally deteriorates leaving areas of open water, especially around the bridge. The onset of breakup occurs when ice cracks and jams in lower Reach 4 at the Pine Point Bridge site. This ice pushes though the deteriorated ice between the Pine Point Bridge and the Forks to create the small ice accumulations in the delta. When this occurs, the backwater sends a small wave upstream, which chips away at the intact ice further upstream. Typically, the initial ice push from the Pine Point Bridge (*km 1098*) shoves primarily into the West Channel. The toe of the initial East Channel jam usually forms at, or upstream of, *km 1110* then pushes downstream when the remaining javes arrive to lift and compound the existing jams in the delta. Ultimately, these jams cause the peak stage and possible flooding. Whether or not flooding occurs is variable, depending on: how far the toes of the jams shove down the East and West Channels; if the ice and water are able to discharge onto the lake; and the timing of the arrival of the peak snowmelt runoff.

Stage 10. ***Ice Jam melting out in the Hay River delta:*** When all the ice runs from upstream have arrived and consolidated in the Hay River delta, the ice jam sits in the East Channel (and sometimes West Channel) and thermally deteriorates. Large quantities of ice can be left on the river banks in the form of shear walls, but once the jam melts out to the intact lake ice, the flood risk has passed. Solar radiation is the main factor in this process, as it heats the open water upstream which erodes and melts out the ice jam much more effectively than warm air temperature. The tributaries in the upper basin carry a high sediment load. It is possible that because of this, this sediment laden water has a greater heat capacity, making it more effective at absorbing and retaining the sun's heat and at melting encountered ice.

- Heat appears to be transferred (melting is visible) to the leading (upstream) edge of the ice jam over a length of about one to two river widths. This segment at the upstream end of the ice jam darken and melts, and small open leads can appear. Then, this deteriorated ice collapses, creating a mini-shoving event.

- The leading edge of this melting front (indicating that all ice runs have arrived from upstream) is identifiable by the logs, woody debris and sediment are observed in the ice at the head of the ice jam (Figure 2.16). This phenomenon occurs when ice jams form upstream and backwater and ice runs accumulate until the jam overcomes its physical constraints and releases. This causes bank erosion, uproots trees and sweeps any existing downed material into the ice jam. The eroded silt and trees are carried downstream in ice runs, and become more and more concentrated at the head (leading edge) of the jam as the ice melts.

- The warm, sediment laden water from the tributaries is very effective at melting out the delta ice jams. The historical record shows that the jam in the delta can melt out on the day of the peak stage jam, or can take more than a week.

Once this general sequence of breakup was determined, analysis of meteorological data, water levels and dates was done to quantify these steps of breakup. Consolidating the qualitative with measurable parameters allowed specific patterns in the timing and sequencing of breakup to be determined.

2.3 Meteorological Data

Meteorological data relevant to the Hay River basin was available from two Environment Canada stations; one at the Hay River Airport, located on Vale Island and one at the High Level Airport, located 14 km north of the town of High Level (Figure 1.1). High Level weather data was considered in addition to the Hay River data in order to investigate whether daily temperatures in the upper basin contributed to the progression of breakup to a different extent than those in the lower basin.

Solar radiation was originally the meteorological parameter of choice to consider, but unfortunately there is no continuous record available for Hay River. Prior to 1996, solar radiation measurement was done by Environment Canada using sunshine balls. Since then, pyronometers have been used through a joint effort by DIAND and the University of Alberta; however, due to a number of equipment malfunctions, this record is intermittent. Therefore, the accumulated degree-days of thaw (ADD_t) have been used as a surrogate for heat input to the system. Accumulated degree-days of thaw (ADD_t) are the sum of all mean daily air temperatures above a specified baseline temperature. This tally begins once the mean daily temperatures are greater than this baseline temperature for five consecutive days. Six conventions were considered when calculating the accumulated degree-days of thaw (ADD_t), as discussed in Chapter 3 to determine which might be the most useful surrogate for heat input in the breakup process. Mean daily air temperatures recorded at the Hay River and High Level Airports have been used to calculate accumulated and total degree-days of thaw throughout the breakup period for each year. Hay River temperature data was available for 1951, 1954, 1956 and all years since 1963, while meteorological data was available for High Level since 1970. Although there were gaps in the Hay River record, a regression equation was developed between the Hay River meteorological station and the nearby Paradise Gardens station to determine replacement temperatures (Zhao *et al.* 2010).

2.4 Historical Flood Severity and Associated Breakup Dates in the Town of Hay River

The historical breakup accounts document the timing and/or severity of breakup for most years since 1894 (Appendix A). Most tended to focus primarily on years in which flooding occurred; consequently, very little is known about the uneventful years. Table 2.2 summarizes the available data. Here, “some” flooding refers to years in which flooding was documented to have occurred, but was not described as “significant”. As it is unknown in these cases whether minor or moderate flooding occurred, and as there is really no quantitative assessment tool for distinguishing minor versus moderate flooding, they have been grouped together under the descriptor “some” flooding.

Also included in Table 2.2 are the following key dates (where known):

- D_o – the date of the onset, or initiation, of breakup. This refers to the first sustained ice movement in the Hay River delta, which occurs when ice runs from upstream (from between the Pine Point Bridge (*km 1098*) and the Forks at *km 1108*) break up local ice causing small ice jams to form in the East and/or West Channels.
- D_p – the date on which the peak breakup stage occurred in the Hay River delta during breakup. This generally occurs as a result of incoming ice runs from upstream consolidating the small ice jams that formed on the date, D_o, and causing water levels to rise. If the incoming ice was insufficient to consolidate the small ice jams already in place, then the peak water levels were those associated with the initial jams ($D_p = D_o$).
- D_m – the date on which the ice jam(s) in the Hay River delta melted out to leave a clear flow path right to Great Slave Lake.

Over the 116 year period between 1894 and 2010, significant ice jam flooding was documented in 11 years and at least some (mild or moderate) flooding was documented in 23 years. No ice jam flooding was documented in 83 years. Thus, at least some ice jam flooding occurs, on average, about once every 3 years. This historical record of dates of breakup allows the range of dates during which the onset of breakup, peak stage jam and melt out occurred to be determined. Also, the number of days between these breakup stages are considered, as are rates of melting front advance for years when this is known.

2.4.1 Historical Breakup Dates in the Town of Hay River

Figure 2.17 illustrates the dates of the onset of breakup (first sustained ice movement) in the Hay River delta, D_o, for all years and flood severity types. This date is known for all 11 years of record in which significant flooding occurred and, for the years when at least some flooding occurred, it is known for 21 out of 23 events. This date was documented for only 52 of the 83 years of no known flooding. Although the years with no known flooding are under-represented in Figure 2.17, they were included to illustrate the full range of known breakup dates, which extend from 22-Apr to 21-May. It is interesting to note that the earliest and latest breakup onset dates corresponded to years with no flooding.

Figure 2.18, which excludes the years with no known flooding, illustrates that this range is tighter for events that eventually led to flooding. For example, for years in which significant flooding occurred, the dates are clustered between 23-Apr to 6-May. For years in which minor or moderate flooding occurred (i.e. ‘some’ flooding) the onset of breakup in the delta mostly occurred between 23-Apr and 7-May. There are two exceptions to this range; both occurred later than 7-May:

- 11-May-79: The spring of 1979 was unseasonably cold with a ten day period of sub zero temperatures (totalling -85˚C-days) ending two days before the onset of breakup in the delta. It is likely that this delayed the onset of breakup.
- 9-May-33: There was no meteorological data available to aid in interpreting the reason behind this late onset of breakup.

For the largest ice jam flood on record (1963), D_o occurred on 27-Apr (Gerard and Stanley 1988a and b). The most common date for the onset of breakup in the Hay River delta, for those years in which some or significant flooding occurred, was 2-May.

Figure 2.19 illustrates the date of peak stage due to ice jam flooding in the Hay River delta, D_p. This peak stage typically occurs when all of the upstream ice arrives, consolidating the existing initial jam that had formed on date D_o. D_p was documented for all 11 significant flood events and for 20 of the 23 events involving at least some flooding. Of the 83 years with no known flooding, this date was documented for only 16 years. Although the years with no known flooding are under-represented, the inclusion of these 16 dates helped to illustrate the historical range of known dates, which extended from 23-Apr to 19-May.

Figure 2.20 shows the dates of peak stage in the Hay River delta, D_p, for only those cases where ice jam flooding occurred. These were clustered between 28-Apr to 7-May for significant flood years. For those years with some flooding, the peak stage in the delta occurred primarily between 25-Apr and 10-May, with only one exception: 14-May-79. As discussed above, the cold pre-breakup period in 1979 is believed to have delayed breakup that year. Including all years where flooding occurred, the most common date for the peak breakup stage in the delta was 7-May. It is interesting to note that the peak stage in 1963 occurred on 1-May (Gerard and Stanley 1988a and b).

The date that ice jams melted through to Great Slave Lake, D_m, were also documented intermittently in the historical records. These dates represent the point when the flood risk has passed for the Town of Hay River, as there is no ice jam left to cause backwater and associated flooding. As with the dates of the onset of breakup and peak stage, the melt out dates for all severity types were also examined for commonality, as shown in Figure 2.21. These were documented for 10 of the 11 significant floods and in 20 of 23 years when some flooding occurred. Of the 83 years with no known ice jam flooding, the melt out date was recorded for 70 years.

As with D_o and D_p, there has been a wide range of historical melt out dates (D_m). This is especially true for years with no known flooding, ranging from 22-Apr and 19-May. Figure 2.22 shows the melt out date, for only those years in which flooding occurred. The range for significant flood event years was between 30-Apr and 12-May, while ice jams resulting in some flooding have typically melted out between 28-Apr and 10-May. Exceptions to this are 17-May-79 and 13-Apr-

56, both later than typical. As previously mentioned, 1979 experienced a late breakup due to an extended subzero pre-breakup period; this likely accounts for the usually late melt out date as well. There was no meteorological data available to aid in interpreting the reason behind the late onset of breakup in 1956.

2.4.2 Days Between the Stages of Breakup in the Town of Hay River

In addition to the dates of occurrence of these three stages in the breakup process occurring in the delta, the number of days between these stages of breakup were also examined. Figure 2.23 shows the distribution of number of days between the onset of breakup in the delta, D_o, and the date of peak stage, D_p, for all known cases. In 15 of 83 years when no flooding occurred, there tended to be less time between the onset of breakup and peak stage, ranging from 0 to 2 days. Note that value of zero days between D_o and D_p can be interpreted in two ways:

1. The peak stage can be attributed to the initial (small) ice jam(s) that formed in the delta channels (i.e. there was no subsequent 'push' from upstream ice to consolidate the ice jam(s) and raise water levels further). This is generally associated with the non-flood events.
2. The two separate events: the initial ice jam formation in the delta and the subsequent push from upstream ice occurred on the same day. This is more likely to be associated with flooding events.

Figure 2.24 shows the number of days between the onset of breakup, and the peak stage due to ice jam formation, ΔD_p (= D_p - D_o), for only those years in which flooding occurred. This is known for all 11 known significant floods, 19 of the 23 years with some flooding, and 15 of the 83 non- flood events. In 26 of 30 cases of flooding, the peak stage occurred within 4 days of the onset of breakup in the delta. The five cases involving longer intervals between the onset of breakup and the peak stage are discussed below.

- 1951: There were 13 days between the onset of breakup and the peak stage. This might possibly be explained by a 20 day sub-zero period (totalling -206˚C-days) between 4-Apr and 25-Apr. Although the onset of breakup was early (D_o = 23-Apr), the extended cold temperatures are thought to have delayed subsequent breakup stages.
- 1956: There was a five day delay between the onset of breakup and the peak stage in the delta. However, there is no meteorological data available to aid in interpreting the possible cause of this delay.
- 1972: The peak stage in the delta occurred 5 days after the onset of breakup. The pre-breakup temperatures in 1972 were not noteworthy, and do not indicate why there was a delay between the onset of breakup and the peak stage in the delta.
- 1974: the peak stage occurred 6 days after the onset of breakup in the delta. Here, the onset of breakup (D_o = 27-Apr) was followed by six days of subzero temperatures (totalling -33˚C) between 29-Apr and 4-May; this is thought to have delayed the peak stage event.
- 1977: the peak stage occurred 6 days after the onset of breakup in the delta. The pre-breakup temperatures in 1977 were not noteworthy, and do

not indicate why there was a delay between the onset of breakup and the peak stage in the delta.

The number of days between the onset of breakup and complete melt out of the ice in the delta, ΔD_m (= D_m - D_o), are shown in Figure 2.25 for all known cases; Figure 2.26 shows ΔD_m for only those years where flooding occurred. This was known for 44 of 83 cases with no known flooding, 18 of 23 years with some flooding and 10 of 11 cases with significant flooding. As the figures illustrate, this can take as little as one day, or as long as two weeks. However, there is a difference in ΔD_m between the flood and non flood years; this took less time when no flooding occurred. In 24 of 44 cases of no flooding, the jam melted out within 2 days of the onset of breakup, but ΔD_m has taken as long as 12 days. In known cases of flooding, 24 of the 28 flooding events, the ice jams melted out to Great Slave Lake between 2 and 8 days of the onset of breakup. Significant flooding cases had ΔD_m between 2 and 7 days, while cases of some flooding took between 3 and 8 days. There are only three known flood related cases where the melt out followed the onset of breakup by more less than 2 days or more than 8 days: 1951, 1956 and 1963. As discussed above, in 1951 an extended cold period occurred just prior to or surrounding the onset of breakup and this is believed to have delayed and prolonged the breakup processes (ΔD_m = 14 days). Also discussed above, there is no meteorological data available for 1956 to aid in interpreting the possible cause of this delay (ΔD_m = 11 days). In 1963, the onset of breakup occurred 15 days before the jam melted out. The peak stage in the delta occurred 4 days after the onset of breakup (ΔD_p = 4 days), and then the jam remained in place for an additional 11 days. The temperatures before and during breakup of this year were not noteworthy, and do not indicate why there was such a delay between the onset of breakup and the ice jam melting out to Great Slave Lake.

The number of days between the peak stage due to ice jam formation in the delta and ice jam melt out, ΔD_{m-p} (= D_m – D_p) describes the duration of flood persistence in the community, for years in which flooding occurred. These were documented for 10 of the 11 significant floods and in 17 of 23 years when some flooding occurred. Of the 83 years with no known ice jam flooding, ΔD_{m-p} was recorded for 15 years. Figure 2.27 shows this for all known events and suggests that melt out is generally complete within 7 days of the peak stage in the delta, independent of whether flooding occurs or not. Figure 2.28 presents the known data for only those years where flooding actually happened. For 23 of the 27 cases of flooding for which D_{m-p} is known, the ice jam melted out within 3 days of the peak stage occurrence. The 4 anomalous cases (taking 5, 6, 7 and 11 days) are 1923, 1956, 1904 and 1963. As previously mentioned, there is no historical meteorological data available for the 1904, 1923 and 1956 which would aid in interpreting this. As previously discussed, the data for 1963 provides no clues as to why breakup was of prolonged duration that year. It is especially interesting to note that, for the 26 cases where D_{m-p} is known and flooding occurred, the ice jams all melted out between 1 and 3 days for 9 of the 10 cases in which significant flooding occurred.

2.4.3 Rate of Melting Front Advance

The historical dates of peak stage due to ice jam formation and when the ice jams melted out to Great Slake Lake have been documented for many years. The first of these stages is when maximum flooding occurs. The second is when the danger of additional flooding has passed. Between these stages, the ice jams thermally deteriorate until there is open water throughout the Hay River delta. The time interval between the peak ice jam stage and complete melt out is quite variable, as was seen in the previous section. For years with sufficiently detailed records, the speed and progression of these melting fronts could be determined. These melting fronts were tracked by noting the time and a description of the physical location of the front (head of the jam) throughout the melting period. Global positioning system (GPS) way points were also used to track the location of the melting front in some cases.

Figure 2.29 illustrates the location of these melting fronts for the 11 years in which this progression was documented; Appendix B presents the corresponding data. Most observations follow the East Channel; however, in some cases, the melting front progression was also documented in the West Channel. (West Channel data are illustrated in Figure 2.29 using symbols with no fill.) In many instances, the rates of melt down the two channels were similar.

Although the melting front has been documented to progress as fast as 5 km/hr (specifically for a period of 25 minutes in 1987), typical rates are much slower than this. Note the tendency for there to very little melt in the initial 12 hours of data, shown by a short, steep slope (very slow rate of advance) followed by more representative gradual slope (faster rate of advance) over several days. This trend is present in 1988, 1990, 2008 and 2010 and is thought to be the case for years when the melting front was tracked since the occurrence of the peak stage jam, rather than cases where the front locations were documented some time afterward the occurrence of the peak stage. Regardless of whether the melting fronts were tracked since the occurrence of the peak stages or if documentation began some time after, the representative melting rates (slope of the trends in Figure 2.29) are very consistent.

The average rate of melting front advance in any given year was taken as the linear best fit to the points on Figure 2.29; these were found to range from ~200 to ~480 m/hr. To put this in perspective, an ice jam extending upstream to the Pine Point Bridge (*km 1098*) would be expected to melt out along the East Channel to Great Slave Lake (*km 1114*) in 31 to 103 hours (1.3 to 4.3 days). An ice jam extending upstream to the Courthouse (*km 1106.1*), the melting front would be expected to reach the lake in 16 to 52 hours (0.8 to 2.2 days). Melt out from the Forks (*km 1108*) to the lake would be expected to take between 12 to 38 hours (0.5 to 1.6 days).

These representative speeds are grouped by flood severity class in Figure 2.30. Here, it is clear that there is a propensity for ice jams resulting in no flooding to melt out faster than ice jams causing some or significant flooding. All melt out rates greater than 313 m/hr corresponded to ice jams resulting in no flooding, but one non-flood year melted out more slowly (219 m/hr). Ice jams resulting in floods are typically thicker than those resulting in no flooding, and as such take more time to melt out. The rates of melt out for ice jams resulting in significant or some flooding ranged from 202 to 224 m/hr and 216 to 312 m/hr, respectively.

Although this historical analysis of past breakup events on the Hay River cannot fully be used in a predictive capacity, it gives an indication of the dates of and time between breakup stages in the Hay River delta. These thresholds and windows of time can be used to anticipate the most active period for the Flood Watch Committee. Windows of dates of past onsets of breakup, peak stages and melt out stages were grouped by severity, as were the past number of days between these stages. As well, they can be used to gauge how flooding can be expected to persist.

2.4.4 Long term Trends in the Timing of Breakup Stages in the Delta

The long term trends in the dates of onset of breakup (D_o), peak stage (D_p) and melt out (D_m) were examined. Figures 2.31 (a), 2.32 (a) and 2.33 (a) illustrate that there are no significant correlations showing that the dates of onset of breakup, peak stage and melt out occurred earlier over time. The dates of D_o, D_p and $D_{m,}$ appear relatively constant between 1894 and 1980, but between 1980 to 2010 there does appear to be a negative trend. In order to investigate this trend, D_o, D_p and D_m between 1894 and 1980, and between 1980 and 2010 were considered separately. Figures 2.31 (b), 2.32 (b) and 2.33 (b) illustrate this for D_o, D_p and D_m, respectively. The average dates of D_o, D_p and $D_{m,}$ between 1980 to 2010 are three days earlier than the average dates from 1894 to 1980. A similar analysis was done separating the dates of breakup before and after 1990. The results were similar to those before and after 1980.

Another approach to examining this data was to consider each breakup event individually. The average D_o between 1894 and 2010 ($D_{o\ 1894\text{-}2010}$) was 2-May. The average D_o before 1980 ($D_{o\ 1894\text{-}1980}$) was 3-May; within one day (representative) of the historical average. However, the average D_o after 1980 ($D_{o\ 1980\text{-}2010}$) was 30-Apr. This indicates that since 1980, on average the date of onset of breakup occurs earlier than before 1980. Similarly, the average D_p and D_m between 1894 and 2010 (D_p and $D_{m\ 1894\text{-}2010}$) were 3-May and 5-May, respectively. The average D_p and D_m before 1980 (D_p and $D_{m\ 1894\text{-}1980}$) were 4-May and 6-May; also within one day (representative) of the historical averages. But when the dates after 1980 are considered, the average D_p and D_m (D_p and $D_{m\ 1980\text{-}2010}$) were 1-May and 3-May, respectively. For all breakup stages considered here, those occurring since 1980 have tended to happen earlier.

2.5 Direct / Photographic Documentation

Highly detailed information is required to study the progression of breakup on the Hay River. As breakup, ice jams and subsequent flooding in the delta are what locals are most concerned with, this is where the historical documentation efforts were concentrated, while very little mention is made of the sequence of breakup upstream. For example, the details about the progression of breakup provided for the springs of 1977, 1985, 1987, 1988 and 1989 in Section 2.2.1 are localized to Reaches 3, 4 and 5 (downstream of *km 1034.5* at Alexandra Falls). At a minimum, this level of detail is required along the entire study reach.

For this study, the progression of breakup was documented from the NWT/AB border to the town of Hay River in 2005, 2007, 2008, 2009 and 2010[1], through aerial reconnaissance flights and photography, as well as by photos taken from the ground. These photos were taken by UA and DIAND researchers, local residents and EMO volunteers and by time lapse photography at remote stations using UA/DIAND and EMO equipment. Daily aerial photographic documentation began consistently in 2008; flights were more irregular in earlier years due to funding constraints. The time-lapse photography began in 2007, with the number of stations increasing each subsequent year. Although five years of data is not a particularly long record, it is enough to reliably determine key spots for further study and future monitoring and to identify relevant indicators of breakup timing and sequence.

[1] As noted earlier, insufficient funds were available to conduct comprehensive monitoring in 2006.

2.5.1 Aerial Photography and Observations

Aerial observation flights following the river from the Town of Hay River to the NWT/AB Border, and back, allow for a full view of the progression of breakup along the river. Members of the Town Flood Watch Committee have long been aware that breakup stages happening upstream were important indicators of the timing and severity of breakup in the Town of Hay River, and have often embarked on aerial observation flights during breakup. These flights have sometimes been confined to the lower Hay River basin, though they have on a number of occasions extended far upstream into the headwaters of the Chinchaga River. By necessity, the purpose of those flights was operational in nature with the information gained typically being used for immediate emergency preparedness planning only. Consequently, the photographs available prior to 2004 typically focus on documenting flood conditions rather than describing the various stages of breakup. In addition to this, until recently the available technology did not allow observation flight photos to be of high enough resolution to be meaningful for detailed breakup progression analysis. Since then, equipment has evolved such that much more detailed photographic documentation is now possible. The advent of digital cameras has also greatly improved the continuity and coverage of flight photos, bypassing the expense and delay associated with developing photographs from film, as was the limiting case in earlier scientific studies (Stanley *et. al* (1959), Stanley *et. al* (1963), Diamond Jenness (1978), UMA (1978), Jasper (1983), GWNT/IWD (1984), Harrison

(1984), Gerard and Stanley (1988a and b), Wedel (1988), Gerard and Jasek (1990a), Gerard *et. al* (1990b), Jasek *et. al* (1993), and Jasek (1993)).

When the University of Alberta resumed research on the Hay River in 2004, local experts were most generous in sharing their knowledge of the importance of upstream stages in determining the progression of breakup on the Hay River. Consequently, aerial observation flights were conducted over the upper reaches of the Hay River intermittently during the late breakup period 2004, 2005 and 2007. The research team quickly realized that in order to identify indicators as to the timing of upstream breakup stages, ice conditions in the reach had to be documented before breakup began, and daily thereafter so as not to miss any steps in the breakup evolution.

In 2008, 2009 and 2010, sufficient funds were available to allow for daily flights throughout the entire breakup period, and two flights per day during the most active period. Several hundred images were taken on each flight, and these were synchronized with GPS track logs from the same flights to match each photograph to its specific location along the river (Table 2.3). These images were used to document the pattern of ice deterioration, transverse cracks, sheet ice accumulations, the locations of ice jams, ice runs and surface ice concentrations.

In total, ~28,000 aerial observation photographs were available from various sources for this study. A complete list of flights, and corresponding dates of coverage, are provided in Appendix C.

2.5.2 Time-Lapse Photography and Ground Observations

Photographs of breakup stages have been taken from the banks of the river for years by locals, the media, and researchers. These photographs are usually taken at random locations after significant events (particularly ice jams) occur. These are not necessarily time stamped to document the date; therefore, although useful for the interpretation of historical records, these photographs do not provide the continuous data required to aid in understanding the progression and sequence of breakup on the Hay River.

In order to aid in the interpretation of recorded water levels at Alexandra Falls, Paradise Gardens and the Pine Point Bridge, ice conditions have been documented by UA and DIAND at each of these sites using time-lapse photography since 2007. Images were recorded every 60, 30, 15, 10 or 5 minutes. Additional time-lapse cameras were acquired in each subsequent year, enabling additional key sites to be including in documenting the progression of breakup from the ground (Table 2.4). In addition, a number of the cameras were subsequently set up to be accessible remotely using communications equipment purchased by THR, UA and DIAND. Although most of the photographic documentation has been confined to day light hours, in 2009 and 2010, the UA did employ lighting and higher quality time-lapse camera systems capable of capturing images at night.

In total ~62,000 photos were collected, providing detailed documentation of ice conditions over the breakup period at key sites of interest. A complete list of time-lapse camera station locations and summary of dates of coverage, photograph intervals, and camera owners/operators is provided in Appendix D.

2.6 Water Level Data

2.6.1 Stage Hydrograph Data

There are ten water level gauge stations in operation during breakup in the Hay River basin; four are located in the headwaters of the basin (south of the NWT/AB border) and six are along the Hay River within the study reach. The water level hydrographs of the gauge stations outside the study reach were analyzed to determine the date and water level at which the first transverse crack occurs. As the dates of breakup stages at the six gauge stations within the study were already known from observation flights, the water levels during break stages and water level increases between breakup stages were determined. The UA/ DIAND research team also measured water levels as well as ice jam profiles in the Hay River delta during breakup. These ice jam profiles were compared to the historical profiles provided in a number of consultant reports.

2.6.1.1 Water Survey of Canada (WSC) Gauges

Figure 1.1 shows the locations of the six Water Survey of Canada (WSC) gauges in the Hay River basin where water levels are continuously monitored during the breakup period. There are two Water Survey of Canada (WSC) gauges in the study reach: one located at the NWT/AB Border (HRNWTAB 07OB008) at *km 945.6*, and the other is located just upstream of the Town of Hay River at *km 1095.2* (HRHR 07OB001). These two water level gauges will thereafter be referred to as the WSC Border gauge (HRNWTAB) and WSC gauge near Hay River (HRHR), respectively. The WSC Border gauge (HRWNTAB) is set up before breakup each spring so that this water level data is available online for use in the Town of Hay River's breakup monitoring program, while the WSC gauge near Hay River (HRHR) is operational year round. Appendix E notes the locations of these stations, the years and dates of data coverage for each and the time increment that water levels were recorded.

There are an additional four WSC gauges in the Alberta portion of the Hay River basin. Of these four gauges, one is located on the Chinchaga River near High Level (WSC CRHL 07OC001), while another is on the Hay River near Meander River (WSC HRMR 07OB003). The remaining two gauges are located on small tributaries to the Hay River: at Sousa Creek near High Level (WSC SCHL 07OA001) and Steen River near Steen River (WSC SRSR 07OB004).

2.6.1.2 Town of Hay River (EMO) Gauges

Since 2003, the Town of Hay River's (EMO) has operated acoustic water level sensors at four sites along the Hay River (Figure 2.2): 2 km upstream of Alexandra Falls (*km 1032.0*), Paradise Gardens (*km 1067.9*), the Pine Point Bridge (*km 1098.1*) and the West Channel Bridge (*km 1108.3*). These sites were chosen based on accessibility and function: all have road access and these sites are also known to experience predictable breakup patterns. These gauge sites consist of acoustic sensors suspended over the river from either a cantilever boom (Alexandra Falls (Figure 2.34 a) and Paradise Gardens (b)) or a bridge (Pine Point Bridge (c) and West Channel Bridge (d)). Appendix F summarizes these stations, their locations, the years and dates of data coverage for each and the time increment that water levels were are recorded.

2.6.1.3 University of Alberta (UA) gauges

The University Alberta and DIAND research crew have measured water levels along the Hay River since 2004, using a variety of techniques, including:

- manual surveying using a rod and level;
- manual surveying using a real time kinematic global positioning system (RTK GPS);
- automated measurements using laser rangefinders;
- automated measurements using submersible pressure transducers; and
- manual measurements using staff gauges (documented photographically).

These manual water level measurements are being used in concurrent flow modeling research at the University of Alberta, but are not immediately relevant to this aspect of the Hay River breakup study.

2.6.1.4 Discussion of Stage Hydrograph Data

As discussed, the stage hydrographs from six WSC and four EMO gauges were made available for analysis. The dates of breakup at the gauge sites within the study reach were determined through the analysis of aerial and time-lapse photographs. When known, these dates were annotated on the available stage hydrographs. Appendix G contains the annotated stage hydrographs from the two WSC and six EMO water level gauge sites located in the study reach. Appendix H contains the annotated stage hydrographs from the four WSC gauges in the basin headwaters. As these sites are outside the study reach, there was no photographic coverage of the area to determine the dates of local breakup stages at these sites. However, the dates of first cracking at the WSC gauges near Chinchaga River (CRHL), Sousa Creek (SCHL), Steen River (SRSR) and Meander River (HRMR) were based on the dates of the first erratic fluctuation in the gauge records. These dates are annotated on the stage hydrographs in Appendix H.

2.6.2 Water Surface Profile Data

The historical reports include documented ice jam profiles for a number of past events along the East and West Channels. (Figures 2.35 and 2.36, respectively).

The sources of these profiles are listed in Table 2.5. The UA/DIAND research crew also surveyed ice jam profiles in 2008, 2009 and 2010 after each stage of ice jam shoving in the Hay River delta (Table 2.6). The highest profiles measured in the East and West Channels in each of these years is also presented in Figures 2.35 and 2.36. The severity of flooding caused by ice jams depended on the location of the toe of the jam; in this way, flooding can be quite localized and variable. Figure 2.35 shows that in 1963, the toe of the ice jam shoved to *km 1114.1* in the East Channel, while in 1985 the toe formed at *km 1111.3*. These two ice jams resulted in the most significant flooding of the Hay River delta communities, however the extent of the flooding was quite different.

Table 2.1: List of key sites and river stationing in each reach.

Reach	Key Site	Acronym	River km	Figure No.
2	NWT\AB Border	Border	945.5	Figure 2.3
2	Island at km 974	Island	974.0	Figure 2.4
2	Grumbler Rapids	Grumb	986.0	Figure 2.5
2	Mink Creek	MC	1027.0	Figure 2.6
2	Alexandra Falls	AF	1034.0	Figure 2.7
3	Escarpment Creek	Esc	1040.5	Figure 2.8
3	Enterprise	Ent	1048.0	Figure 2.9
4	Paradise Gardens	PG	1071.0	Figure 2.10
4	Golf Course	GC	1088.5	Figure 2.11
4	Pine Point Bridge	PPB	1098.0	Figure 2.12

Table 2.2: Summary of flood severity, onset of breakup date (D_o), date of peak stage (D_p) and melt out (D_m) dates for all known years (1894 to 2010). Full details are found in Appendix B.

Year	D_o	D_p	D_m	Flood Severity
1894	9-May[1]	-	15-May[1,5]	None[2]
1895	3-May[1]	-	3-May[1,5]	None[2]
1896	11-May[1]	-	11-May[1,5]	None[2]
1897	-	-	-	None[2]
1898	29-Apr[1]	-	-	None[2]
1899	-	-	-	None[2]
1900	22-Apr[1]	-	-	None[2]
1901	-	-	-	None[2]
1902	13-May[1]	-	-	None[2]
1903	19-May[1]	-	-	None[2]
1904	27-Apr[2,3,4]	28-Apr[2,3,4]	5-May[1,5,6]	Some[4,6,28]
1905	4-May[1]	-	4-May[1,5]	None[3]
1906	26-Apr[1]	-	26-Apr[1,5]	None[1,3]
1907	12-May[1]	-	21-May[1,5]	None[1,3]
1908	8-May[1]	-	9-May[1,5]	None[1,3,28]
1909	21-May[1]	21-May[1]	21-May[1,5]	None[1,3]
1910	7-May[1]	-	7-May[1,5]	None[1,3]
1911	3-May[1,2,28]	4-May[1,2,4]	6-May[5]	Some[2,4,6,28]
1912	-	-	13-May[1,5]	None[1,2,3]
1913	-	-	10-May[1,5]	None[1,2,3]
1914	30-Apr[1.2,3.4]	1-May[1,2,4]	2-May[1,2,4,5,6]	Significant[1,2,3,4,6]
1915	22-Apr[1]	-	22-Apr[1,5]	None[1,2]
1916	1-May[1]	-	3-May[1,5]	None[1,2]
1917	-	-	12-May[1,5]	None[1,2]
1918	7-May[3]	-	9-May[1,2,3,5]	None[1,2,3]
1919	1-May[1]	-	2-May[1,5]	None[1,2,3]
1920	15-May[1]	-	16-May[1,5]	None[1,2,3]
1921	25-Apr[1]	25-Apr[1]	27-Apr[1,5]	None[1,2,3]
1922	7-May[1]	-	8-May[1,5]	None[1,2,3]
1923	29-Apr[1,2,4]	2-May[1]	7-May[1,2,5]	Some[1,2,4]
1924	-	-	-	None[2,3]
1925	-	-	6-May[1,5]	None[1,2,3]
1926	25-Apr[1]	-	29-Apr[1,5]	None[1,2,3]
1927	-	-	12-May[1,5]	None[1,2,3]
1928	6-May[1]	-	12-May[1,5]	None[1,2,3]
1929	5-May[1]	-	12-May[1,5]	None[1,2,3]
1930	9-May[1]	-	10-May[1,5,28]	None[1,2,3]
1931	9-May[1]	-	10-May[1,28]	None[1,2,3]
1932	2-May[1,2,4]	3-May[1,2,4]	3-May[1,2,5]	None[1,2,28]

Table 2.2 (continued): Summary of flood severity, onset of breakup date (D_o), date of peak stage (D_p) and melt out (D_m) dates for all years (1894 to 2010). Full details are found in Appendix B.

Year	D_o	D_p	D_m	Flood Severity
1933	9-May[1,2,4]	9-May[1,2]	-	Some[1,2,3]
1934	2-May[1,2,4]	2-May[1,4]	2-May[1,5,6]	Some[1,2,4,28]
1935	9-May[1]	-	-	None[1,2]
1936	7-May[1]	-	11-May[1,5]	None[1,2]
1937	28-Apr[1]	29-Apr[1]	2-May[5]	None[1,2,3]
1938	8-May[1]	-	9-May[1,5]	None[1,2,3]
1939	-	-	1-May[1,5]	None[2,3]
1940	29-Apr[1]	-	1-May[1,5]	None[1,2]
1941	-	-	29-Apr[1,5]	None[1,2]
1942	-	-	3-May[1,5]	None[1,2]
1943	-	-	3-May[5,7]	None[2,7]
1944	-	-	27-Apr[5,7]	None[2,7]
1945	-	-	18-May[5,7]	None[2,7]
1946	-	-	2-May[5,7]	None[2,7]
1947	7-May[4,7]	7-May[7]	10-May[4,5,6,7]	Some[4,6,7,28]
1948	9-May[7]	10-May[7]	11-May[5,7]	None[7,8]
1949	3-May[7]	-	4-May[5,7]	None[7,8]
1950	-	7-May[8,9]	7-May[5,8,9]	Some[1,8,9]
1951	23-Apr[13,10]	6-May[13,10,11]	7-May[10,11,13,28]	Significant[13,10,11]
1952	25-Apr[9,11,28]	28-Apr[4,9,11]	-	Some[4,9,11]
1953	-	-	29-Apr[5,9,12]	None[9,12,13]
1954	12-May[14]	13-May[14]	17-May[5,14]	None[5,14]
1955	1-May[15,28]	5-May[15]	6-May[5,15,28]	Some[13,28]
1956	2-May[13,28]	7-May[13,28]	13-May[5,13,16]	Some[13,16]
1957	30-Apr[13,28]	2-May[13,28]	4-May[13,28]	Some[10,11,13]
1958	22-Apr[9,13,16]	23-Apr[13,16]	30-Apr[5,9,13,16]	None[9,13,16]
1959	-	-	14-May[5,9]	None[9,12]
1960	24-Apr[9,12]	-	1-May[5,12]	None[9,12]
1961	8-May[9,12]	-	12-May[5,12]	None[9,12]
1962	-	-	17-May[9,12,28]	None[9,12]
1963	27-Apr[9,10]	1-May[10]	12-May[6,28]	Significant[6,9,10]
1964	28-Apr[12]	-	10-May[5,6,9,12]	None[6,9]
1965	28-Apr[9]	2-May[9,12]	4-May[5,6,9,12]	Some[9,12]
1966	-	-	12-May[5,6,9,17]	None[9,17]
1967	-	-	13-May[5,6,9,17]	None[9,17]
1968	-	-	4-May[5,6,17,18]	None[17,18]
1969	26-Apr[17]	-	29-Apr[5,6,17,18]	None[17,18]
1970	-	-	7-May[5,6,17,18]	None[17,18]

Table 2.2 (continued): Summary of flood severity, onset of breakup date (D_o), date of peak stage (D_p) and melt out (D_m) dates for all years (1894 to 2010). Full details are found in Appendix B.

Year	D_o	D_p	D_m	Flood Severity
1971	-	-	30-Apr[5,6,17,18]	None[17,18]
1972	5-May[17]	10-May[17]	10-May[5,6,18]	Some[17,18]
1973	-	-	2-May[5,6]	None[5]
1974	27-Apr[17,28]	3-May[10,17]	4-May[5,6,10,17,18]	Significant[10,17,18]
1975	-	-	1-May[5,6,17,18]	None[17,18]
1976	-	-	27-Apr[5,6,12,18]	None[12,18]
1977	27-Apr[19,20]	3-May[19,20]	4-May[5,6,18,20]	None[18,20]
1978	3-May[12]	4-May[12]	7-May[12,21]	Significant[12,20]
1979	11-May[12,21]	14-May[12]	17-May[21,28]	Some[12,21]
1980	-	-	29-Apr[20,21]	None[20]
1981	4-May[21]	-	9-May[21,28]	Some[20,21]
1982	8-May[21]	-	10-May[21,28]	None[20]
1983	28-Apr[20]	-	4-May[20,21]	None[20]
1984	-	-	30-Apr[21,28]	None[20]
1985	6-May[6,11]	7-May[6,11,22]	9-May[11,21,28]	Significant[6,11,12]
1986	4-May[11]	7-May[11]	8-May[11]	Significant[11,28]
1987	26-Apr[11]	28-Apr[11]	1-May[11]	None[11]
1988	27-Apr[11]	27-Apr[11]	2-May[11]	None[11]
1989	2-May[21,23,24]	5-May[21,24]	6-May[21]	Significant[21,23,24]
1990	27-Apr[21,25]	28-Apr[21,25]	2-May[21]	None[21,25]
1991	24-Apr[21,25]	25-Apr[21,25]	1-May[21,25]	None[21,25]
1992	26-Apr[21,25]	28-Apr[21,25]	30-Apr[21,25]	Significant[21,25]
1993	5-May[21]	5-May[21]	6-May[21]	None[21,26]
1994	27-Apr[24]	30-Apr[24]	1-May[24]	Some[24]
1995	2-May[21]	-	-	None[24]
1996	1-May[24]	-	2-May[24]	None[24]
1997	2-May[24]	-	-	Some[24]
1998	30-Apr[24]	2-May[24]	-	None[24]
1999	-	-	-	None[24]
2000	-	-	-	None[24]
2001	4-May[24]	4-May[24]	-	Some[24]
2002	15-May[24]	-	-	None[24]
2003	28-Apr[24]	1-May[24]	-	Significant[24]
2004	-	1-May[27]	5-May[27]	None[24]
2005	23-Apr[27]	25-Apr[27]	28-Apr[27]	Some[27]
2006	24-Apr[27]	-	29-Apr[27]	Some[27]
2007	26-Apr[27]	27-Apr[27]	29-Apr[27]	Some[27]
2008	4-May[27]	5-May[27]	8-May[27]	Significant[27]

Table 2.2 (continued): Summary of flood severity, onset of breakup date (D_o), date of peak stage (D_p) and melt out (D_m) dates for all years (1894 to 2010). Full details are found in Appendix B.

Year	D_o	D_p	D_m	Flood Severity
2009	2-May[27]	6-May[27]	7-May[27]	Some[27]
2010	24-Apr[27]	25-Apr[27]	28-Apr[27]	Some[27]

[1] Diaries of the St. Peter's Anglican Mission as reported by Diamond Jennesse Social Studies Class (8C) (1978).
[2] St. Anne's and St. Peter's Mission Records as reported by Gerard and Stanley (1988a).
[3] T. Blench's notes as reported by Stanley, Grimble and Roblin Ltd. (1959).
[4] St. Anne's and St. Peter's Mission Records as reported by Jasper (1983). (1959).
[5] List compiled in Diamond Jennesse Social Studies Class (8C) (1978).
[6] Wedel (1988).
[7] Personal letter from Father Dessy dated 26-Apr-1978, as reported by Diamond Jenness (1978).
[8] Douglas (1952) as reported by Gerard and Stanley (1988a).
[9] EMO files as reported by Diamond Jenness (1978).
[10] Jasper (1983)
[11] Gerard and Stanley (1988a).
[12] EMO file as reported by Gerard and Stanley (1988a).
[13] Engineering reports as reported by Stanley *et. al* (1959).
[14] Ross (1954) as reported by Gerard and Stanley (1988a).
[15] Personal communications from E. Ramsey as reported by Diamond Jenness (1978) and Gerard and Stanley (1988a).
[16] Harriot (1956) as reported by Gerard and Stanley (1988a).
[17] TAPWE newspaper, as reported by Gerard and Stanley (1988a).
[18] TAPWE newspaper, as reported by Diamond Jenness (1978).
[19] UMA (1979).
[20] The HUB newspaper, as reported by Gerard and Stanley (1988a).
[21] Personal communications with D. Harrison (11-Feb-11).
[22] Environment Canada Report (1988)
[23] Gerard and Jasek (1990).
[24] HUB newspaper.
[25] Jasek et. al (1993).
[26] Jasek (1993).
[27] University of Alberta/DIAND research.
[28] University of Alberta interpretation of historic reports.

Table 2.3: Number of reconnaissance flights and photos taken in five years of record.

Year	No. Flights	No. Photos
2005	4	686
2007	8	1,642
2008	13	6,537
2009	16	10,578
2010	13	8,310

Table 2.4: Number of remote stations sites and photos taken in 4 years of record.

Year	No. Remote Sites	No. Photos
2007	3	10,953
2008	5	8,171
2009	9	19,254
2010	13	23,686

Table 2.5: List of sources of the surveyed ice jam flood profiles.

Year	Flood Severity	Report Source
1947	Some	Stanley, Grimble and Roblin, Ltd. (1959)
1951	Significant	Stanley, Grimble and Roblin, Ltd. (1959)
1963	Significant	Stanley, Grimble and Roblin, Ltd. (1959)
1985	Significant	Gerard and Stanley (1988a)
1989	Significant	Gerard and Jasek (1990)
1992	Significant	Jasek et al. (1993)
2008	Significant	University of Alberta/DIAND
2009	Some	University of Alberta/DIAND
2010	Some	University of Alberta/DIAND

Table 2.6: List of ice jam flood profiles taken in the Hay River delta in 2008, 2009 and 2010.

Year	Flood Severity	Date
2008	Significant	5-May-08
2008	Significant	6-May-08
2009	Some	30-Apr-09
2009	Some	3-May-09, am
2009	Some	3-May-09, pm
2009	Some	3-May-09, late pm
2009	Some	4-May-09
2009	Some	5-May-09
2009	Some	7-May-09
2010	Some	24-Apr-10
2010	Some	25-Apr-10
2010	Some	26-Apr-10

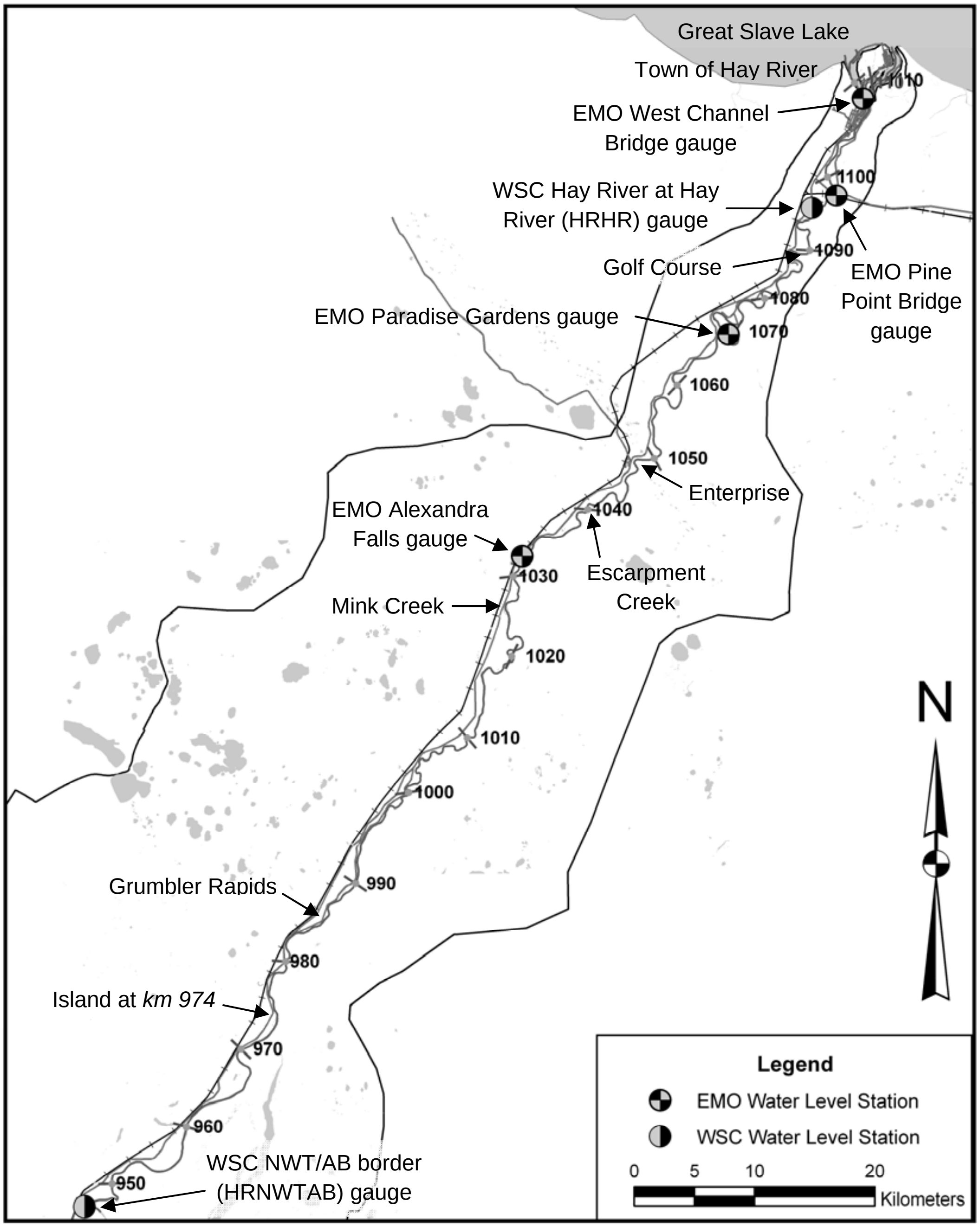


Figure 2.1: Location of the ten study sites, two WSC water level gauges and four EMO water level gauges located along the Hay River study reach.

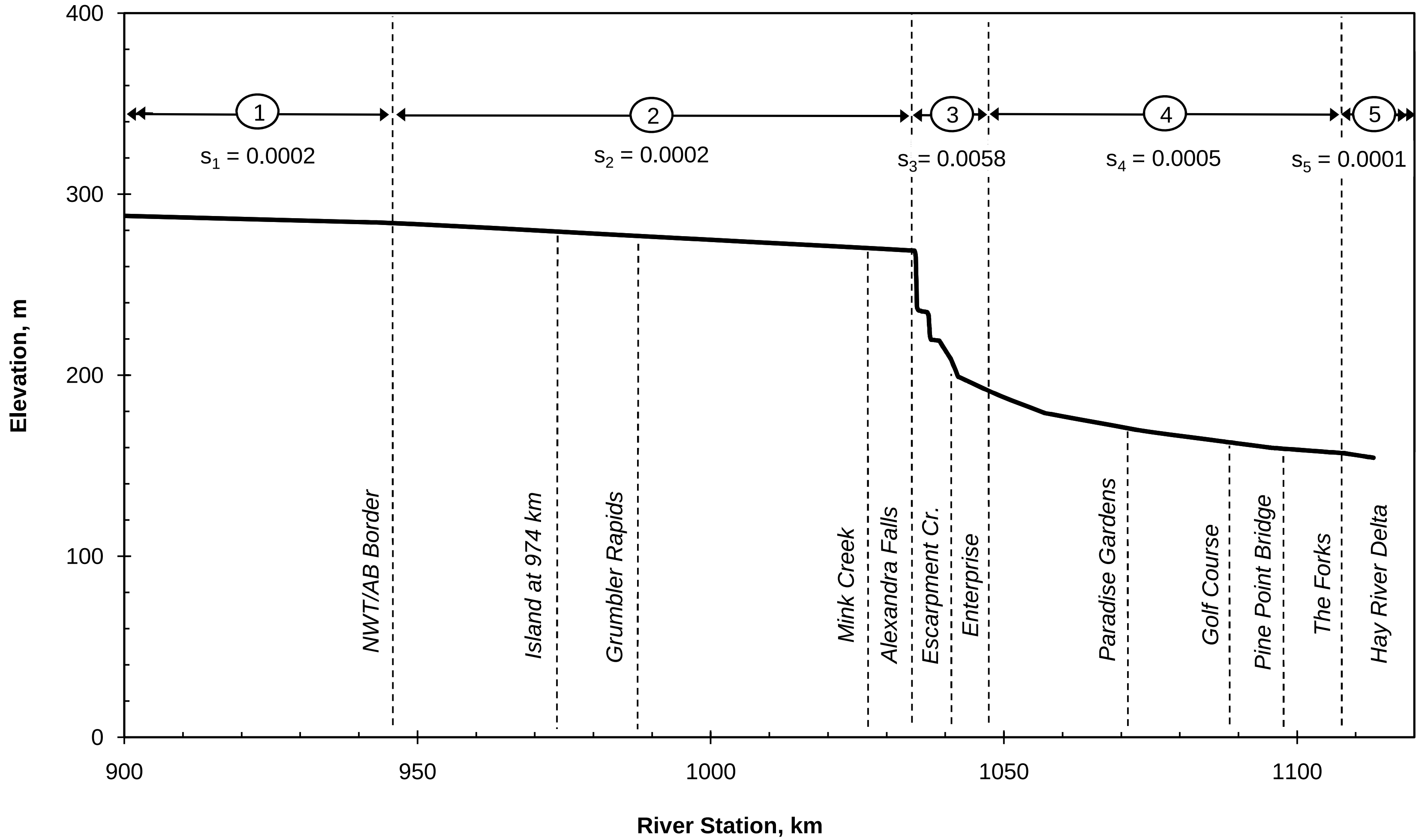
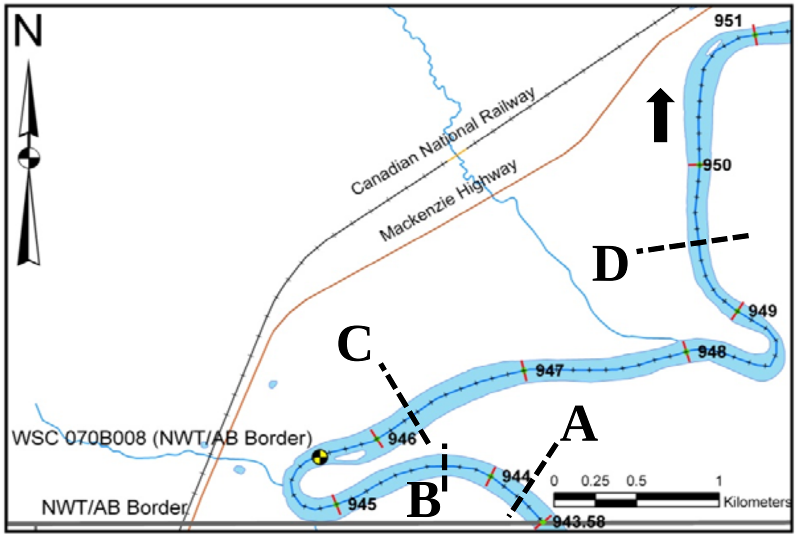


Figure 2.2: Profile of the Hay River, its ten study sites and its five sub-reaches. The Forks and the Hay River delta are mentioned for context, but are not among the ten study sites.

Figure 2.3: NWT/AB Border, *km 945.3* to *949.5*

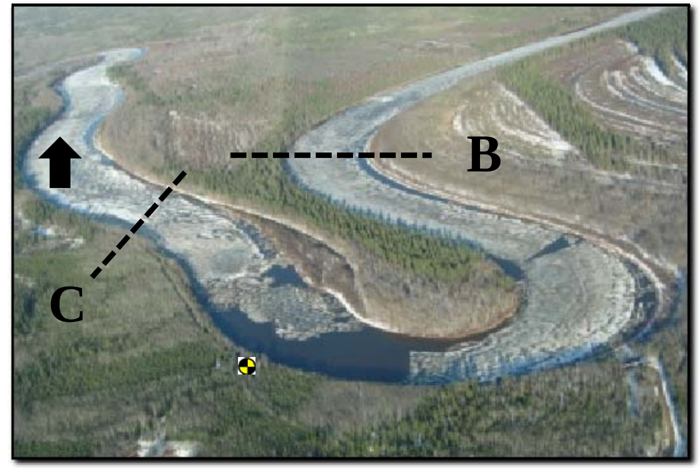


Site description: This site extends to cover the two180˚ bends just downstream of the border (A to D).

First transverse crack (D_c): First transverse cracks have typically occurred in the southern most bend (B to C).

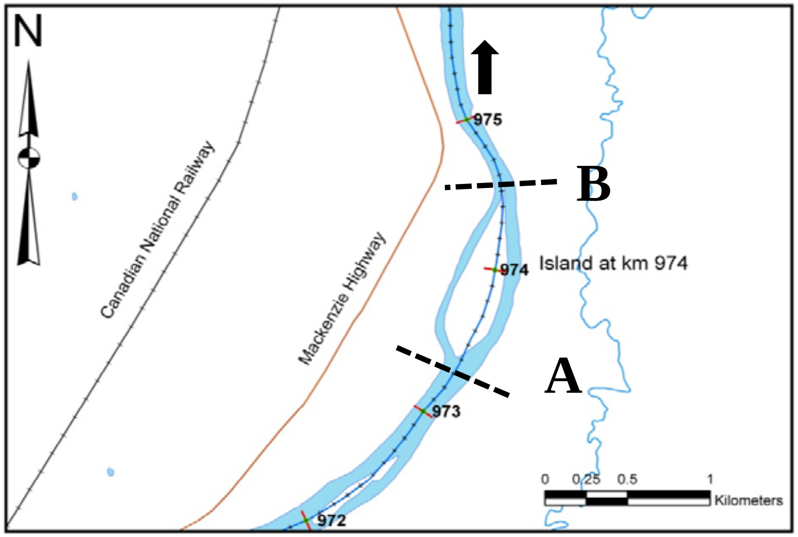
Local ice jam (D_j): Local ice jams have formed anywhere between A and D.

First transverse crack

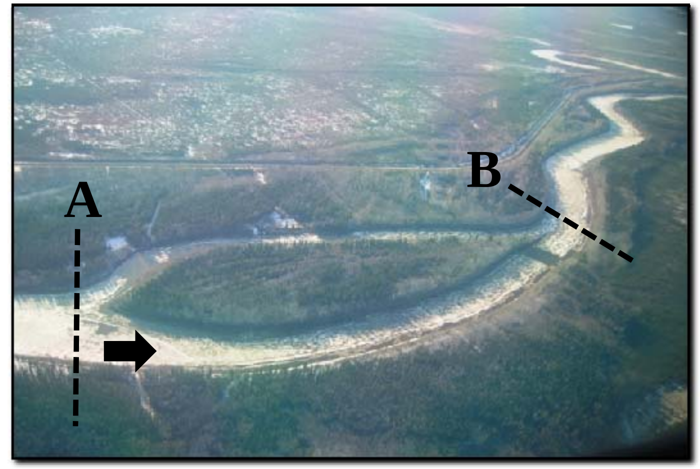


Local ice jam

Figure 2.4: Island at *km 974*, *km 973.3* to *974.5*



First transverse crack



Local ice jam

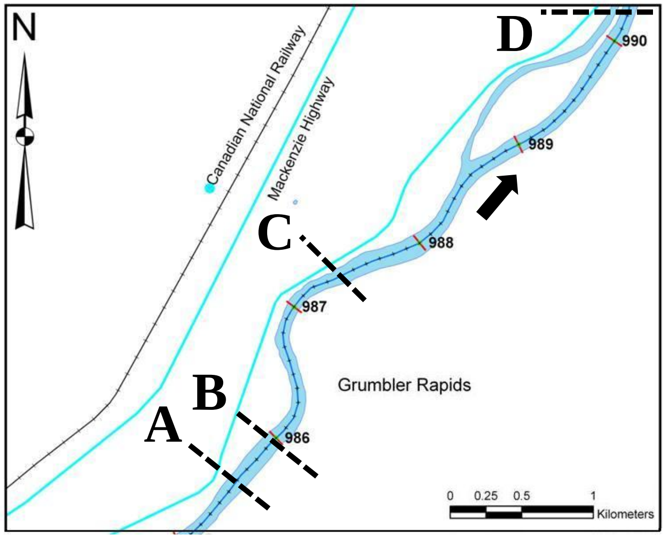
No picture of local ice jam at Island at 974 km.

Site description: Reach A to B brackets the island at 974 km. Note the classic shape of the island, seen in a number of places along the Hay River. This elongated downstream point is cause by to erosion due to ice runs.

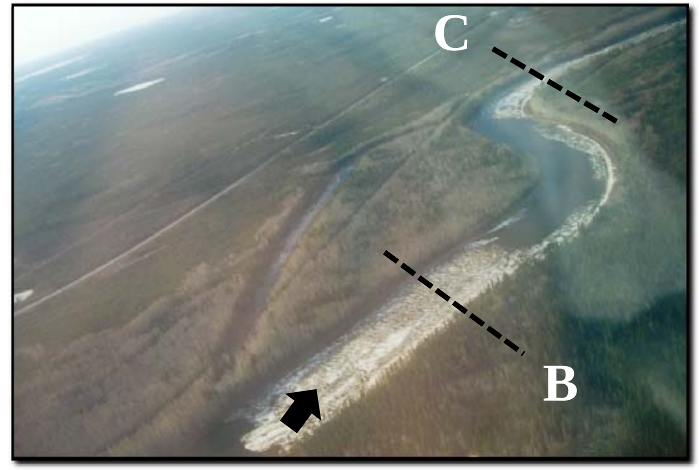
First transverse crack (D_c): The first transverse cracks usually occurs adjacent to the island itself (A to B).

Local ice jam (D_j): There are no photographs available of local ice jamming at this site. In 4 out of 5 years of record, ice jams did not occur here.

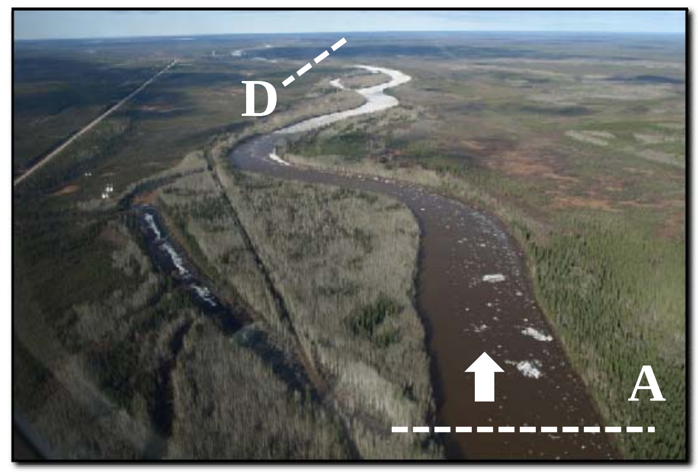
Figure 2.5: Grumbler Rapids, *km 945.3* to *945.5*



First transverse crack



Local ice jam

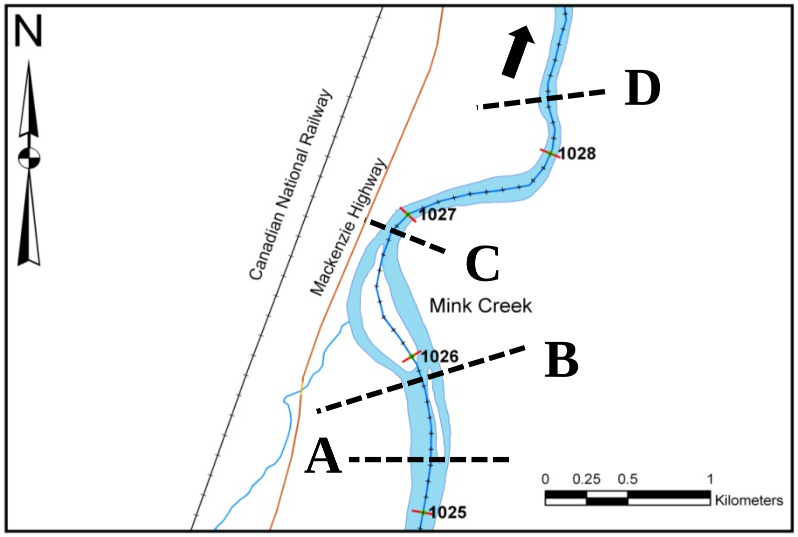


Site description: This site is easily identified from aerial photos by the presence of the abandoned channel, and its location just upstream of the island at Suede Creek (A to D).

First transverse crack (D_c): Transverse cracking was not observed at this site, but a short open lead between B and C did consistently develop.

Local ice jam (D_j): Although the jam toe forms between B and C, the head has extended further upstream. Alternatively, the entire jam has shoved until the toe extends to the island (D).

Figure 2.6: Mink Creek, *km 1025.3* to *1028.2*

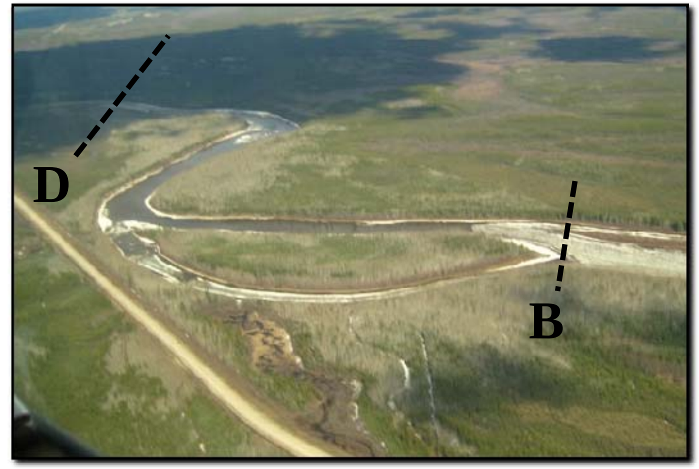


Site description: At this location, there are two approximately 90˚ bends with an island upstream of the second bend (A to D).

First transverse crack (D_c): First cracking has occurred between B and D.

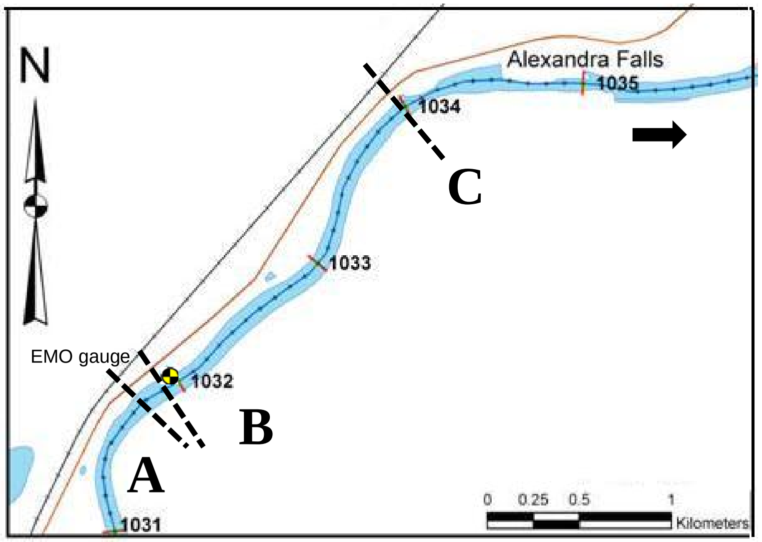
Local ice jam (D_j): Ice jams typically form between A and C. The head of the jam has occurred around the island. However, these jams did not remain in place for more than one day before releasing downstream.

First transverse crack



Local ice jam

Figure 2.7: Alexandra Falls, *km 1031.9* to *1034.0*

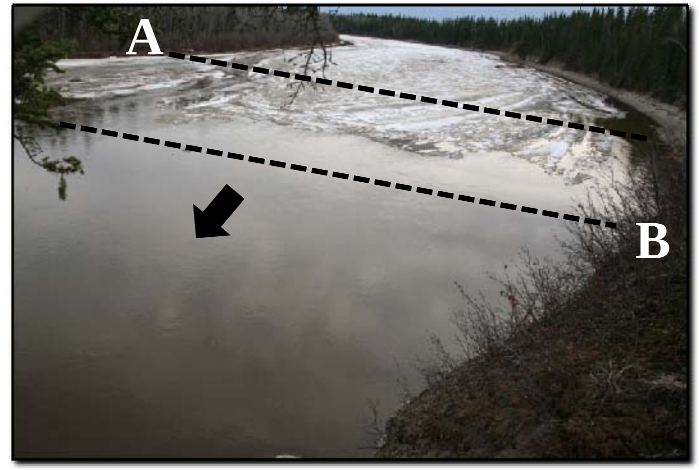


Site description: The 33 m high Alexandra Falls is located at river station 1034 (C). The EMO water level gauge is installed 2 km upstream of the falls (A).

First transverse crack (D_c): The first transverse crack (D_C) in the vicinity of the falls happens at the same location every year: immediately upstream of the EMO water level gauge (A to B).

Local ice jam (D_j): Local ice jams are defined for this reach to be when the reach from the EMO gauge to the falls clears of ice (A to C). This event also represents ice jam release (D_r).

First transverse crack



Local ice jam

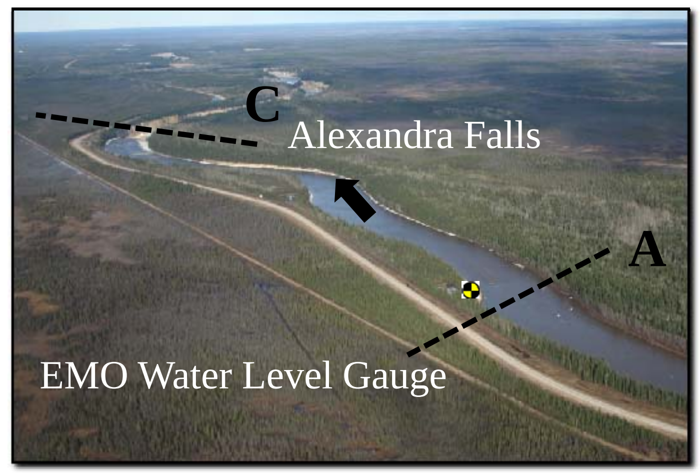
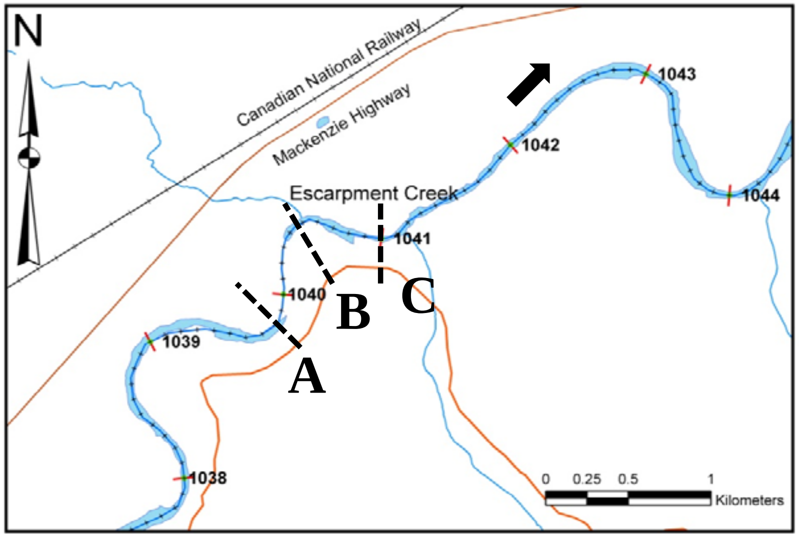
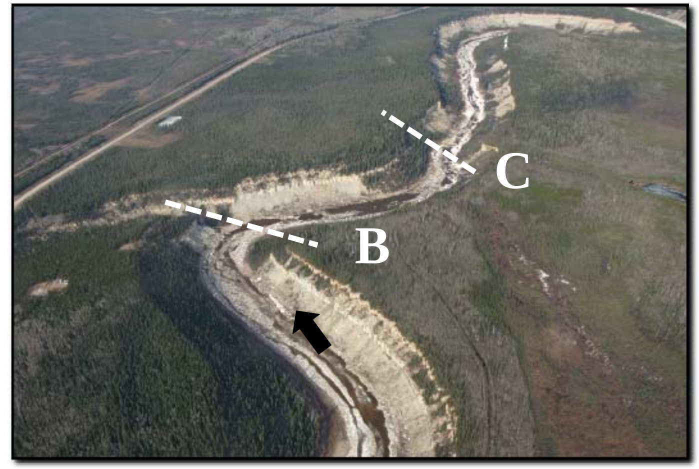


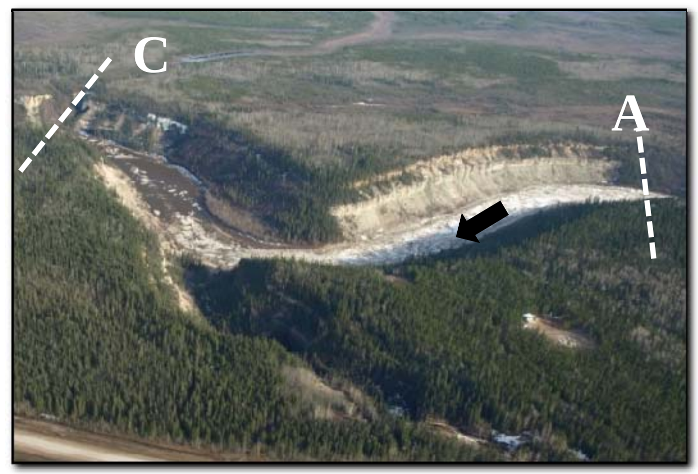
Figure 2.8: Escarpment Creek, *km 1040* to *1041.3*



First transverse crack



Local ice jam

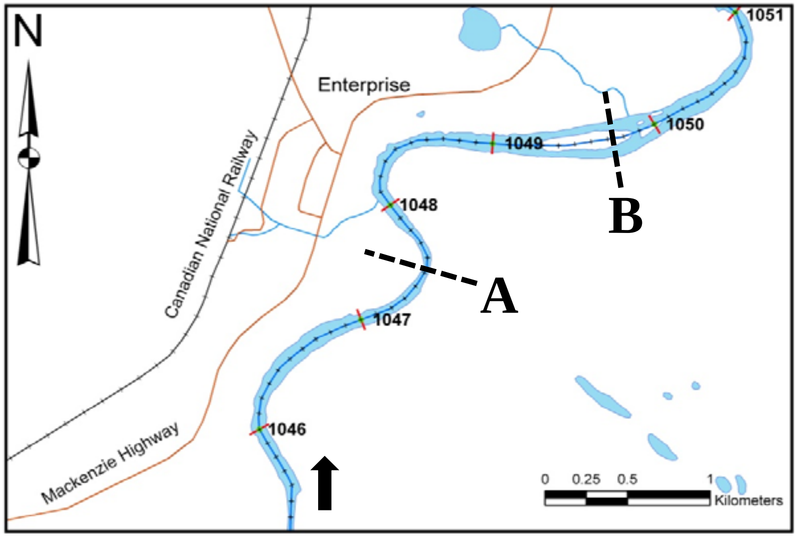


Site description: This site is located in the gorge downstream of Louise Falls and adjacent to Escarpment Creek (A to C).

First transverse crack (D_c): Transverse cracking is not observed at this site. However, a small open lead has consistently developed downstream of the creek outlet (B to C).

Local ice jam (D_j): In three years of record, this site formed large, 7 km long ice jams. The toe typically forms from A to C, and over time shoves to Enterprise.

Figure 2.9: Enterprise, *km 1047.5* to *1049.6*



Site description: This site is the river bend visible from the highway at the Hamlet of Enterprise (A to B). It is bounded by the island on the downstream side.

First transverse crack (*D_c*): Transverse cracking was not observed at this site. This ice here is hummocky and thick, and does not experience sufficient thermal deterioration to crack before ice runs arrive from upstream.

Local ice jam (*D_j*): Ice runs arrived from upstream and were arrested by the island (B). Typical jam durations before releasing are 1 to 2 days.

First transverse crack

This site does not experience transverse cracking.

Local ice jam

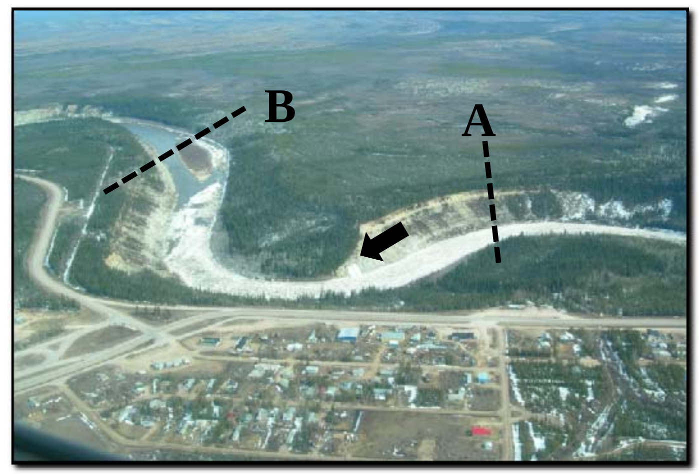
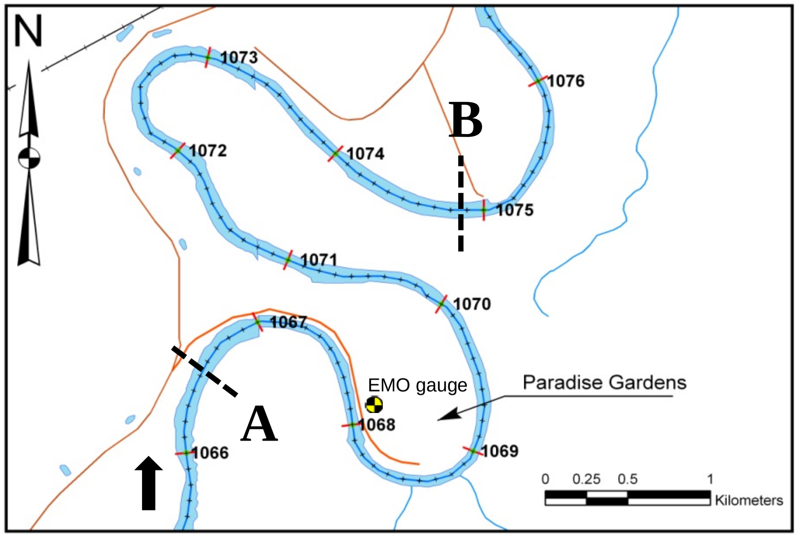


Figure 2.10: Paradise Gardens, *km 945.3* to *945.5*



First transverse crack

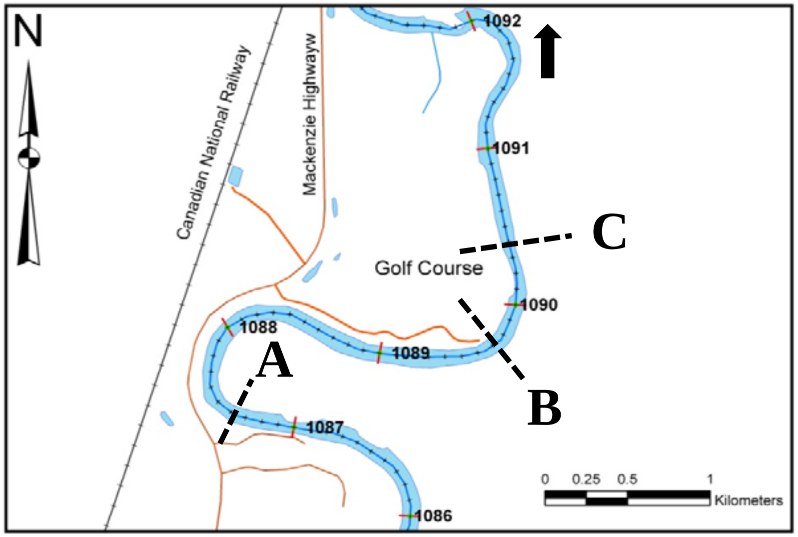
Local ice jam

Site description: This site includes two 180˚ bends at Paradise Gardens settlement (A to B).

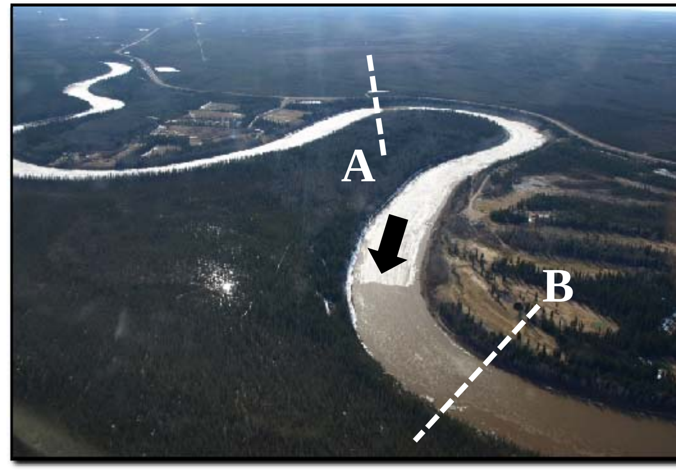
First transverse cracking: Cracking has occurred anywhere in the vicinity of the two bends (A to B). The photograph (upper right) shows sheet accumulation that occurred after transverse cracking broke sheets of ice from the intact ice.

Local ice jam (D_j): Ice jams can also occur at any location in these two bends (A to B).

Figure 2.11: Golf Course, *km 945.3* to *945.5*



First transverse crack



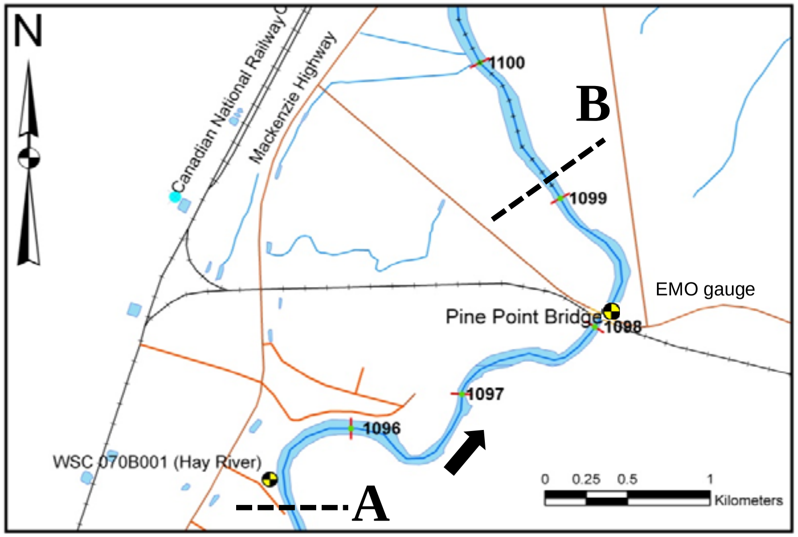
Local ice jam

Site description: This reach (from A to C) is adjacent to, and extends one bend upstream of the golf course.

First transverse crack (D_c): First transverse cracking typically occurred between A and B.

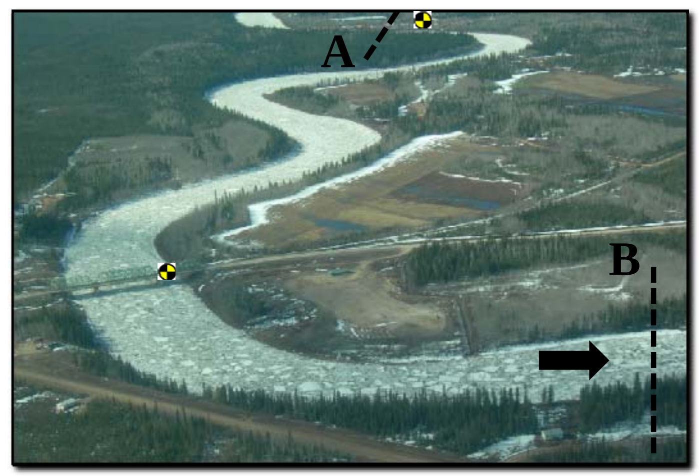
Local ice jam (D_j): Local ice jams formed between A and B, but can extend further in both the upstream and downstream directions.

Figure 2.12: Pine Point Bridge, *km 945.3* to *945.5*



First transverse crack

Local ice jam



Site description: This reach extends from the WSC Hay River at Hay River (HRHR) gauge at Delancy Rd (A) to 1 km downstream of the Pine Point Bridge (B).

First transverse crack (D_c): Transverse cracking has occurred anywhere along this reach (A to B). Once the first crack occurred, the rest of the reach has cracked within one day. The photograph shows sheet accumulation that occurred after transverse cracking.

Local ice jam (D_j): Jams have formed anywhere along this reach (A to B). The head of the peak stage jam in the Hay River delta often occurs in this reach, or further upstream.

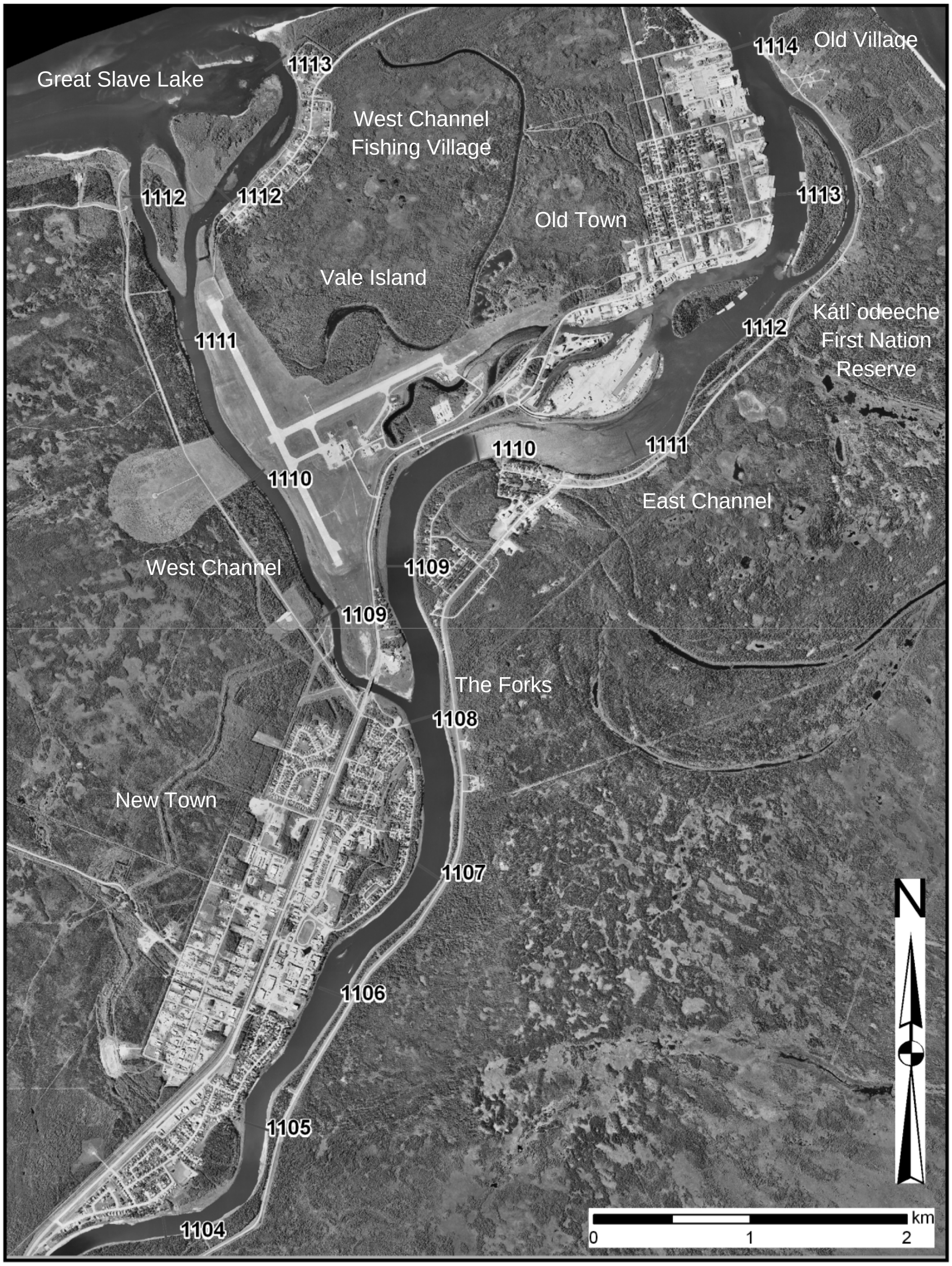


Figure 2.13: Map of the Hay River Delta and the communities located there.

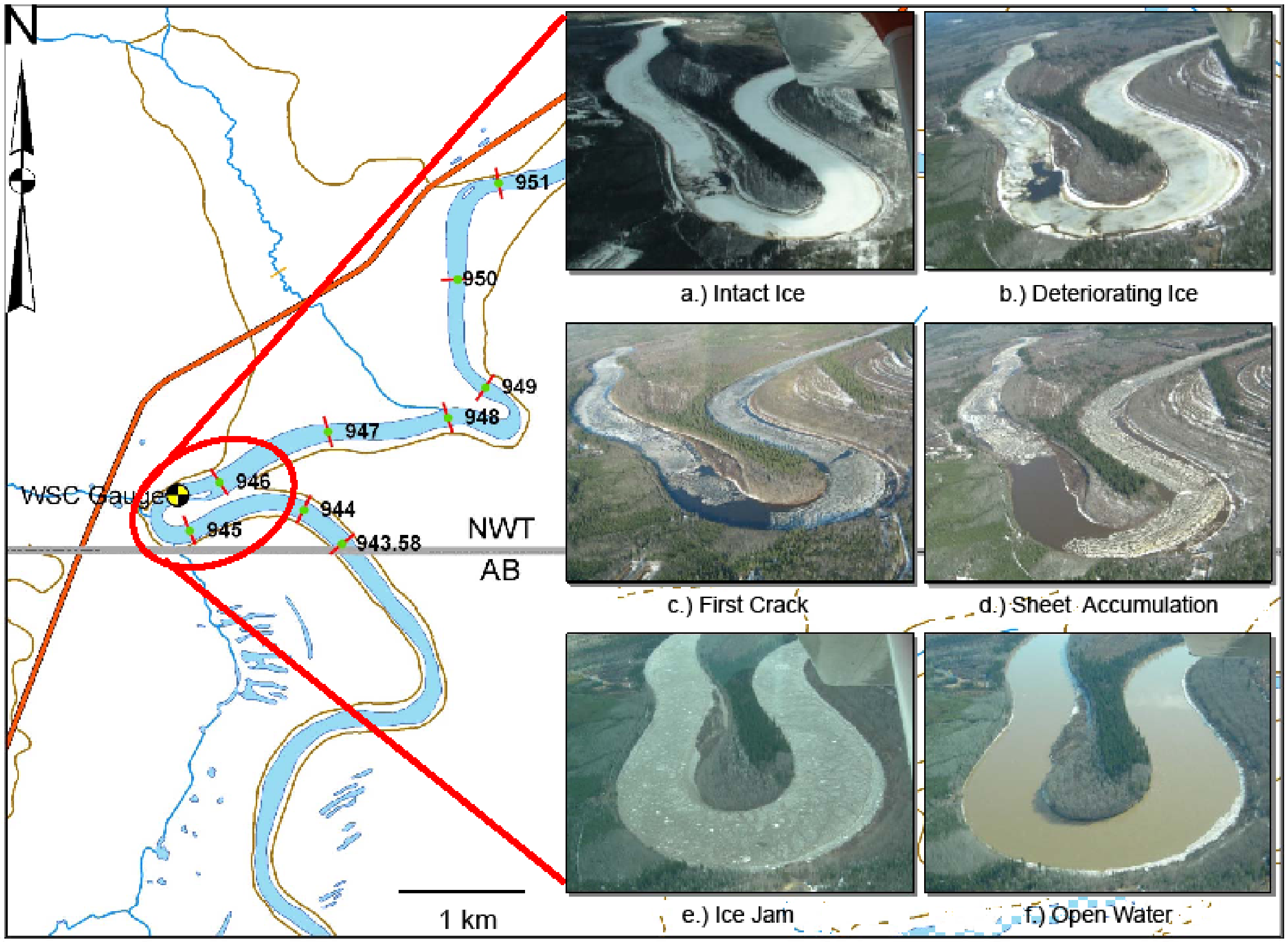


Figure 2.14: Stages of breakup at the NWT/AB border (*km 945.5*).

Figure 2.15 a: Thermal deterioration of ice in the Forks and West Channel of the Hay River Delta (Reach 5).

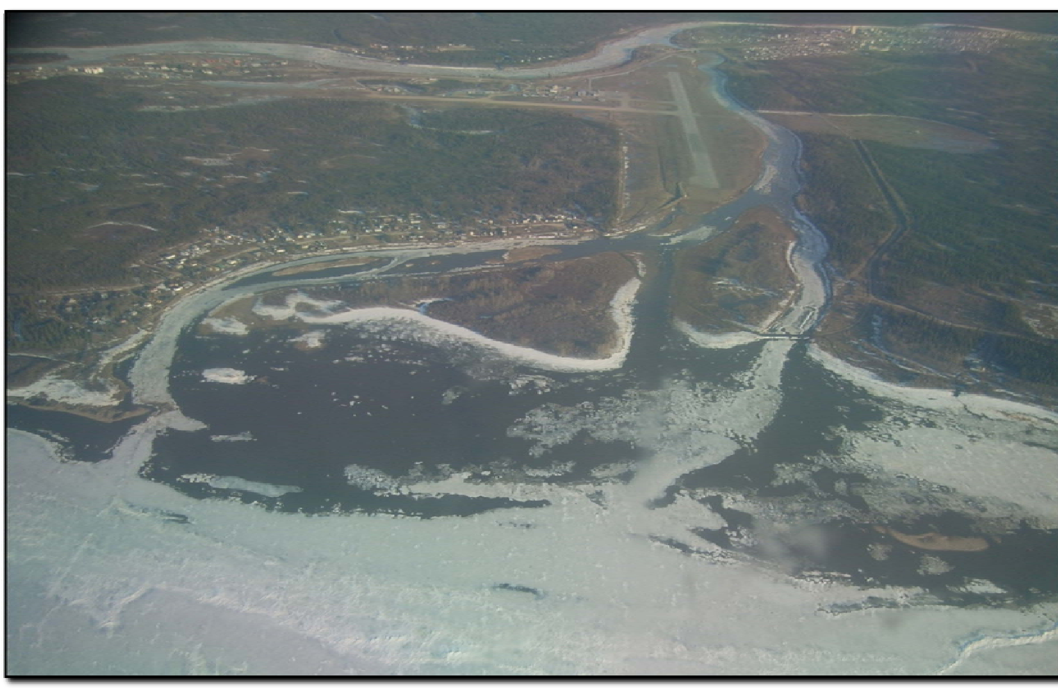


Figure 2.15 b: Thermal deterioration of ice in the West Channel of the Hay River Delta (Reach 5).

Figure 2.16 a: The toe of the log jam composed of trees, sediment and downed woody debris as the melting front advances, consolidating and melting the head of the ice jam.

Figure 2.16 b: High concentration of trees, sediment and downed woody debris as the melting front advances.

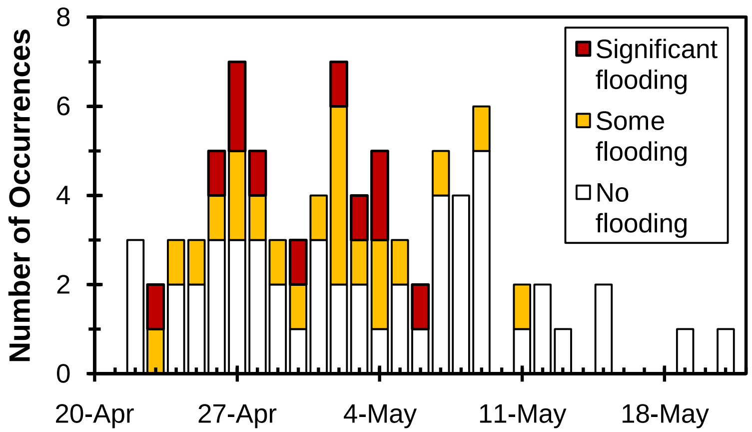


Figure 2.17: Dates of the onset of breakup (D_o) for all known events between 1894 and 2010.

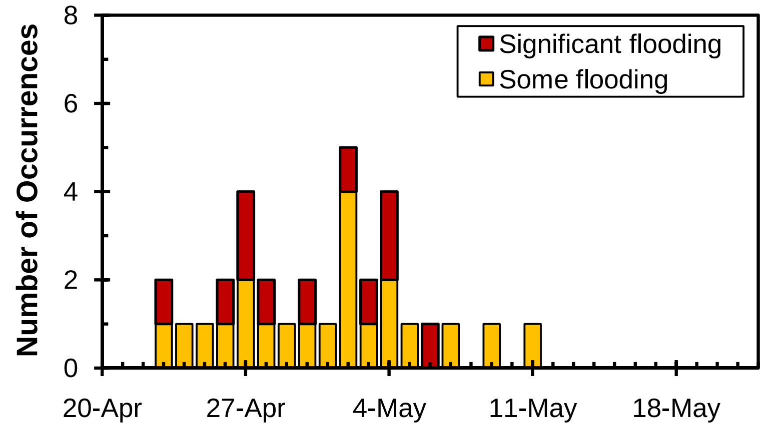


Figure 2.18: Dates of the onset of breakup (D_o) for all known events between 1894 and 2010, excluding years of no flooding.

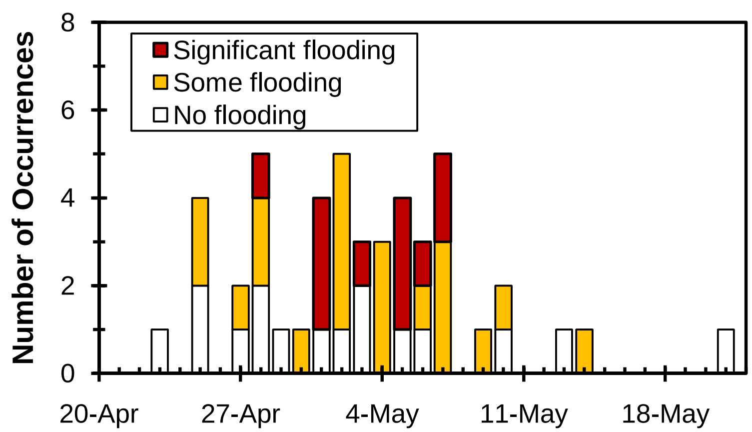


Figure 2.19: Dates of peak stage ice jams (D_p) for all known events between 1894 and 2010.

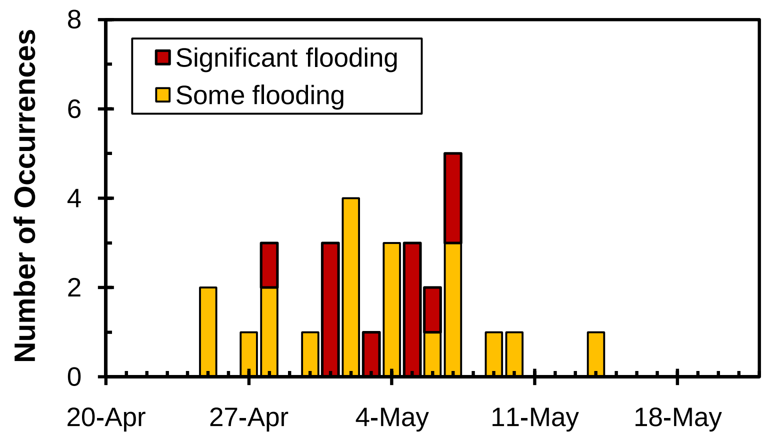


Figure 2.20: Dates of peak stage ice jams (D_p) for all known events between 1894 and 2010, excluding years of no flooding.

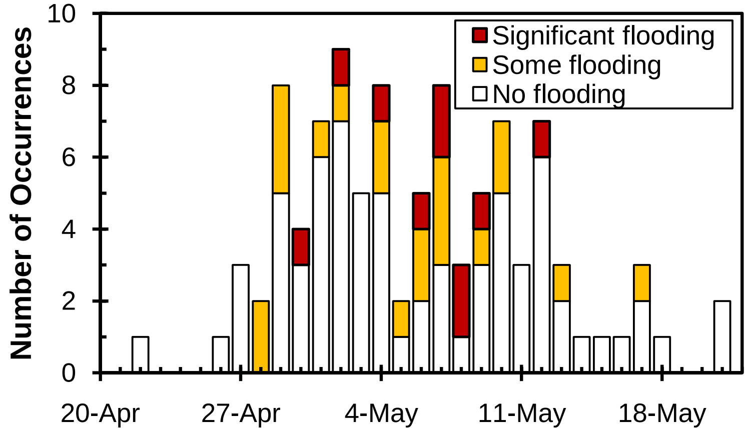


Figure 2.21: Dates of ice jam melt out (D_m) for all known events between 1894 and 2010.

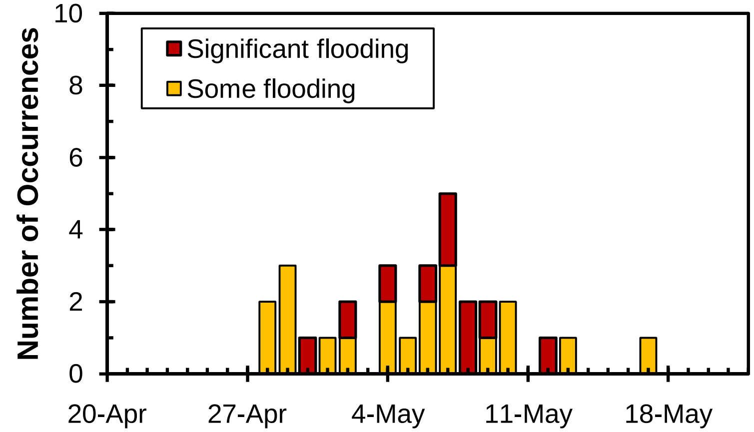


Figure 2.22: Dates of ice jam melt out (D_m) for all known events, excluding years of no known flooding.

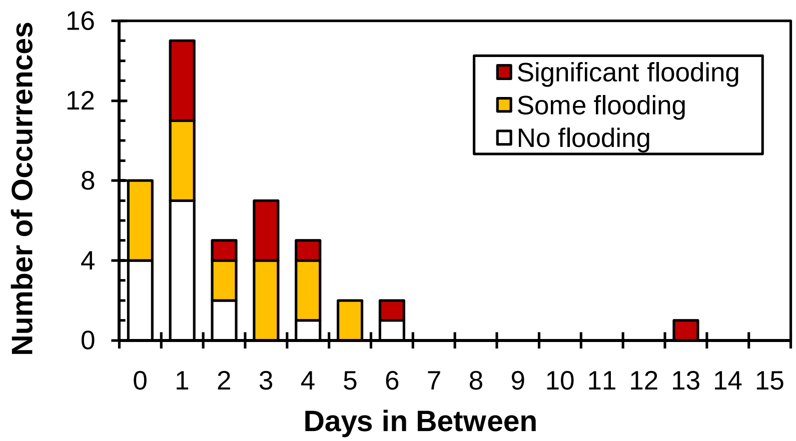


Figure 2.23: Number of days between the onset of breakup and peak stage (ΔD_p) of known events between 1894 and 2010.

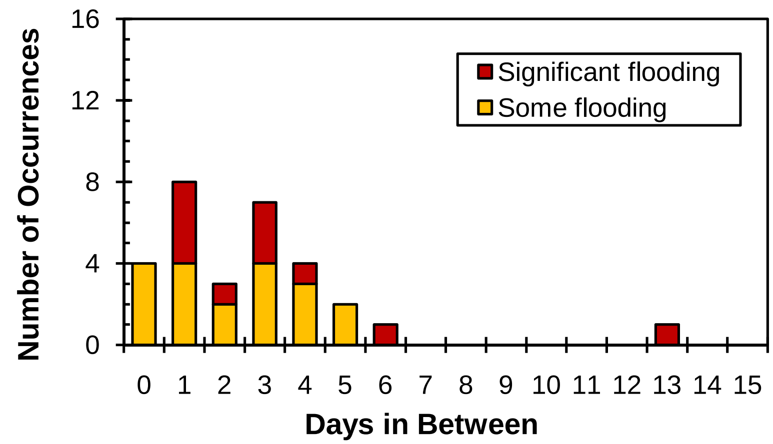


Figure 2.24: Number of days between the onset of breakup and peak stage (ΔD_p), of known events between 1894 and 2010.

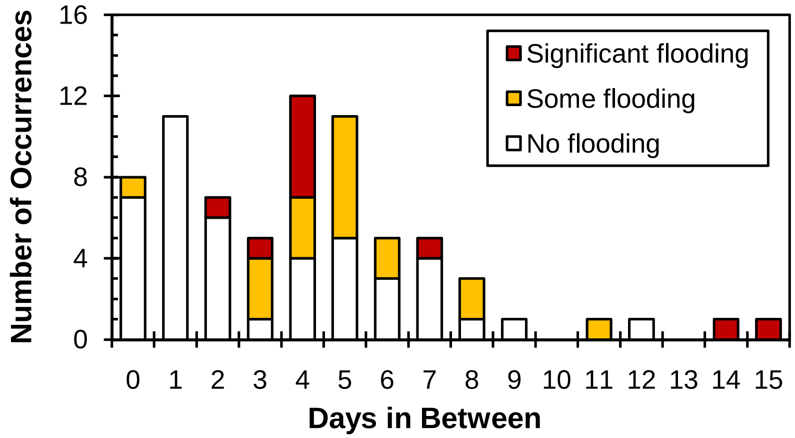


Figure 2.25: Number of days between the onset of breakup and jam melting out (ΔD_{m}) of known events.

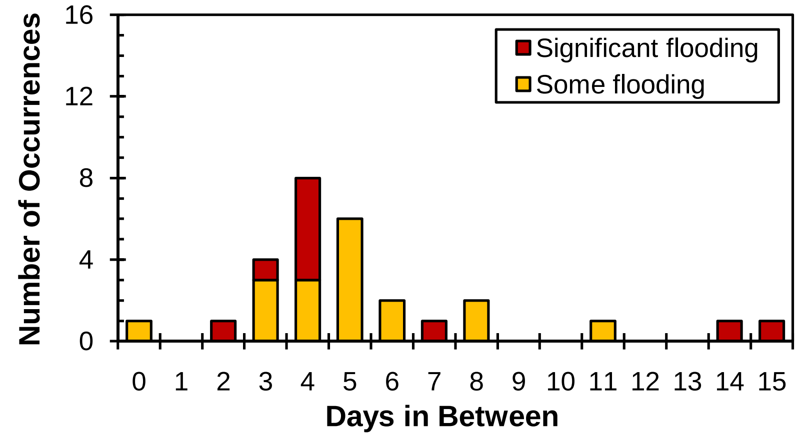


Figure 2.26: Number of days between the onset of breakup and jam melting out (ΔD_{m}), excluding years of no flooding.

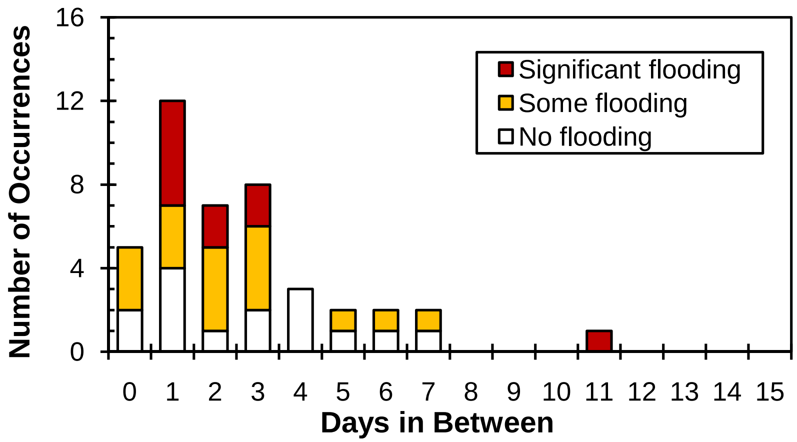


Figure 2.27: Number of days between peak stage and jam melting out ($\Delta D_{m\text{-}p}$) of known events between 1894 and 2010.

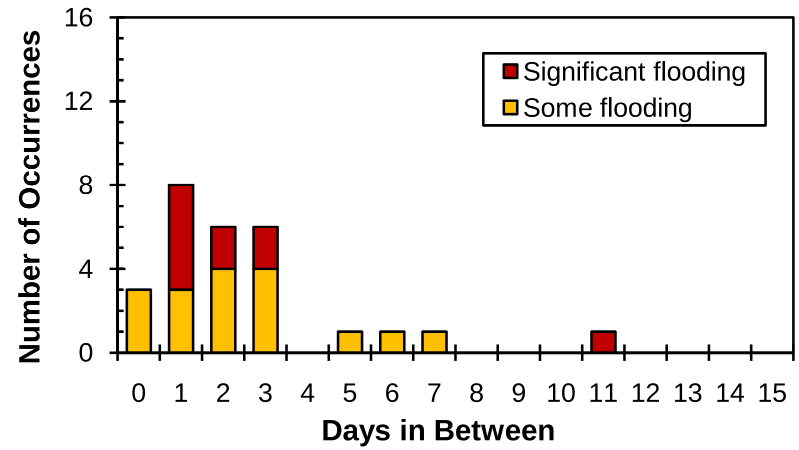


Figure 2.28: Number of days between peak stage and jam melting out ($\Delta D_{m\text{-}p}$) of known events between 1894 and 2010, excluding years of no flooding.

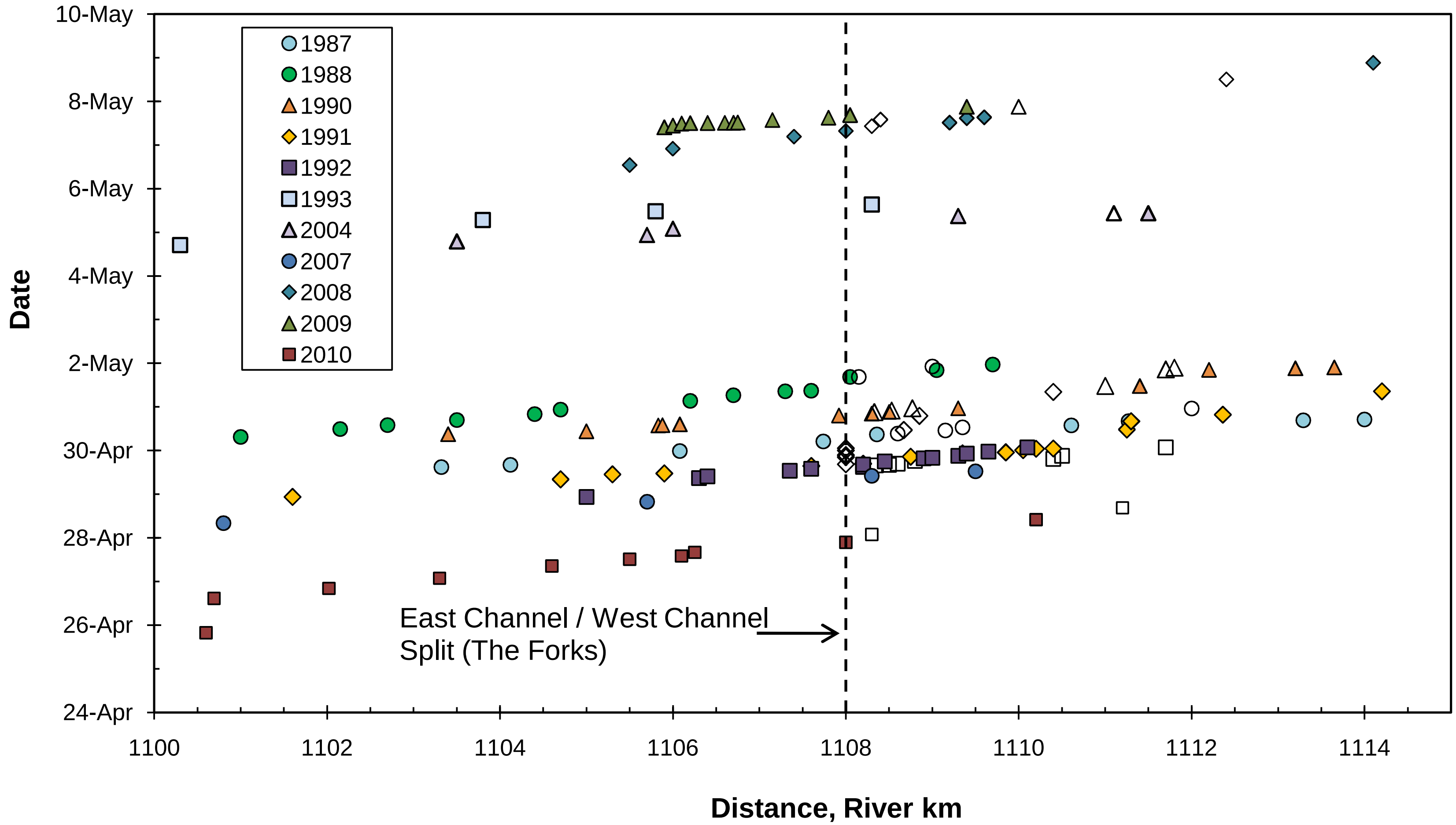


Figure 2.29: Melting front locations showing rates of advance for 11 years of record.

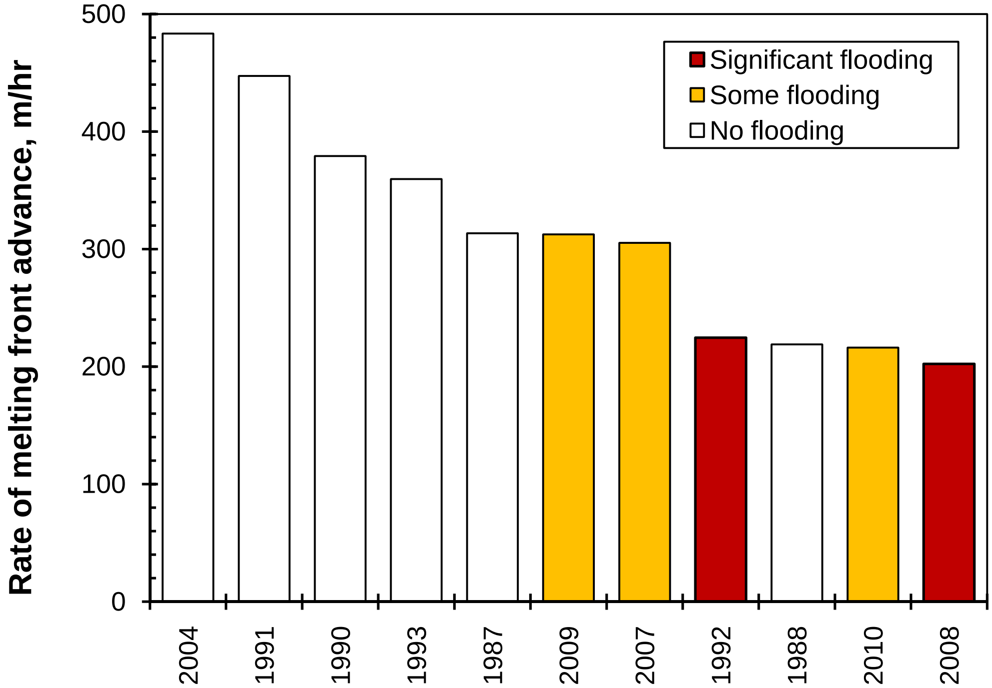


Figure 2.30: Melting front speeds for 11 years of record.

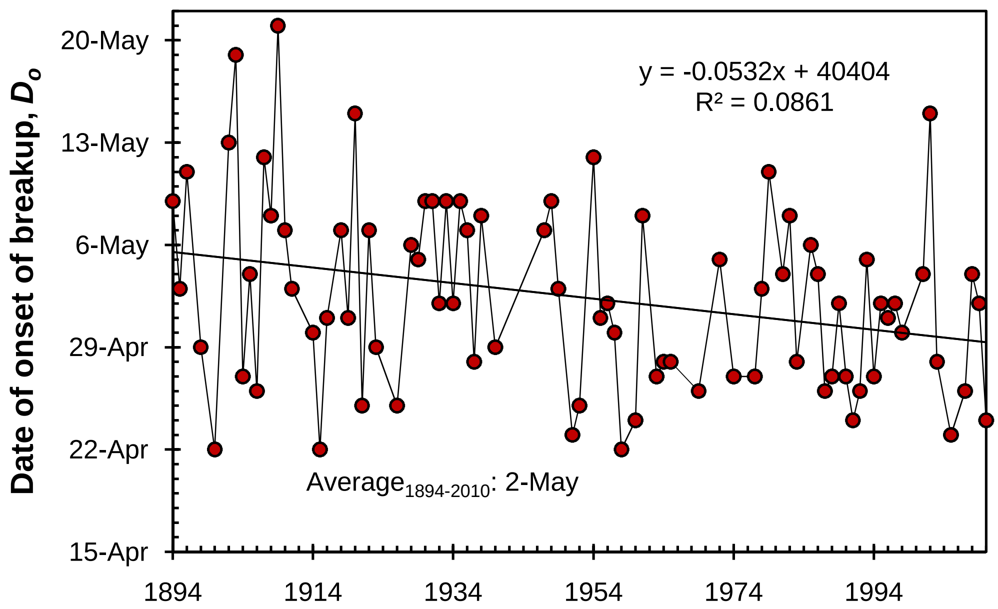


Figure 2.31 (a): Dates of known onsets of breakup (D_o) from 1894 to 2010.

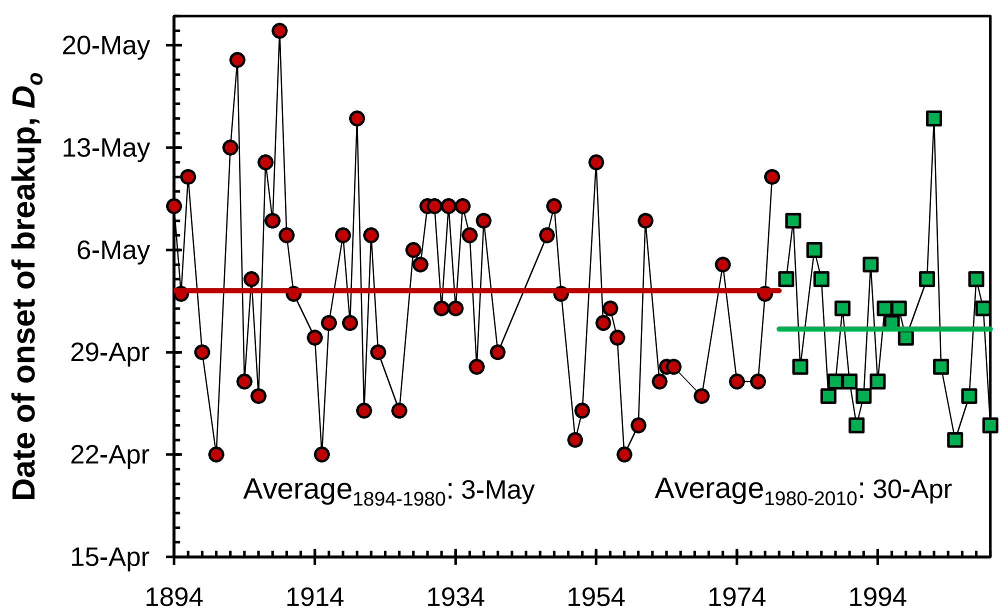


Figure 2.31 (b): Dates of known onsets of breakup (D_o) from 1894 to 1980, and from 1980 to 2010.

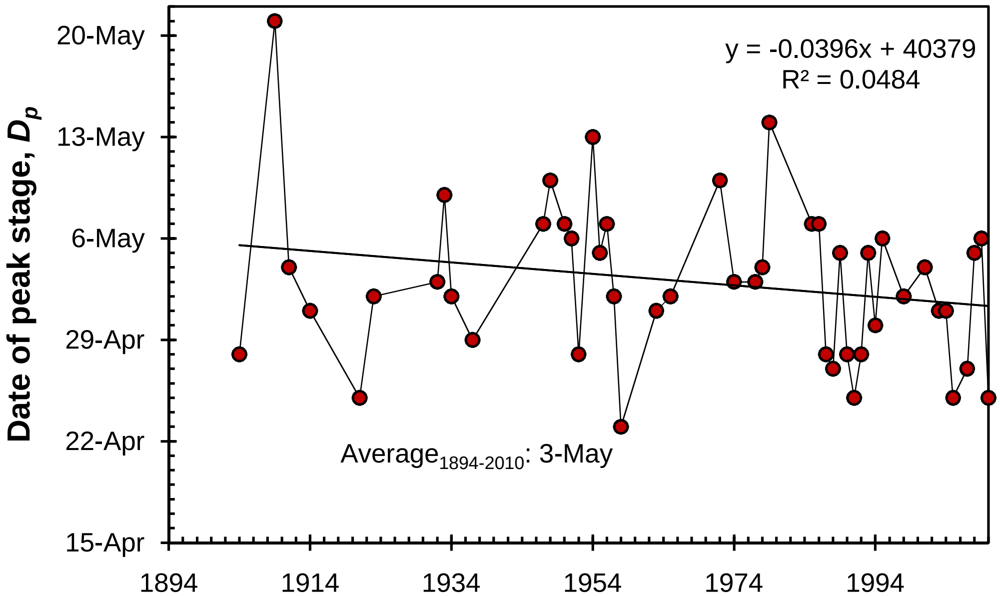


Figure 2.32 (a): Dates of known peak stages (D_p) from 1894 to 2010.

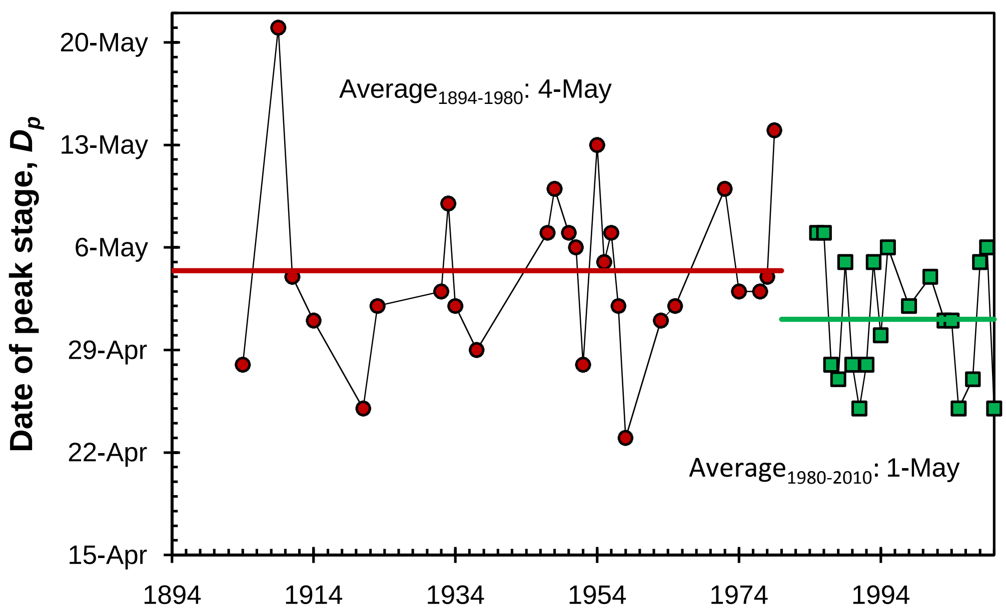


Figure 2.32 (b): Dates of known peak stage (D_p) from 1894 to 1980, and from 1980 to 2010.

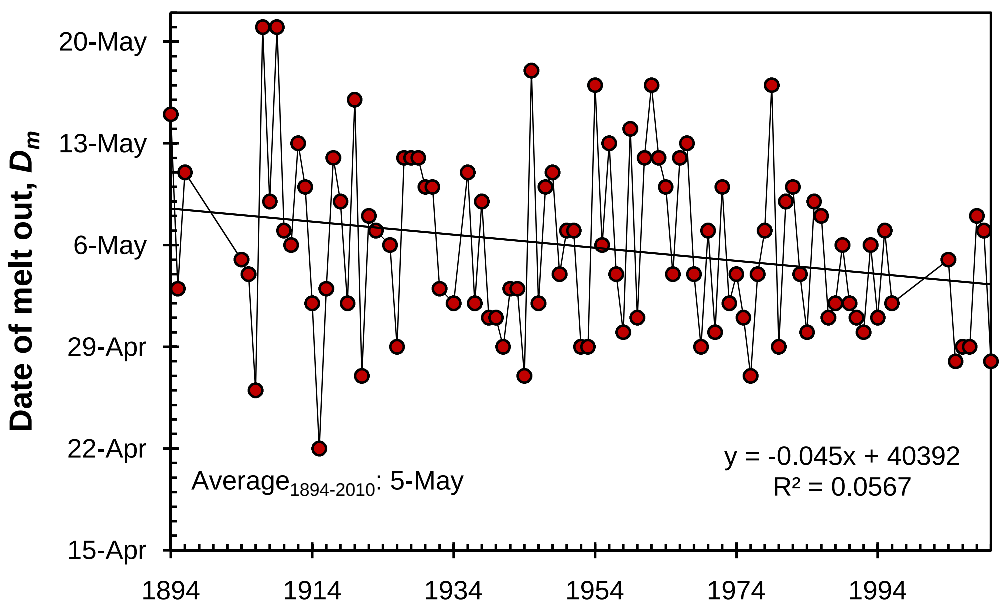


Figure 2.33 (a): Date of known melt out (D_m) from 1894 to 2010.

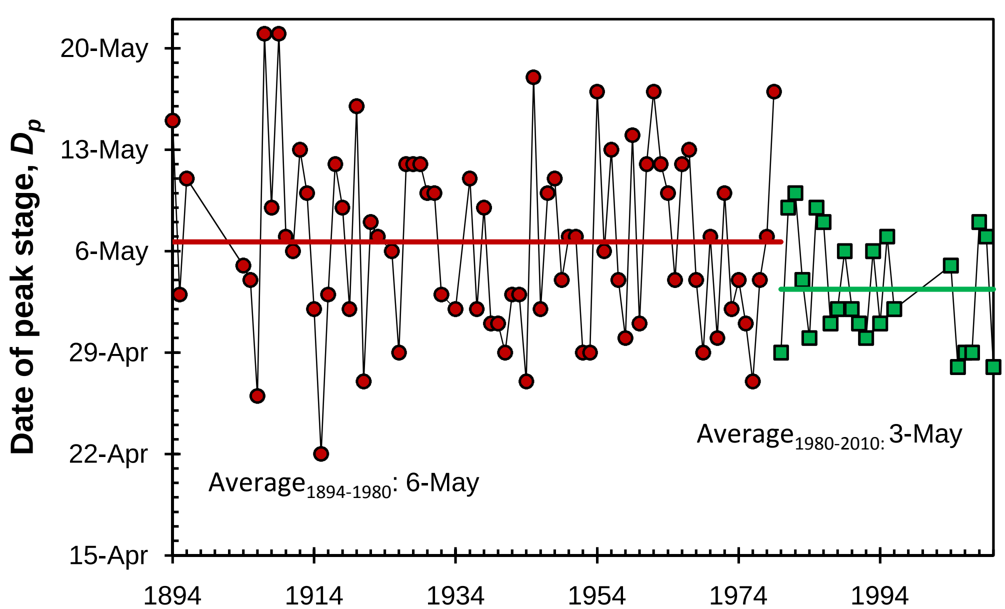


Figure 2.33 (b): Date of known melt out (D_m) from 1894 to 1980 and from 1980 to 2010.

Figure 2.34 (a): EMO Alexandra Falls water level gauge suspended off a boom.

Figure 2.34 (b): EMO Paradise Gardens water level gauge suspended off a boom.

Figure 2.34 (c): EMO Pine Point Bridge water level gauge suspended off the Pine Point Bridge.

Figure 2.34 (d): EMO West Channel Bridge water level gauge suspended off the West Channel Bridge.

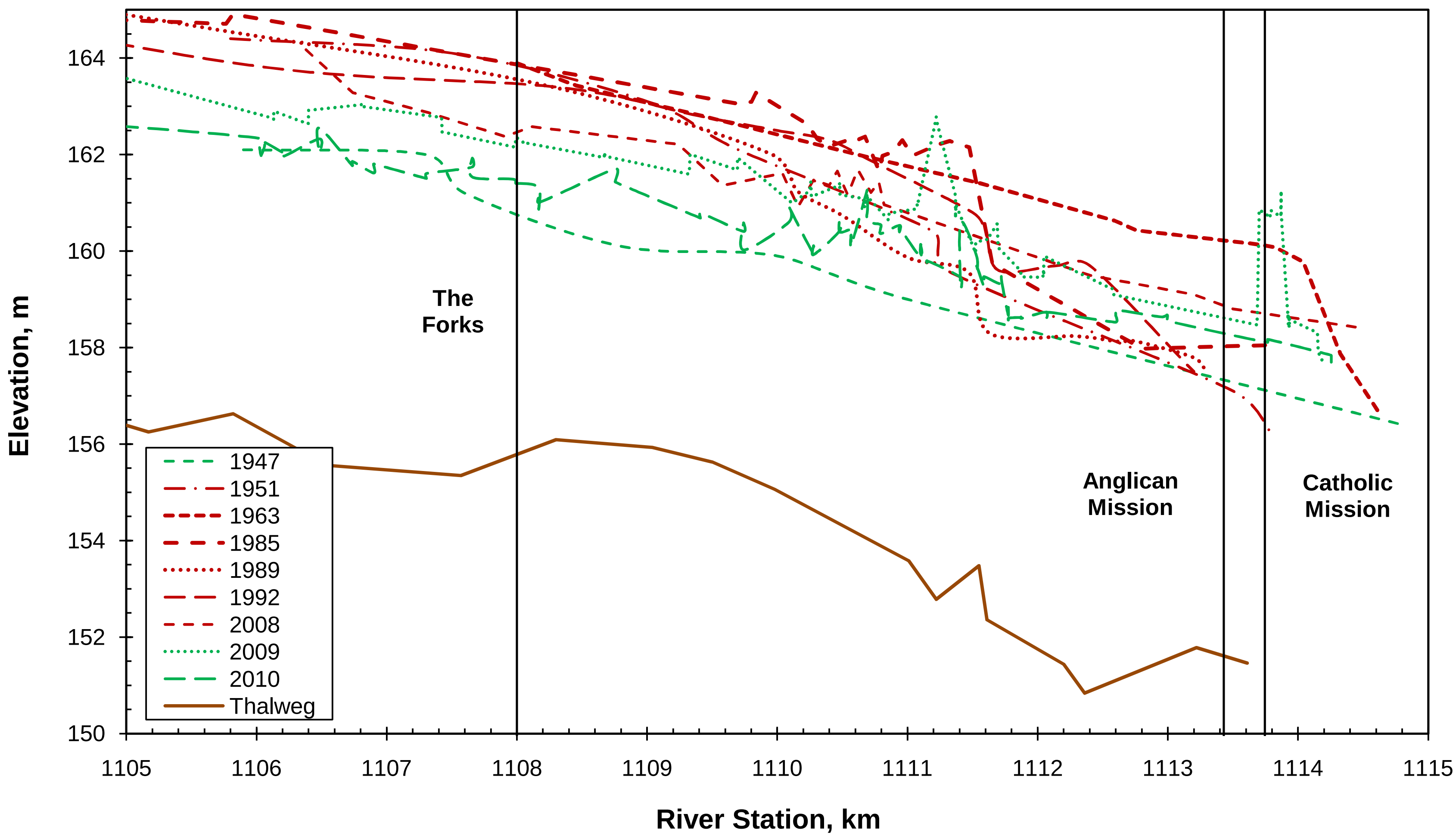


Figure 2.35: Known flood profiles in the Main and East Channels of the Hay River, grouped by flood severity class.

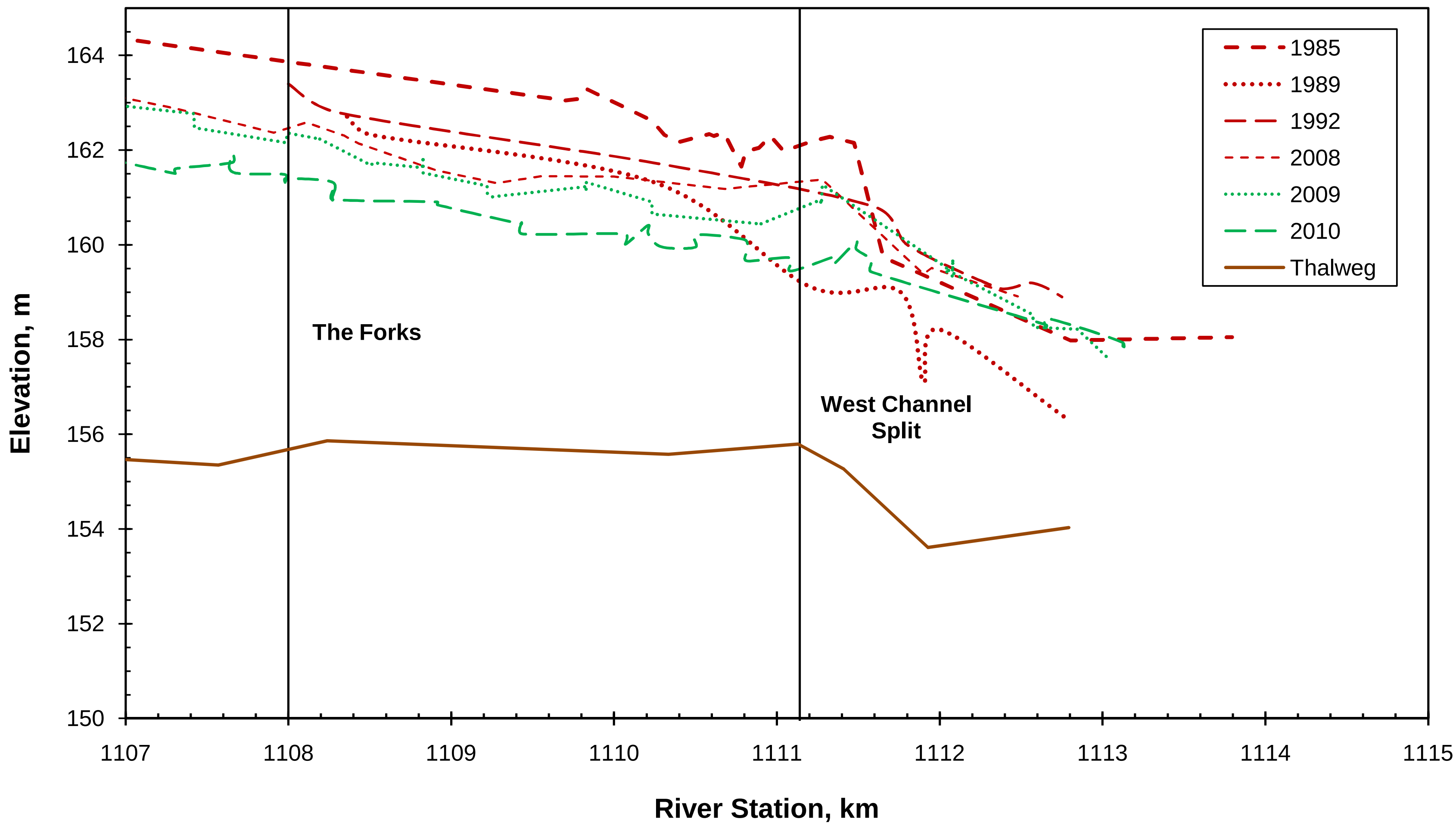


Figure 2.36: Known flood profiles in the West Channel of the Hay River, grouped by flood severity class.

Chapter 3: Interpretation of Available Data

From 2005 to 2010[1], the UA/DIAND research team collected and collated a wide body of data documenting breakup on the Hay River. This included thousands of ground and aerial photographs, meteorological records and water level data, in addition to the historical record of breakup in the Hay River Delta, found in Appendix A. Four methods of analysis were adopted to explore patterns in the progression of breakup on the Hay River, including:

- a site-specific approach considering how conditions vary at discreet sites during the progression of breakup,
- a reach-based approach examining how conditions change between sites during the various stages of breakup,
- an analysis of the general order in which breakup stages occur, and
- an analysis of historical records of breakup events.

Different types of data necessitated different approaches. The combination of the results of these four methods helped to clarify the general progression of breakup, as well as to identify promising indicators and thresholds for monitoring.

3.1 Progression of Breakup Based on Timing of Key Stages

Determining the dates of stages of breakup at each of the ten study sites was the necessary first step for each of the above methods of analysis. Table 2.1 lists the

[1] The exception was in 2006, for which negligible funding was available for monitoring breakup, and consequently very little data was obtained.

key sites in each study reach, and their river stationing. Of the ten steps in the progression of breakup discussed in Chapter 2, three key stages of breakup were chosen for study. These stages were:

- Stage 3: formation of first transverse cracks
- Stages 5 and 6: formation mini-jams and local ice jams
- Stage 7: ice jam release

The first transverse crack (Stage 3) is the first dynamic step in the progression of breakup. Typically, the dynamic progression is too rapid for the identification of transverse cracks, but these are occasionally observed. Daily observation flights allowed this date to be determined, regardless of whether breakup had progressed beyond this stage. Stages 5 and 6 (mini- and ice jams) were categorized as the same event; it was the timing of local ice jam formation that was of interest, not the length of jam that accumulated. Ice jam release (Stage 7) was the last of the dynamic stages of breakup considered at the sites upstream of the Hay River delta. As previously mentioned, ice jam release events often progressed in domino fashion, and ultimately resulted in the ice runs causing ice jams and flooding in the Town of Hay River. When possible, the dates of three key stages of breakup at all ten study sites were extracted from approximately 90,000 aerial and ground photographs. These dates are listed in Appendix I. Determining these dates and studying the corresponding patterns facilitated the assimilation of the heuristic knowledge of local residents, academic researchers, government experts and the Town of Hay River flood watch committee.

As previously discussed, over the course of this study (with the exception of 2006), available funding and manpower increased every year[2]; consequently, spatial and temporal observations of breakup increased as well. Specifically, the number of aerial flights and automated time-lapse camera stations increased in each year of the study. In some (typically earlier) cases, the dates of key breakup stages could not be determined at one or more of the ten study sites, specifically at the locations where:

- there were no ground photos collected at the site;
- daily flights started after breakup had already begun;
- the air photos taken on that day did not document key breakup stages;
- there were no flights on the previous day, and no way to tell if breakup stages happened on the day of observations, or the day before; and/or
- the breakup stage did not occur at that location during that year.

Table 3.1 provides the details of the reasons for the unknown dates of breakup stages at all ten study sites, over the five years of record.

In some cases, it was necessary to employ judgment to assign a date to a particular breakup stage. For example, during the flight on 19-Apr-10 it was observed that the ice cover at the NWT/AB border (*km 945.5*) was intact, whereas a transverse crack was observed at this site during the flight on 20-Apr-10. For this case, the date of the transverse crack was assumed to be 20-Apr-10. Because

---

[2] The exception was in 2006, for which negligible funding was available for monitoring breakup, and consequently very little data was obtained.

observation flights were typically conducted in the late afternoon or early evening (16:00 to 19:00) leaving only several hours in that day for the event to occur, it was more probable that the breakup event occurred during the following day. The exception is if there was an ice run present immediately upstream of the site in question, then the event was assumed to have happened that day. Once these dates of breakup stages were identified, they were analyzed using three methods of analysis:

1. site specific analysis
2. reach based analysis
3. analysis of historical records

The results for each analysis are discussed below.

3.1.1 Site Specific Method of Analysis

The site-specific approach to analyzing breakup dates considered each site independently and examined the consistency of dates of breakup stages, for all years of record (2005, 2007, 2008, 2009 and 2010). This method investigated the similarities in dates on which the first transverse crack, local ice jam and ice jam release occur, as well as the number of days between breakup stages at each site.

The dates of the first transverse crack, local ice jam and ice jam release at each of the ten sites located in the Hay River study reach were determined for five years of record, and were defined as:

- D_c – the date of the first transverse crack,
- D_j – the date of local ice jam, and
- D_r – the date of ice jam release.[3]

The windows of dates when the first transverse cracks occurred at all sites (D_c) ranged from 8 to 12 days. The dates of local ice jamming (D_j) and release (D_r) at all sites varied by 10 to 13 days and 9 to 15 days, respectively. Over 5 years of record, the active breakup period at all sites began on or after 20-Apr and ended by 6-May. This indicates that that all EMO water level gauges and cameras should be installed and operational before 20-Apr. From start to finish (i.e. from the first transverse crack in Reach 2 [between the NWT/AB border at *km 945.5* and Alexandra Falls at *km 1034.0*] to the peak stage jam formation in the Hay River delta), the dynamic river ice breakup in the study reach occurred over a 5 to 7 day period.

The sites with the most consistent dates of breakup are presented in Table 3.2.

- The consistencies in dates of transverse cracks (D_c) at Alexandra Falls (*km 1034.0*) and Escarpment Creek (*km 1040.5*) were particularly useful, as in all five years of record, the first transverse crack in the study reach occurred at one of these two sites. Transverse cracks at Alexandra Falls

[3] Note that, for the Alexandra Falls site, this typically involved a small ice accumulation that was poised only briefly at the lip of the falls. Thus, the timing of 'jamming' at this site was defined as when the reach between the local EMO gauge and Alexandra Falls was clear of ice and so represents ice jam release at Alexandra Falls as well. Of the 4 years where the dates of these stages are known, the small accumulation formed on the same day as the reach between the gauge and falls cleared in 2 cases. For the other two cases, the small accumulation preceded the reach clearing by up to 2 days.

occurred in a window of 8 days (between 22-Apr and 30-Apr) in three years of record while cracks at Escarpment Creek occurred in a window of 9 days, between 20-Apr and 2-May. Thus, the first cracks at these sites (D_c) are one of the first indicators that Hay River breakup is underway.

- The dates of local ice jams (D_j) were most consistent at Escarpment Creek (*km 1040.5*), occurring within a 10 day range between 23-Apr and 3-May. The dates of ice jam releases (D_m) were most consistent at the Golf Course (*km 1088.5*) and Pine Point Bridge (*km 1098*), occurring within 9 and 10 day windows, respectively.

Although these ranges of dates of breakup stage occurrences were useful in a general sense, they were too broad to be used to forecast the specific timing of breakup stages. The numbers of days between breakup stages at each site were also examined, and defined as:

- ΔD_{cj} – the number of days between the first transverse crack and local ice jamming.
- ΔD_{cr} – the number of days between the first transverse crack and the ice jam release.
- ΔD_{jr} – the number of days between the local ice jam formation and the ice jam release.

When the number of days between breakup stages were examined at all sites, patterns at individual sites became apparent. The sites with the most consistent number of days between breakup stages are found in Table 3.3, and a summary of the ranges of dates and number of days between breakup stages, as well as the number of years of data available at all sites is described in Appendix J. A one day range in timing variability between the first transverse crack and local ice jamming (ΔD_{cj}) occurred at six sites, indicating that there was a consistent pattern in timing between crack and ice jam formation. This included all 4 sites in Reach 2, from the NWT/AB border (*km 945.5*) to Alexandra Falls (*km 1034.0*). In four of the six sites that exhibited this pattern, local ice jams occurred on the same day, or 1 day following the first transverse crack. The reach between the EMO gauge (*km 1032.0*) and Alexandra Falls (*km 1034.0*) cleared 1 to 2 days after the first transverse crack occurred. The NWT/AB border jammed 2 to 3 days after the first transverse crack occurred, while a range of two days between the first transverse crack and jam formation at Escarpment Creek (*km 1040.5*) (from 1 to 3 days) and the Pine Point Bridge (*km 1098.0*) (from 0 to 2 days) was observed.

Several sites exhibited consistencies in the number of days between the first transverse crack and ice jam release (ΔD_{cr}). In all three years for which data was available, there were three days between the first transverse crack and ice jam release at the NWT/AB border (*km 945.5*). At three other sites, the variability in ΔD_{cr} was only one day: the jam at the Golf Course (*km 1088.5*) released on the same day or the day after the transverse crack occurred, while at Grumbler Rapids (*km 986*) and the Pine Point Bridge (*km 1098.0*) release occurred between 1 and 2 days after first transverse crack. At Mink Creek (*km 1027.0*) and Paradise

Gardens (*km 1071.0*), ice jam releases occurred between 0 and 2 days after the formation of the first transverse cracks.

There were also consistencies in the number of days between ice jam formation and ice jam release (ΔD_{jr}) at a number of sites. Ice jam formation and release occurred on the same day at the Golf Course (*km 1088.5*) in all four years for which data were available, while ice jam releases occurred on the same day, or one day following ice jam formation at the NWT/AB border (*km 945.5*), Mink Creek (*km 1027.0*) and Paradise Gardens (*km 1071.0*). A range of 0 to 2 days between jam formation and ice jam release has been observed at Grumbler Rapids (*km 986*) and the Pine Point Bridge (*km 1098*).

The variability ranges in days over which breakup stages occurred help to illustrate the general breakup timeline at each individual site. Although the numbers of days between breakup stages cannot be used in long lead forecasting, knowing these patterns is extremely useful for short term forecasting and evacuation planning. This can be especially useful when combined with the reach-based approach for examining the dates and timing of stages of breakup between sites along the study reach.

3.1.2 Reach-based Method of Analysis

The reach-based method of analysis examined the timing of stages between sites, rather than looking at the specific dates of breakup stages at individual sites. The complete index of days between the first transverse crack, local ice jamming or ice jam release at one site and the first transverse crack, local ice jam or ice jam release at all other sites along the study reach are shown in Appendix K. Ranges of two days or less for all available years of data were considered consistent enough to discuss further here. The number of available data points (i.e. the number of years of data) for each of these comparisons were also considered. In general, three to five years of data were available for each combination of sites and breakup stages (Appendix L). The range of days between stages and sites were combined with the years of available data for quality control in Appendix M.

Consistencies in the timing between first transverse cracks at all sites were identified using the reach-based approach. All but one of the key sites within Reach 2 (from the NWT/AB border (*km 945.5*) to Alexandra Falls at *km 1034.0*) and all sites within Reach 3 (from Alexandra Falls to Enterprise at km *1048.0*) cracked within two days of the first transverse crack at any site within the same reach. The exception in Reach 2 was Grumbler Rapids (*km 986*), which followed 1 to 3 days later. Upper Reach 4 (Paradise Gardens at *km 1071* and the Golf Course at *km 1088.5*) cracked 2 to 4 days after the first transverse crack at Alexandra Falls. Lower Reach 4 (the WSC gauge at Hay River (HRHR) at *km 1095.2* and the Pine Point Bridge at *km 1098*) cracked 1 to 3 days after the first transverse crack at Alexandra Falls (*km 1034.0*) and 0 to 1 days after the first transverse crack at Mink Creek (*km 1027.0*).

The reach-based approach to examining the timing between transverse crack and local ice jam formation at all sites also revealed a number of consistent patterns. For example, the peak stage in the Hay River delta (*km 1108.0*) occurred 2 to 5 days after the first crack at the NWT/AB border (*km 945.5*), the Island (*km 974.0*) and/or Grumbler Rapids (*km 986.0*). The ice at Alexandra Falls (*km 1034.0*) cracked 1 to 4 days before ice jams formed at Mink Creek (*km 1027.0*), Alexandra Falls, Enterprise (*km 1048.0),* Paradise Gardens (*km 1071.0*) and the Golf Course (*km 1088.5*). The first transverse cracks at the NWT/AB border (*km 945.5*) and Grumbler Rapids (*km 986*) occurred 1 to 3 days before the jam formed at the NWT/AB border. The first transverse cracks at any location happened 1 to 3 days before ice jams formed at Grumbler Rapids (*km 946*), Mink Creek (*km 1027*) and Escarpment Creek (*km 1040.5*) and 4 to 6 days before the peak stage occurred in the Hay River delta (*km 1108*). The first transverse cracks at the Island (*km 974*) and Grumbler Rapids (*km 986*) happened 0 to 2 days before jams formed at Grumbler Rapids and Mink Creek (*km 1027.0*). The first transverse cracks at Alexandra Falls (*km 1034.0*) happened 1 to 3 days before jams formed at Mink Creek (*km 1027.0*), Alexandra Falls (*km 1034.0*), Enterprise (*km 1048.0*), Paradise Gardens (*km 1071*) and the Golf Course (*km 1088.5*). In Reaches 2 and 3 (between the NWT/AB border (*km 945.5*) and Enterprise (*km 1048.0*), transverse cracks and jams occurred at the majority of sites within 3 days of the first transverse crack formation anywhere. When the first transverse crack formed at the Pine Point Bridge (*km 1098.0*), the onset of breakup in the Hay River delta (*km 1108.0*) followed within 1 to 2 days.

This reach-based approach was also used to examine the timing between local ice jam events along the study reach. It was found that Alexandra Falls (*km 1034.0*) jammed 0 to 1 days before jams formed at Mink Creek (*km 1027*) and the Pine Point Bridge (*km 1098.0*), 0 to 2 days before jams formed at Enterprise (*km 1048.0*) and 1 to 3 days before ice jammed at Paradise Gardens (*km 1071*.0), the Golf Course (*km 1088.5*) and the onset of breakup in the Hay River delta (*km 1108*.0) (the onset of breakup in the Hay River delta is always an ice jam). Ice jams have formed at Mink Creek (*km 1027.0*) at approximately the same time as (within one day of) Grumbler Rapids (*km 986*), Enterprise (*km 1048.0*) and the Pine Point Bridge (*km 1098.0*). Ice jams occurred at Paradise Gardens (*km 1071.0*) and the Golf Course (*km 1088.5*) 1 to 2 days after the ice at Pine Point Bridge (*km 1098.0*) has cracked and pushed into the Hay River delta. In general, the peak stage (D_p) in the Town of Hay River occurred 1 to 4 days after any jams formed in Reaches 2 and 3 (between the NWT/AB border (*km 945.5*) and *km 1948.0* at Enterprise), which in turn occurred between 1 and 2 days after the reach immediately upstream of Alexandra Falls (*km 1032.0 to 1034.0*) cleared.

Several trends were identified when the timing between transverse cracks or jams at one site and jam releases at another were examined. Ice jams at the NWT/AB border (*km 945.5*) released 2 to 4 days after the first crack anywhere in Reaches 2 through 5, and 1 to 3 days after the first crack formed at the border, Island (*km 974.0*) or Grumbler Rapids (*km 986*). Ice jams at Grumbler Rapids (*km 986.0*) released 2 to 3 days after the ice cracked at the border (*km 974.0*). Once the head of the gorge jam shoved from Escarpment Creek (*km 1040.5*) to Enterprise (*km 1048.0*), it released within 0 to 1 days. This is especially important, as this gorge jam release ultimately resulted in the ice run creating the peak stage and associated flooding in the Town of Hay River[4]. The gorge jam at Enterprise (*km 1048.0*) also released 2 to 5 days after the ice cracked at Grumbler Rapids (*km 986.0*) and at Escarpment Creek (*km 1040.5*). Ice jammed in Reach 4 (between Enterprise (*km 1048.0*) and the Hay River delta (*km 1108.0*) and released from downstream to upstream. As ice runs accumulate and compound the jam in the Hay River delta, small (regressive) waves propagate upstream and chip away at the intact ice, resulting in ice jam releases from downstream to upstream. The ice jam at the Pine Point Bridge (*km 1098*) released, resulting in the onset of breakup in the Hay River delta 2 to 4 days after the first crack at Alexandra Falls (*km 1034.0*). When the ice at the Pine Point Bridge (*km 1098*) has cracked and pushed into the Hay River delta, the ice from the Golf Course (*km 1088.5*) followed 0 to 1 days later and the jam released at Paradise Gardens (*km 1071.0*) 0 to 1 days after that.

When the timing between ice jam release events are examined, several trends were observed. Mink Creek was typically one of the first sites to experience an ice jam release, occurring either on the first or second day that jam releases occur

[4] This ice run can be impeded by intact ice between Enterprise and the Pine Point Bridge, and can either re-jam in Reach 2, or shove through the ice until it arrives at the delta. Alternatively, the ice run may pass unimpeded through Reach 2.

at any site. In 4 out of 5 years, the ice run from Mink Creek (*km 1027.0*) arrived at the Golf Course (*km 1088.5*) the following day. The exception was in 2010 when this took 3 days, as the ice run was impeded by a jam at Enterprise (*km 1048.0*). Ice jams in upper Reach 4 (Paradise Gardens at *km 1071.0* and the Golf Course at *km 1088.5*) released 0 to 2 days after the jam released at Mink Creek (*km 1027.0*). There were overall fewer consistencies in timing between ice jam release events at all sites than there was with transverse cracks or ice jam formation.

The reach-based approach of analyzing the dates of occurrence of stages of breakup along the study reach provided a detailed account of the relationship between breakup stages at all sites over five years. Several historical reports contained intermittent dates of breakup stages occurring upstream of the Town of Hay River. Additional years of observation of the progression of breakup allowed this to be further refined. The dates and days between breakup stages available in the historical records were used to validate the trends identified using data from 2005, 2007, 2008, 2009 and 2010. This will be discussed next.

3.1.3 Analysis of Historical Records

The pattern of dates of breakup stages and days between breakup stages at all sites were examined using the site-specific and reach-based methods of analysis. However, there are only 5 years of detailed observations available as a result of this study directly. However, three sources of additional information on the historical progression of breakup were available:

- Observed hydrographs at each of the four WSC gauge stations located in the basin headwaters (Figure 1.1) were used the estimate the dates of the first transverse cracks in the upper basin. These dates were compared to the dates of onset of breakup, peak stage and melt out in the same years.
- The dates of first transverse crack formation (from 1964 to 2010) at the WSC gauge station near Hay River (HRHR) at *km 1095.2* were determined through analysis of the station strip charts (Zhao *et al.* 2010) and were compared to historical breakup dates in the Hay River delta.
- Historical engineering consultant and research reports contain the dates of several breakup stages occurring upstream of the Town of Hay River for the breakups of 1977, 1985, 1987, 1988 and 1989. The dates of these stages were analyzed using both the site-specific (local) and reach-based methods of analysis.

These additional sources of progression of breakup dates along the Hay River study reach were used to validate the reach-based ranges of dates of breakup stages established from the 2005 to 2010 data.

3.1.3.1 First Transverse Crack Formation at the WSC Gauge Stations in the Hay River Headwaters

Of the ten water level gauges located in the Hay River basin, four were WSC stations located in the headwaters (Figure 1.1). As these stations were located outside the study reach, there were no aerial photographs of these sites and the dates of breakup stages were not definitively known. However, the dates of the first transverse cracks could be estimated from the hydrographs, as this stage is typically marked by a sudden and erratic change in water level. These ranges of variability in the dates of the first transverse crack at each station are summarized in Table 3.4 and, as the table illustrates, the range was relatively wide (12 to 16 days).

The number of days between the transverse cracks at these stations and the onset of breakup, peak stage jam and ice jam melt out in the Hay River delta were also considered. Figure 3.1 illustrates the number of days between transverse crack formation (D_c) at Sousa Creek near High Level (SCHL), Chinchaga River near High Level (CRHL), Steen River near Steen River (SRSR) and Hay River near Meander River (HRMR) and the onset of breakup (D_o) in the Hay River delta. This was most consistent for Meander River (HRMR) and Steen River (SRSR), with ranges of 1 to 3 days and 5 to 8 days, respectively. The most upstream gauges (Sousa Creek (SCHL) and Chinchaga River (CRHL)) were more variable, with ranges of 4 to 14 and 1 to 12 days, respectively.

When the number of days between cracking at each of the four headwaters gauges was considered, several consistencies were found. Table 3.5 (a) illustrates the range of days between cracking at each of the gauges, while Table 3.5 (b) shows the number of year of data available for each site combination. Table 3.5 (c) combines the information from (a) and (b), showing the range of days between cracking at the sites, color coded by the number of years of data available. The most consistent patterns between cracking at the headwaters gauge sites were between Steen River (SRSR) and Meander River (HRMR) (2 to 5 days) and Sousa Creek (SCHL) and Meander River (HRMR) (-1 to 2 days). The next closest ranges were between Steen River (SRSR) and Chinchaga River (CRHL) (0 to 4 days) and Chinchaga River (CRHL) and Meander River (HRMR) (1 to 5 days). These ranges were based on 3, 3, 3 and 4 years of data, respectively. The largest range in days between cracking was between Sousa Creek (SCHL) and Chinchaga River (CRHL) (-9 to 6 days), when there was 7 years of available data.

Figure 3.2 illustrates the number of days between the first transverse crack at the headwaters gauge sites (D_c) and the peak stage jam (D_p) in the Hay River delta. Again, this was most consistent for Meander River (HRMR) and Steen River (SRSR), with ranges of 2 to 6 days and 6 to 9 days, respectively. The number of days between the ice cracking at the basin gauge stations and the peak stage jam (D_p) in Hay River ranged from 3 to 9 days at the Chinchaga River station (CRHL), and 6 to 18 days at the Sousa Creek (SCHL) station.

Figure 3.3 illustrates the number of days between transverse crack formation at the four WSC gauge stations (D_c) in the upper basin and the jam melting out in the Hay River delta (D_m). These ranged from 4 to 6 days at Meander River (HRMR), 8 to 12 days at Steen River (SRSR) and 6 to 12 days at Chinchaga River (CRHL). The number of days between transverse crack formation at Sousa Creek (SCHL) and melt out was more variable, from 9 to 19 days.

The headwaters sites with the most consistent number of days between first transverse crack formation and breakup stages in town were Meander River (HRMR) and Steen River (SRSR). The timing of the first crack at Meander River (HRMR) consistently preceded the onset of breakup (D_o), peak stage jam (D_p) and melt out (D_m) by 1 to 3 days, 2 to 6 days and 4 to 6 days, respectively. The timing of the first crack at Steen River (SRSR) consistently preceded the onset of breakup (D_o), peak stage jam (D_p) and melt out (D_m) by 5 to 8 days, 6 to 9 days and 8 to 12 days, respectively. The WSC gauge stations located further upstream near High Level (Chinchaga River (CRHL) and Sousa Creek (SCHL)) were less consistent. The hydrographs for all WSC gauge stations are updated in real-time on the WSC website and should be monitored as early as 15-Apr to watch for the first crack formation.

The number of days between first cracking at the headwaters gauges and transverse cracking at Alexandra Falls, and the WSC at Hay River gauge site (HRHR) were also considered. Figure 3.4 shows that cracking at the Hay River near Meander River (HRMR) and the Chinchaga River near High Level (CRHL) gauge sites has occurred after the first transverse cracking at Alexandra Falls (shown by negative numbers). These sites did not provide any advance lead time with respect to the timing of cracking at Alexandra Falls. The Sousa Creek near High Level (SCHL) and Steen River at Steen River (SRSR) happened consistently at least 1 and 2 days before cracking at Alexandra Falls.

Cracking at the Hay River near Meander River (HRMR) and the Chinchaga River near High Level (CRHL) gauge sites has occurred on the same day as cracking at the WSC gauge near Hay River (HRHR), as shown in Figure 3.5, so these did not provide any warning. The Sousa Creek near High Level (SCHL) and Steen River at Steen River (SRSR) happened consistently at least 3 days before cracking at the WSC near Hay River gauge site. Further monitoring and additional years of data would help validate these findings.

3.1.3.2 First Transverse Crack Formation at the WSC Near Hay River Gauge Station

The WSC gauge station near Hay River (HRHR) is located at *km 1095.2,* the upstream end of the Pine Point Bridge (*km 1098*) study site. The timing of first transverse cracking at this site has been the subject of a concurrent study, and the dates of first cracks since 1964 were extracted from the water level charts by Zhao *et al.* (2010). Figure 3.6 illustrates the historical dates of the first transverse cracks (D_c) obtained from the WSC gauge records. As discussed above, the site-specific analysis of photos obtained in 2005 and from 2007 to 2010 established that the first transverse cracks occurred at this location between 22-Apr and 3-May, and this range is also shown on Figure 3.6, for comparison. As the comparison illustrates, the range observed from the site-specific analysis of photos encompass all seven known occurrences associated with known severe flooding, and 8 of the 12 breakups that resulted in some flooding, thus illustrating the representativeness of the site specific analysis results.

In addition to the dates of the first transverse cracking at the WSC gauge near Hay River (HRHR) located at *km 1095.2*, the dates of the onset of breakup (D_o) in the Hay River delta are also known from 1964 to 2010. Figure 3.7 illustrates the interval between these two occurrences and for the 32 known cases in the historical record it has varied from 0 to 14 days. It is interesting to note that the interval is only 1 to 5 days for the majority (23) of the events, including 14 of the 18 events associated with flooding. The range observed in the reach-based analysis (discussed earlier) is also shown in Figure 3.7 for comparison. That analysis indicated that the interval between the first transverse crack at the WSC near Hay River gauge and the onset of breakup it the delta occurred within 1 to 2 days of each other. The comparison in Figure 3.7 suggests that the of the reach-based analysis of photos (from 2005 and 2007-2010) is not particularly representative of the true variability of this interval.

3.1.3.3 Historical Dates for the Various Breakup Stages

As discussed earlier, Appendix A contains the consolidated records of breakup at the Town of Hay River based on all known data sources, including historical consulting and research reports. Included in the historical data are the dates of several of the key stages in the breakup evolution occurring upstream of the Town of Hay River for 1977, 1985, 1987, 1988 and 1989[5], which can be compared to the detailed analysis of dates of breakup stages from 2005 to 2010. Appendix N summarizes the available dates of historical first transverse cracks, local ice jams and jam releases in sites upstream of the Hay River delta.

These historical breakup dates were first compared to the results of the site-specific analysis of the 2005 to 2010 (excluding 2006) data, discussed earlier. As Figure 3.8 illustrates, the known historic dates of first transverse cracking at Paradise Gardens *(km 1071.0)* and Pine Point Bridge *(km 1098.0)* all fell within the ranges estimated earlier using the 2005-2010 data. Figure 3.9 illustrates a similar comparison, in this case for all documented ice jam events upstream of the Town of Hay River, and Figure 3.10 illustrates the comparison for ice jam release events. Both confirm the representativeness of the date ranges observed in the site specific analysis of the 2005-2010 data.

Where possible, the number of days between breakup stages at individual sites, as determined from the 2005 to 2010 observations, were compared to those found in the historical record. This information was available for only a few sites, as summarized in Table 3.6. All agreed with the one to two day ranges suggested by the site-specific analysis of the 2005 to 2010 data.

---

[5] In terms of consequent flood severity, the spring breakups in 1985, 1986 and 1989 resulted in significant flooding, while no flooding occurred in 1977 and 1987.

A full study of the dates of ice jam stages in the Hay River delta from 1894 to 2010 is described in Section 2.3.2. That extended historical record of breakup dates in the delta was compared to the range of dates established by the site-specific method. Of the 32 onset of breakup dates (D_o) on record for years when flooding occurred, 23 of them fall within the range delineated by the site-specific method. The non-flood years were more variable, with 23 of 52 cases falling within the site-specific range. Of the 32 recorded dates of peak stage due to ice jams (D_p) causing flooding, 23 occurred within the site-specific range. Of the non-flood cases, D_p occurred in the range for 12 of 16 years.

After the site-specific and reach-based analyses were applied to investigate patterns in breakup dates from 2005 to 2010, the representativeness of the results were compared to any available historical data available in the records. For practical purposes, only those relationships that had proved promising (i.e. had relatively tight date ranges of 0 to 2 days) were evaluated for consistency with the historical data. The combinations of breakup stages and sites that did agree well between both data sources are shown in Table 3.7. Those that are not shaded had a range of one day for all years of record and were the most promising and consistent indicators. Those shaded in grey had a two day range for all available years of record. Table 3.8 shows those cases where the historical data contradicted the promising tendencies suggested in the reach based analysis of the 2005 to 2010 data. Most notable among these disagreements was that the historical data did not support the onset of breakup in the town (D_o) occurring 0 to 1 days after transverse cracking at the Pine Point Bridge (*km 1098*).

In several cases, there was more than one historical example of the number of days between sites and breakup stages to compare to the reach based analysis of the 2005 to 2010 data. Often, one of these fell within the range of days indicated by the 2005 to 2010 data, while another did not. These ambiguous cases are summarized in Table 3.9, with the contradictory historical cases shown in bold. The majority of these ambiguous cases were related to the time interval between breakup stages along the reach and the onset of breakup and peak stage in the Hay River delta. This illustrates that the ranges of day between upstream stages and breakup stages in the delta actually varied by more than 1 or 2 days. Once these corrections were applied, there were several new relationships to note. Including the historical information, the onset of breakup (D_o) occurred 1 to 3 days after the local ice jam at Alexandra Falls (*km 1034.0*). The peak stage jam (D_p) occurred 1 to 4 days after the jam released at the NWT/AB border (*km 945.5*) and the ice jam formed at Enterprise (*km 1048.0*). Ice jam formation at Escarpment Creek (*km 1040.5*) and transverse cracks at Paradise Gardens (*km 1071*) occurred 3 to 5 days and 1 to 4 days, respectively, before the peak stage jam (D_p) occurred in the Hay River delta.

It is important to collect additional years of data to allow the ranges of dates between breakup stages along the reach to be refined and adapted. The more years of data available, the more representative these will become. However, an increase in variability in breakup patterns may result when more data sets are considered.

3.1.4 Sequence of Breakup Stages

In order to determine the general pattern of key breakup stages from the NWT/AB border to the Town of Hay River (i.e. Reaches 2 to 5), the sequence of stages at key sites along the river were numbered chronologically. Table 3.10 presents the chronological orders of each type of breakup stage (i.e. first transverse crack, local ice jam and ice jam release) for the five years of data collected for this study (2005 and 2007 to 2020); the colour coding indicates the reach in which each site is located, the numbers indicate the sequence as well as the number of days. Appendix O presents this same data in varying forms to aid further interpretation.

As discussed earlier, more extensive photographic documentation was available in the later years of this study. As a result, the timing of stages at one or more of sites was unknown in some of the earlier years, particularly for the first transverse crack. For such instances, water level records at the station were investigated to see if they could be used to help to deduce sequences of stages (i.e. in a manner similar to that employed for identifying the first crack at some of the WSC gauges). For example, if the water level record indicated an ice run passing the gauge at Alexandra Falls, then the first cracking must have occurred prior to that time. This information proved useful only in 2005 in terms identifying the sequencing of first cracking.

As Table 3.10 (a) illustrates, the timing and sequence of the first transverse cracks did exhibit some consistent trends. For example, in all five years, the first transverse cracking occurred earliest in Reach 2 (upstream of Alexandra Falls), with the first site to crack being either at the EMO Alexandra Falls gauge site (*km 1034.0*) or the NWT/AB border (*km 945.5*). First cracking at the remainder of key sites in Reach 2 followed within 1 to 4 days. For all three years in which the timing of the first transverse crack was documented at Escarpment Creek *(km 1040.5)* in Reach 3, it occurred within 1 to 3 days of the first observed cracking in Reach 2 and, in two of these three known cases, it occurred before the first transverse cracking at several sites within Reach 2. Similarly, although the first transverse cracks in Reach 4 followed those in Reaches 2 and 3, on two occasions the first cracking at one site in Reach 4 occurred before the first transverse crack at two or more sites in Reach 1. Also, in Reach 4, the first transverse cracking occurred at the Pine Point Bridge (*km 1098.0*) in 3 of these 5 years.

Based on these observations the general pattern for the onset of breakup along the Hay River downstream of the NWT/AB Border (*km 945.5*) is hypothesized as follows:

- The onset of breakup commences in Reach 2, with the first cracking occurring at Alexandra Falls (*km 1032.0*), the NWT/AB Border (*km 945.5*) or both.
- Breakup initiation progresses in a generally downstream direction, with first cracking in Reach 3 following within 1 to 3 days, and in Reach 4 with 2 to 4 days. The first site to crack in Reach 4 is often the Pine Point Bridge.
- First cracking at the various key sites within Reach 2 can occur all in a single day, or can be spread over as many as 4 days. In the prolonged cases, the first transverse cracking at some sites in Reach 2 can overlap with, or even follow, the first transverse cracking in Reaches 3 and 4.

Thus although general progression of the onset of breakup is in the downstream direction, there is some overlap between the reaches.

Table 3.10 (b) illustrates the general order of ice jam stages documented; again a number of tendencies were observed. The progression was generally from upstream to downstream with the first ice accumulations forming in Reach 2, followed by Reach 3, then 4, then 5. However, as with the first transverse cracking, there was some overlap between reaches, with 2009 being especially irregular[6]. In Reach 2, the first ice accumulations formed between the Alexandra Falls EMO gauge (*km 1032.0*) and Alexandra Falls *(km 1034.0)* in 4 of the 5 years. Then, ice accumulations formed at Mink Creek (*km 1027.0*) in Reach 2 and Escarpment Creek (*km 1040.5*) or Enterprise *(km 1048.0)*, or both, in Reach 3 within 0 to 3 days (though most often on the following day). In Reach 4, ice accumulations formed first at the Pine Point Bridge (*km 1098*) or at Paradise Gardens (*km 1071.0*), and occurred within 0 to 3 days of the first ice jams in Reach 2. For all five years of data, once the first ice accumulation occurred in Reach 2, all key sites in Reaches 2, 3 and 4 had started jamming within 3 to 5 days, and the onset of breakup (D_o) in Reach 5, which involves the formation of small ice jams in the East and/or West Channels at Hay River, occurred within 2 to 3 days. In four of the five years, the onset of onset of breakup (D_o) and peak stage jam (D_p) in the Town of Hay River occurred just 1 day apart. The exception was in 2009, when the peak stage jam occurred 4 days after the onset of breakup in the Town of Hay River. This illustrates the speed with which breakup stages unfold once dynamic events commence.

As Table 3.10 (c) shows, the sequence of ice jam release events is comparable to that observed for the first transverse cracks and ice jams. That is, the general progression is from upstream to downstream by reach, with some overlap between

---

[6] It may be significant to note that, in 2009, a later winter snowfall blanketed the ice cover in Reaches 1, 2 and 3, increasing ice surface albedo and delaying the progression of breakup there. No snowfall was recorded at the Hay River Airport, and the progression of breakup in Reaches 4 and 5 continued unimpeded. This same event delayed the arrival of basin snowmelt runoff event peak, such that it arrived after the main ice jamming events in the Town of Hay River, thus averting a major flood (Maxwell and Hicks 2011).

reaches. The notable exception was 2009, in which ice jam release events in Reach 4 preceded those in Reach 2. As discussed above, this can likely be attributed to the late snowfall that occurred in the upper basin. Nevertheless, in all five years, the first ice jam release event occurred in Reach 2 (typically at Alexandra Falls (*km 1034.0*), followed by Mink Creek (*km 1027.0*)), all ice jams in Reaches 2, 3 and 4 released within 1 to 4 days, again illustrating the rapidity of dynamic breakup on the Hay River.

Tables 3.11 shows the same data, organized by year instead of by stage type, elucidating possible patterns in the sequence and timing between these three key stages of breakup. The following tendencies were observed:

Reach 2: *NWT/AB border (km 945.5) to Alexandra Falls (km 1034.0)*

- Transverse cracking most often occurred first at the Alexandra Falls EMO gauge (*km 1032.0*), and an ice accumulation between that gauge and Alexandra Falls *(km 1034.0)* occurred within 0 to 2 days in all four known cases. This ice accumulation can be very localized, and is not always composed of all the ice between the gauge and the falls. It usually slipped over Alexandra Falls on the same day, or in the 2 days preceding the ice clearing between the gauge and the falls. The latter occurred when the accumulation was more local to the lip of the falls.

- Once transverse cracking occurred at the NWT/AB border (*km 945.5*), an ice accumulation occurred there within 0 to 2 days and then released on the same day.
- Once transverse cracking occurred at Mink Creek (*km 1027.0*), an ice accumulation occurred there within 0 to 1 days and then typically released on the same day. (In one case it released on the following day.)
- Once transverse cracking occurred at the Grumbler Rapids (*km 986.0*), an ice accumulation occurred there on the same or following day and then released within 0 to 2 days.

<u>Reach 3:</u> *the Gorge (km 1034.0 to 1048.0)*

- Once transverse cracking occurred at Escarpment Creek (*km 1040.5*), an ice jam occurred there within 0 to 3 days, and then next at Enterprise (*km 1048.0*) within 2 to 4 days. Ice jams at Escarpment Creek released within 1 to 4 days, those at Enterprise within 0 to 3 days. The longer durations were the exceptions, associated with the 2009 breakup.

<u>Reach 4:</u> *Paradise Gardens (km 1071.0) to the Pine Point Bridge (km 1098.0)*

- Transverse cracking in this reach most often occurred first at the Pine Point Bridge gauge (*km 1098.0*), and an ice jam formed there on the same day in four of the five years (and 2 days later in 2010). Ice jam release followed within 0 to 2 days.
- When transverse cracks first occurred at Paradise Gardens (*km 1071.0*), an ice jam formed there on the same, or next, day and then released on the

same or following day. The total duration between first cracking and ice jam release at this site ranged from 0 to 2 days.

- When transverse cracks first occurred at the Golf Course (*km 1088.5*), ice jamming followed on the next day in four of the five years; it occurred on the same day in 2007. In all four known cases, the release occurred the same day as the ice jam formed.

Reach 5: *East and West Channels at the Town of Hay River*

The following time increments were documented between the stage noted and the peak stage jam (D_p) in Hay River:

- Reach 2: first cracking, 4 to 6 days and first jamming and release, 3 to 5 days.
- Reach 3: first cracking, 3 to 5 days; first jamming 2 to 4 days; and first release, 0 to 4 days.
- Reach 4: first cracking, 2 to 5 days; first jamming 1 to 5 days; and first release, 1 to 5 days (with the longest durations being for the 2009 event).

Thus, in general, the critical risk period in the Town of Hay River (when the peak stage jam and associated flooding occurs) follows the onset of breakup in Reach 2 within 1 week.

The minimum time increments between ice jam release events and the peak stage jam (D_p) in Hay River were:

- Reach 2: 0 to 3 days, with the most severe flooding (2008) being associated with the same day event.

- Reach 3: 0 to 3 days; the most severe flooding (2008) was associated with one of the same day events.
- Reach 4: 0 to 2 days, with the longest duration case associated with ice the most severe flooding (2008). Essentially this cleared the path through to the Town and an ice jam release from Grumbler Rapids (*km 986.0*) precipitated the release of an ice jam in the Gorge (between *km 1040.5* and *1048.0*), and the combined wave of ice and water progressed unimpeded right to the Hay River delta.

Clearly any jam release events in Reaches 2 and 3 have the potential to come straight to Town the same day. When Reach 4 clears of ice before the release of the ice jams from Reaches 1, 2 or 3, the way is clear for ice runs from the upper reaches to push straight through to the Town in one day (unimpeded ice run scenario).

3.2 Progression of Breakup Based on Degree-day Analysis

Heat inputs to the snowpack and ice cover are key factors affecting the progression of breakup, since snowmelt increases stream flow and direct heat input to the ice cover decreases its strength. To take such effects into account degree-day analyses were undertaken to determine whether there were any consistent patterns and trends that might help in determining the timing of various stages of breakup at the key study sites.

Degree-days of thaw are typically calculated by summing up the positive mean daily temperatures over the spring period. Although simple to calculate, a number of possible conventions can be used. The variations typically relate to the following three issues:

1. When to start summing the mean daily temperatures: This can commence on a specific date, on the first day of above-zero mean daily air temperatures or it can require a few consecutive days of warm weather to commence the calculations (typically 5), so as to exclude brief, but inconsequential, periods of warm weather leading up to breakup.
2. What temperature to use as the base for calculations: Generally, the base is taken as 0˚C; such that the mean daily temperatures are just summed, as noted above. However, in some cases this may not be representative of the heat available to initiate melt, since mean daily temperatures below zero can occur even with above zero maximum daily temperatures. To account for this possibility, one variation is to take the base temperature as -5˚C (e.g. such that a mean daily temperature of -3˚C would count as 2 ˚C-days).
3. How to consider freezing degree-days that occur once degree-days of thaw are being accumulated: These can be ignored, or they can be included in the accumulation, thus temporarily decreasing the degree-days of thaw. Alternatively, degree-days of freezing can be accumulated during the pre-breakup period and used as a criterion for resetting the cumulative degree-

days of thaw to zero (e.g. if/when degree-days of freezing exceeds the cumulative degree-days of thaw.) In this case, the accumulated degree-days of freezing in the pre-breakup period ($ADDF_{pb}$) are calculated using the same temperature base used to calculate the degree-days of thaw.

As discussed in Chapter 2, air temperature data for the Town of Hay River was available for 1951, 1954, 1956 and all years since 1963, while temperature data was available for the Town of High Level since 1970. Mean daily air temperatures recorded at the Hay River and High Level Airports were each used to calculate three variations of accumulated degree-days of thaw on the dates of breakup stages:

- Accumulated degree-days of thaw, base 0˚C: $ADDT_0$
  - The accumulation commenced on the first day of the first 5 consecutive days of above-zero air temperatures.
  - Negative mean daily air temperatures were ignored in calculating $ADDT_0$, but $ADDT_0$ was reset to zero if it was exceeded by $ADDF_{pb}$.
- Accumulated degree-days of thaw, base -5˚C: $ADDT_{-5}$
  - The accumulation commenced on the first day of the first 5 consecutive days of above -5˚C air temperatures
  - Mean daily air temperatures below -5˚Cwere ignored in calculating $ADDT_{-5}$, but $ADDT_{-5}$ was reset to zero if it was exceeded by $ADDF_{pb}$.
- Total degree–days of thaw, base 0˚C: $TDDT$
  - The accumulation commenced on March 1.

- Negative mean daily air temperatures were ignored.

The accumulated degree-days of freezing in the pre-breakup period (*$ADDF_{pb}$*) were accumulated using the same baseline temperature (0˚C or -5˚C) as *$ADDT_0$ and $ADDT_{-5}$*, but the accumulation of degree-days of freezing was always started on 1-Apr, so as to only take into account the effects of freezing temperatures in the period immediately preceding breakup.

Using 0˚C as a baseline is the most widely accepted practice when calculating accumulated degree-days of thaw. However, a baseline temperature of -5˚C was considered worth investigating also, as it has been found to have the best empirical correlations with various breakup indicators (Zhao *et al*. 2010). Also, it was observed that significant thaw could still occur during warm afternoons (periods of daily high temperatures) on days where the mean daily temperature remained below zero degrees. Considering a threshold of minus five degrees was a method of investigating whether this period of daily high temperatures affected the relationship between accumulated degree-days of thaw and the progression of breakup. Total degree-days of thaw (*TDDT*) took into consideration a warm spring, regardless of whether the warm days were consecutive.

Three approaches were adopted to investigate patterns in the progression of breakup on the Hay River. The site-specific method considered thresholds of accumulated degree–days of thaw (*ADDT*) at which key breakup stages occurred.

The increases in accumulated degree-days (*ADDT*) between breakup stages at individual sites were also considered for the site-specific approach. One convention was used for the remaining two method of analysis. The reach-based approach was also used to analyze the change in total degree-days in Hay River between breakup stages at all sites along the study reach. The total degree-days of thaw (*TDDT*) and total degree-days of freezing in the pre-breakup period ($TDDF_{pb}$) during historical breakup stages in the Hay River delta were also investigated. The pattern of cold snaps and warming in the pre-breakup period was considered, as was the difference in temperatures between High Level and Hay River (headwaters and the delta) during the pre-breakup period.

3.2.1 Site Specific Method of Analysis

All three conventions for calculating degree-days discussed above were applied to the air temperature data from both Hay River and High Level to investigate the applicability of degree-day thresholds for predicting progression of breakup along the Hay River study reach. For each convention and climate station, the accumulated degree-days were calculated for the dates of each breakup stage at each key site. The thresholds of degree-days at which these various stages of breakup occurred, as well as the increase in degree-days between these breakup stages at each site were then examined. Appendix P provides the complete and detailed results; the most salient of these are discussed below.

None of the six variations for calculating degree-days of thaw produced exceptionally consistent results; each had its advantages and disadvantages, but none showed any clear superiority as indicators. Therefore, the simplest convention to implement and interpret was selected: the total degree-days (*TDDT*) at Hay River. The reasoning for this choice was that it is the simplest for the layperson to understand and calculate. Thus, should the Town of Hay River Flood Watch Committee choose to employ these threshold models in the future, they will simply need to sum all positive daily mean temperatures occurring after 1-Mar. This bypasses the complication of having to calculate and reset the accumulated degree-days of thaw (*ADDT*) calculation based on the accumulated degree-days of freezing in the pre-breakup period ($ADDF_{pb}$).

For this site-specific analysis, the total degree-days (*TDDT*) on the dates of the various stages of breakup, as well as the increase in *TDDT* between stages (where known) were calculated for each of the ten study sites (Table 3.12). This included:

- $TDDT_c$ – the total degree-days on the date of the first transverse crack.
- $TDDT_j$ – the total degree-days on the date of local ice jam formation.
- $TDDT_r$ – the total degree-days on the date of the ice jam release.
- $\Delta TDDT_{cj}$ – the increase in total degree-days between the first transverse crack and local ice jam formation.
- $\Delta TDDT_{cr}$ – the increase in total degree-days between the first transverse crack and ice jam release.

- $\Delta TDDT_{jr}$ – the increase in total degree-days between local ice jam formation and the ice jam release.

Figure 3.11 illustrates the total degree-days at which the first transverse crack occurred ($TDDT_c$); no particular consistencies in these thresholds were found for any site. The most consistent range of total degree-days during which any first transverse crack occurred ($TDDT_c$) was at the NWT/AB border (*km 945.5*), which had a range of 66˚C-days over 5 years of data. The total degree-days on the day of the first transverse crack ($TDDT_c$) at all other sites ranged from 29 to 131˚C-days. Similarly, there was no identifiable threshold of total degree-days at which local ice jams ($TDDT_j$) occurred at any site (Figure 3.12). The range of total degree-days for all sites on the date of ice jam formation ($TDDT_j$) was from 29 to 131˚C-days. This is the same range as $TDDT_c$, as cracking and jamming occurred on the same day for the extreme cases. As seen in Figure 3.13, ice jam releases at Grumbler Rapids (*km 986.0*) occurred when the total degree-days ($TDDT_r$) were between 55 and 128˚C-days, a range of 72˚C-days). This was the narrowest of all the ranges for the ice jam releases events at all sites, but was not very precise. The range of degree-days for the date of ice jam releases at all sites ($TDDT_r$) was between 37 and 131˚C-days.

When increases in total degree-days ($\Delta TDDT$) between the first crack in the ice, local ice jam formation and the ice jam release at each site were considered, the best potential indicators were those which ranged by 10˚C-days or less for all years of data (Table 3.13). The increases between the crack and jam formation ($\Delta TDDT_{cj}$), crack and ice jam release ($\Delta TDDT_{cr}$) and ice jam and ice jam release ($\Delta TDDT_{jr}$) are illustrated in Figures 3.14, 3.15 and 3.16, respectively. Although these sites exhibited fairly consistent total degree-days increases ($\Delta TDDT$) between breakup stages, these results were not particularly informative, because 13 of the 14 ranges of total degree-day increases start at zero (which means no advanced warning). However, the range of total degree-days between the transverse crack and jam release (ΔTDD_{cr}) events at the Pine Point Bridge (*km 1098*) was more informative, as the ice jam release occurred between 4 and 8˚C-days after the first transverse crack. If the day following the first transverse crack at the Pine Point Bridge was a cold one (with a mean daily temperature of less than 4˚C), the jam that subsequently formed may not have released immediately. The Pine Point Bridge was also the site immediately upstream of the Town of Hay River, so when the first transverse crack and subsequent ice jam formation and release occurred at this location, this ultimately resulted in ice runs that caused the onset of breakup in the Hay River delta within 1 to 2 days, respectively.

In summary, no particularly consistent thresholds were identified using total degree-days of thaw. This is not surprising given the highly dynamic nature of breakup in the study reach (i.e. hydrodynamic effects dominate over thermal influences) and the rapidly within which breakup stages unfold. However, the increases in total degree-days between breakup stages at a number of sites were rather consistent. Although these do not allow much lead time (increases range from 0 to a certain number of degree-days), they identified a range of temperatures during which subsequent breakup stages have occurred in five years of record (Table 3.12).

3.2.2 Reach-based Method of Analysis

Similar to the reach-based approach of examining days between breakup stages at all sites, this method looked at the change in total degree-days of thaw ($\Delta TDDT$) between breakup stages along all sites. The ranges of total degree-days of thaw (*TDDT)* from the start to finish of known breakups, from the first crack in Reach 2 between the NWT/AB border (*km 945.5*) to peak stage jam (D_p) in the Hay River delta are summarized in Table 3.14. These indicated that the entire active breakup period occurred over 23 to 42˚C-days. Increases of 10˚C-days or less between breakup stages along the reach were considered consistent enough to report. There was ultimately too much overlap in degree-days of thaw between stages at all sites to glean any useful patterns in addition to those extracted in the analysis of breakup timing (Appendix Q). As previously mentioned, the number of years of available data for all the site and breakup stages combinations are summarized in Appendix L. Appendix R combines Appendices Q and L and identifies the increases in total degree-days of thaw (*TDDT*) and the number of years of data that these ranges were based on.

Mean daily temperatures (*MDT*) were extremely variable during the breakup period. Table 3.15 notes the highest and lowest mean daily temperatures occurring during the breakup period over five years of record. Three of the warmest and two of the coldest mean daily temperatures (*MDT*) in the detailed breakup record occurred in 2010. All other years had extreme warm and cold days except for 2009, which experienced a cold snap before and during breakup. Considering the small range of total degree-days over which breakups occurred and the erratic mean daily temperatures (*MDT*) that occurred during breakup, the reach-based method of analysis was unsuitable for considering total degree-days of thaw (*TDDT*) as indicators of the timing of the progression of breakup.

3.2.3 Analysis of Historical Records

The years of record available for a detailed study of the reach extending from the NWT/AB border (*km 945.5*) to the Town of Hay River (*km 1108.0*) were limited to those with continuous daily observation flights and photographic coverage. However, a much more extensive record of historical breakup dates in town was assembled in Appendix A. Hay River temperature data was available for 1951, and all years since 1963, allowing for several studies of degree-days patterns during breakup stages in the Hay River delta. Total degree-days of thaw (*TDDT*) as well as total degree-days of freezing in the pre-breakup period ($TDDF_{pb}$) were considered on the dates of the onset of breakup (D_o), peak stage jam (D_p) and ice jam melt out (D_m). Also considered were the increases in total degree-days of thaw (*TDDT*) and total degree-days of freezing in the pre-breakup period ($TDDF_{pb}$) between these stages. The patterns of total degree-days preceding the onset of breakup (D_o) were also examined.

3.2.3.1 Total Degree-days of Thaw

The total degree-days of thaw *(TDDT)* on dates of the onset of breakup, peak stage due to ice jams and melt out were examined. These were grouped by severity class to identify patterns or thresholds, and were defined as

- $TDDT_o$ – the total degree-days on the date of the onset, or initiation, of breakup in the Hay River delta.
- $TDDT_p$ – the total degree-days of thaw on the date that the peak breakup stage occurred in the Hay River delta during breakup.
- $TDDT_m$ – the total degree-days of thaw on the date that the ice jam(s) in the Hay River delta melted out to leave a clear flow path right to Great Slave Lake.

Figure 3.17 shows the highly variable range in total degree-days of thaw at which the onset of breakup in the Hay River delta ($TDDT_o$) has occurred. $TDDT_o$ were known for 10 of the 11 significant flooding events, 12 of the 23 minor to moderate (i.e. some) flooding events and for 14 of the 83 cases where no flooding occurred. There was no pattern in the thresholds at which years with significant or some flooding have occurred. The ten significant flooding events have occurred anywhere within the range of 17 to 88˚C-days. The onset of breakup resulting in some and no flooding have occurred anywhere from 5 to 131˚C-days, and 6 to 134˚C-days, respectively.

The total degree-days of thaw on the dates of historical peak stages in the Hay River delta ($TDDT_p$) are illustrated in Figure 3.18. As with the total degree-days of that on the dates of the onset of breakup ($TDDT_o$), $TDDT_p$ exhibited no pattern in the thresholds at which years with significant or some flooding occur. $TDDT_p$ values are known for 10 of the 11 significant flooding events, 9 of the 23 events involving some flooding and 9 of the 83 non-flood events on record. The peak stages of significant flooding events have occurred between 35 and 106˚C-days. The peak stages causing some and no flooding have occurred in the range of 11 to 131˚C-days and 25 to 155˚C-days, respectively.

The total degree-days of thaw on the dates that the ice jams melted out to Great Slave Lake ($TDDT_m$) were examined in Figure 3.19. These are known for 9 of the 11 significant flooding events, 10 of the 23 events in which some flooding occurred and 23 of the 83 non-flood events on record. Of the years with significant flooding, this occurred between 42 and 112˚C-days. Melt out for years of some and no flooding occurred over larger ranges; between 12 and 133˚C-days, and 25 and 162˚C-days, respectively.

In addition to the numbers of total degree-days of thaw at which delta breakup stages occurred, the number of degree-days of thaw between stages were also examined and defined as:

- $\Delta TDDT_p$ – the increase in total degree-days between the date of the onset, or initiation, of breakup and peak stage jam in the Hay River delta. This information was known for 10 of the 11 significant floods, 9 of the 23 events resulting in some flooding, and 8 of the 83 historical events resulting in no flooding.

- $\Delta TDDT_m$ – the increase in total degree-days between the date of the onset, or initiation, of breakup and the date that the ice jam(s) in the Hay River delta melted out to leave a clear flow path right to Great Slave Lake. This information was known for 9 of 11 significant floods, 9 of 23 events resulting in some flooding, and 12 of 83 historical events resulting in no flooding.
- $\Delta TDDT_{m\text{-}p}$ – the increase in total degree-days between the date of the peak stage due to an ice jam and the date that the ice jam(s) in the Hay River delta melted out to leave a clear flow path right to Great Slave Lake. This information was known for 9 of the 11 significant floods, 7 of 23 events resulting in some flooding, and 8 of 83 historical events resulting in no flooding.

Appendix S summarized all of the detailed comparison and evaluations, illustrating that there is no consistency or patterns in total degree-days of thaw between any of the onset of breakup date, the date of peak stage or the date of melt out. Overall, this total degree-day (*TDDT*) threshold analysis showed that temperatures during breakup in the Hay River delta do not affect the severity of flooding experienced in town, and reflected the dominance of dynamic effects over thermal influences on breakup of the Hay River.

The relationship between the number of days and total degree-days of thaw between peak stage and melt out was also examined in Figure 3.20. This was known for 9 of 11 significant floods (Figure 3.20 a), 7 of 23 cases where some flooding occurred (Figure 3.20 b) and 8 of 83 years when there was no flooding (Figure 3.20 c). A negative slope was expected if there was a relationship between the number of days and degree-days between the peak stage and jam melt out. The non-flood years did exhibit this negative relationship (as would be expected since dynamic effects would have been slightly less dominant over thermal effects in these cases); however, there appeared to be no definitive relationship between the number of days and total degree-days between peak stage and melt out when flooding occurred. This was also not surprising, as ice jams were melted out more effectively by warm water than warm air temperatures. Solar radiation heated the open water upstream, which eroded and melted out the ice jam much more effectively than warm air temperatures could melt them from above.

The rate of increase in total degree-days of thaw preceding breakup was not investigated. Concurrent research at the University of Alberta has found that there is no significant correlation between this rate of total degree-day rise and the severity of flooding in a given year (Zhao *et al.* 2010). Because of this, it was not included in this study.

3.2.3.2 Total Degree-days of Freezing in the Pre-Breakup Period

As with the total degree-days of thaw on dates of breakup stages, the total degree-days of freezing in the pre-breakup period since 1-Apr ($TDDF_{pb}$) were examined. This was done to determine if there was a relationship between a cold pre-breakup period and the severity of flooding experienced in Hay River. The total degree-days of freezing in the pre-breakup period ($TDDF_{pb}$) were determined on the dates of the onset of breakup, peak stage jam and ice jam melt out are defined as:

- $TDDF_o$ – the total degree-days of freezing during the pre-breakup period on the date of the onset, or initiation, of breakup in the Hay River delta.
- $TDDF_p$ – the total degree-days of freezing during the pre-breakup period on the date of peak breakup stage occurring in the Hay River delta during breakup.
- $TDDF_m$ – the total degree-days of freezing during the pre-breakup period on the date that the ice jam(s) in the Hay River delta melted out to leave a clear flow path right to Great Slave Lake.

Figure 3.21 illustrates the total degree-days of freezing in the pre-breakup period ($TDDF_o$) on the dates of the onset of breakup in the Town of Hay River. $TDDF_o$ values were known for 10 of the 11 significant flooding events, 12 of the 23 events in which some flooding occurred and 14 of the 83 non-flood events on record. The significant flooding events showed the most consistency, as ninety percent (9 out of 10) of documented breakups resulting in significant flooding initiated in the range of 135 to 206˚C-days of freezing. The one exception was

2003, when $TDDF_o$ was 87˚C-days of freezing. Some flooding and no known flooding have occurred anywhere in the range of 37 to 325˚C-days and 26 to 335˚C-days of freezing since 1-Apr, respectively.

The total degree-days of freezing in the pre-breakup period on the date of peak stage jams ($TDDF_p$) are illustrated in Figure 3.22. This was known for 10 of the 11 significant flooding events, 9 of the 23 events in which some flooding occurred and 9 of the 83 non-flood events on record. Ninety percent of peak stages during significant flooding events occurred within the range of 135 to 217˚C-days of freezing. The one exception was again 2003, when $TDDF_p$ was 88˚C-days of freezing. The peak stages in years of some or no flooding have occurred anywhere between 37 to 325˚C-days and 26 to 335˚C-days of freezing, respectively. Of note is that 12 of the 13 $TDDF_p$ that were greater than 135˚C-days of freezing resulted in at least some flooding.

The total degree-days of freezing in the pre-breakup period ($TDDF_m$) on the date of jam melt out are examined in Figure 3.23. This was known for 9 of the 11 significant flooding events, 10 of the 23 events in which some flooding occurred and 23 of the 83 non-flood events on record. For years when breakup ice jams caused significant flooding, melt out occurred between 135 and 217 ˚C-days of freezing. The date of D_m in 2003 was not known to include in this analysis. When ice jams caused some or no flooding, melt out occurred between 48 and 325˚C-days and 19 and 321˚C-days of freezing, respectively.

The number of degree-days of freezing in the pre-breakup period between breakup stages were also examined and defined as:

- $\Delta TDDF_p$ – the increase in total degree-days of freezing in the pre-breakup period between the date of the onset, or initiation, of breakup and peak stage jam in the Hay River delta. This information was known for 10 of the 11 significant floods, 9 of the 23 events resulting in some flooding, and 8 of the 83 historical events resulting in no flooding.
- $\Delta TDDF_m$ – the increase in total degree-days of freezing in the pre-breakup period between the date of the onset, or initiation, of breakup and the date that the ice jam(s) in the Hay River delta melted out to leave a clear flow path right to Great Slave Lake. This information was known for 9 of the 11 significant floods, 9 of the 23 events resulting in some flooding, and 12 of the 83 historical events resulting in no flooding.
- $\Delta TDDF_{m\text{-}p}$ – the increase in total degree-days of freezing in the pre-breakup period between the date of the peak stage and the date that the ice jam(s) in the Hay River delta melted out to leave a clear flow path right to Great Slave Lake. This information was known for 9 of the 11 significant floods, 6 of the 23 events resulting in some flooding, and 9 of the 83 historical events resulting in no flooding.

Full details of this analysis are presented in Appendix T; there were no consistencies or patterns in total degree-days of freezing in the pre-breakup period between any of the: onset of breakup date; the date of peak stage; or the date of melt out. This analysis also supported the conclusion that air temperatures during breakup in the Town of Hay River (from the onset of breakup to ice jam melt out) in the Hay River delta did not affect the severity of flooding that occurred in town.

The relationship between the number of days and total degree-days of freezing in the pre-breakup period between peak stage and melt out was also examined in Figure 3.24. This was known for 9 of the 11 significant floods (Figure 3.24 a), 7 of the 23 cases where some flooding occurred (Figure 3.24 b) and 8 of the 83 years when there was no flooding (Figure 3.24 c). A positive slope was expected if there was such a relationship. This was present in years when some or no flooding occurred; however an inverse relationship was found for years of significant flooding. This tended to confirm that solar radiation (heating the water) rather than air temperature was the most important factor in the speed with which ice jams melt out.

3.2.3.3 Differences Between High Level and Hay River Temperatures on Dates of Breakup

The total degree-day convention was adopted to investigate the relationship between pre-breakup temperatures and the timing and progression of breakup stages. The effect of the differences in temperatures between the headwaters of the Hay River basin (High Level meteorological data) and the Town of Hay River

(Hay River meteorological data) on the dates of the onset of breakup (D_o), peaks stage jam (D_p) and melt out (D_m) were also considered, and defined as:

- $(\Delta TDDT_{HL\text{-}HR})_o$ – the difference in total degree-days of thaw between High Level and Hay River on the date of the onset of breakup in the Hay River delta.
- $(\Delta TDDT_{HL\text{-}HR})_p$ – difference in total degree-days of thaw between High Level and Hay River on the date of peak breakup stage occurring in the Hay River delta.
- $(\Delta TDDT_{HL\text{-}HR})_m$ – difference in total degree-days of thaw between High Level and Hay River on the date that the ice jam(s) in the Hay River delta melted out to leave a clear flow path right to Great Slave Lake.

When there were warm temperatures causing melt in the headwaters, the increase in spring runoff lead to an increase in discharge. If warm temperatures in the Town of Hay River significantly deteriorated the ice, breakup flooding potential was decreased because ice jams advancing through deteriorated ice could simply push through this ice, rather than forming jams and associated backwater. However, if the Hay River temperatures remained cold, there was less thermal deterioration of the ice. This was believed to cause breakup to be more dramatic and dynamic, as more force was required to crack and disturb solid ice.

The differences in total degree-days of thaw between High Level and Hay River on the date of the onset of breakup ($(\Delta TDDT_{HL\text{-}HR})_o$) were ranked from highest to lowest and color coded by flood severity. This information was available for 10 of the 11 significant floods, 21 of the 23 years where some flooding occurred, and 14 of the 83 years where no flooding occurred. Figure 3.25 illustrates that there was no relationship between flood severity and differences in degree-days of thaw between High Level and Hay River on the date of the onset of breakup (D_o). Significant, some and no flooding have occurred throughout the entire range of differences in degree-days of thaw between High Level and Hay River.

The differences in total degree-days of thaw between High Level and Hay River on the date of peak stage ($(\Delta TDDT_{HL\text{-}HR})_p$) in the historical record are compared in Figure 3.26. This information was available for 10 of the 11 significant floods, 9 of the 23 years where some flooding occurred, and 9 of the 83 years where no flooding occurred. Eight of the ten significant flooding events on record occurred when the difference in total degree-days between High Level and Hay River was between 68 and 98˚C-days. The other two significant flooding events occurred when the difference in total degree-days was as little as 14˚C-days. Seven of the eight breakup events resulting in some flooding occurred when the difference in total degree-days of thaw between High Level and Hay River was between 18 and 88˚C-days. The exception was in 1994, when the peak stage resulted in some flooding and occurred when $(\Delta TDDT_{HL\text{-}HR})_p$ was 125˚C-days. The peak stage during non-flood events have occurred over a large range of differences in total degree-days (28 to 147˚C-days).

Figure 3.26 illustrates is that there was a general trend for significant flooding events to occur when the difference in total degree-days on the date of peak stage was greater than 68˚C-days. The general trend was for some flooding events to occur when the difference in total degree-days on the date of peak stage was less than 88˚C-days. However, both flood events of all severities have been documented to occur outside of these ranges.

The differences in total degree-days between High Level and Hay River on the date of melt out $(\Delta TDDT_{HL\text{-}HR})_m$ were also considered (Figure 3.27). This information was available for 9 of the 11 significant floods, 10 of the 23 years where some flooding occurred, and 23 of the 83 years where no flooding occurred. The ice jams causing five of the nine significant floods on record melted out when the difference in total degree-days was between 94 and 110˚C-days. The remaining four significant flooding cases occurred over a large range of differences: 85, 71, 51 and 21˚C-days. Seven of the eight recorded ice jams resulting in some flooding melted out when the difference in total degree-days was less than 88˚C-days. The exception was in 1994, when this occurred with a difference of 136˚C-days. The jams that did not result in flooding melted out when $\Delta TDDT_{HL\text{-}HR})_m$ was between 27 and 153˚C-days.

Another method of investigating the importance of the difference in total degree-days between High Level and Hay River was to plot them against each other on the dates of breakup stages. This information was available for 10 of the 11 significant floods, 12 of the 23 years where some flooding occurred, and 14 of the 83 years where no flooding occurred. Figure 3.28 (a) illustrates that there was a tendency for the onset of breakup in the Hay River delta to occur when the temperatures in the headwaters were warmer than those in Hay River. This was most prevalent in years with no flooding, while there was no difference in the general trend of the points between severity classes when flooding occurred.

Figures 3.28 (b) and 3.28 (c) compare the total degree-days at High Level and Hay River on the dates of peak flood (D_p) and ice jam melt out (D_m). On the date of peak stage (D_p), this information was available for 10 of the 11 significant floods, 9 of the 23 years where some flooding occurred, and 9 of the 83 years where no flooding occurred. On the date of melt out (D_m), this information was available for 9 of the 11 significant floods, 10 of the 23 years where some flooding occurred, and 23 of the 83 years where no flooding occurred. This illustrates that the temperatures in High Level (at the south end of the basin) are greater than those in Hay River (at the north end of the basin). There was no difference in the relationship between flooding severity and the total degree-days of thaw (*TDDT*) at Hay River and High Level on the dates of breakup peak stage and melt out.

3.2.3.4 Presence of Protracted Cool Weather Preceding Warm Temperatures During the Onset of Breakup

Wedel (1985) reported that *"protracted cool weather followed by warm temperatures usually produce the worst floods."* With the benefit of a much more comprehensive set of data, it was possible to investigate whether this might explain the anomalous years (i.e. those years where breakup occurred well outside the common range of degree-day thresholds). For this, the pattern of total degree-days from 15-Apr to 20-May were considered[7]. Appendix U details the total degree-days of freezing over this period at both High Level and Hay River. When known, the dates of the onset of breakup at the Hay River delta and peak stage are also included. These data sets were examined, and years with periods of protracted cool weather or cold snaps (denoted by several days when there was no increase in total degree-days) were identified. The increase in total degree-days from the end of the cold snap to the onset of breakup were then tabulated and grouped by severity class. Figure 3.29 illustrates these increases in total degree-days between the end of the cold snap and onset of breakup. The asterisks (*) denote those years where the cold snap ended within one week of the onset of breakup. This information was available for 10 of the 11 significant floods, 10 of the 20 years where some flooding occurred, and 13 of the 78 years where no flooding occurred. This figure illustrates that there was no obvious relationship in

[7] The occurrence of rain and snow in the pre-breakup period was also examined as a factor in why breakup was delayed in some years, but no obvious tendencies were found.

the severity of flooding that occurred if there was a cold snap preceding and delaying the onset of breakup.

3.3 Thresholds and Incremental Changes in Water Levels Associated with Key Breakup Stages

There were ten water level gauges located in the Hay River basin. Four of these were Water Survey of Canada (WSC) gauges in the Alberta portion of the basin headwaters. Chinchaga River (CRHL) and Sousa Creek (SCHL) were located near High Level, AB, while Steen River (SRSR) and Meander River (HRMR) were located between High Level and the NWT/AB border (Figure 1.1). The water levels at which the first transverse crack occurred were taken as first the erratic fluctuation in the hydrograph (Appendix H). The remaining six water level gauges along the study reach were located at the WSC at the NWT/AB Border (HRNWTAB) at *km 945.5*, Alexandra Falls at *km 1032.0*, Paradise Gardens at *km 1067.9*, WSC at Hay River (HRHR) at *km 1095.2*, the Pine Point Bridge at *km 1098.0* and at the West Channel Bridge at *km 1108.3* (Figure 2.1). The dates of breakup stages at these gauge sites were determined through the analysis of aerial and time-lapse photography. These dates are annotated on the water level hydrographs found in Appendix G[8]. The water levels associated with ice jam and release stages were taken as the maximum measured gauge heights on

[8] It is significant to note that the first transverse crack at the Alexandra Falls and NWT/AB gauges occurred before any noticeable discontinuity in the water level record. This highlights the importance of monitoring these photographically either with web cameras and/or observational flights.

those known dates. All water level analyses performed employed the site-specific approach, evaluating each site independently. If the changes in water levels along a reach were considered (translation and attenuation of waves), this became unsteady flow analysis. Although not included in the scope of this report, unsteady flow analysis was the subject of concurrent research at the University of Alberta (Watson 2011).

Three methods of site-specific analysis were used to analyze the water level data. The gauge heights on the dates of breakup stages as well as the change in water levels between breakup stages at each site were analyzed for consistency. The rates of increase of water levels immediately preceding the first transverse crack at the five gauge sites were also investigated.

3.3.1 Thresholds During Breakup Stages

The following gauge heights were determined during breakup stages:

- H_c – the water level (gauge height) at which the first transverse crack occurred, taken as the first the erratic fluctuation in the hydrograph on the known date of crack formation.
- H_j – the water level (gauge height) at which local ice jams occurred, taken as the maximum measured gauge heights on the specified dates.
- H_r – the water level (gauge height) at which ice jam release occurred, taken as the maximum measured gauge heights on the specified dates.

When analyzing the gauge heights during breakup stages, only ranges less than 2 m over all years of data were considered, while ranges of less than 1 m were considered the most promising indicators. There are two groups of water level data available; the first was the water levels at the four WSC headwaters gauge stations on the date of the first transverse crack (H_c). The dates of the first crack and corresponding gauge heights at these sites were determined by identifying the first erratic change in water levels on the hydrographs. The second group were the six WSC and EMO gauge stations located in the study reach. The dates of the first crack, ice jam and ice jam release were documented using remote stations or aerial photographs. The thresholds of water levels at which breakup stages occurred in the headwaters and study reach were examined.

Table 3.16 summarizes the ranges of gauge heights at which the first crack (H_c) occurred at each of the four WSC headwaters gauge stations. These hydrographs were annotated with the dates of the first crack and were included in Appendix H. Of these four stations, three exhibited ranges in gauge heights of less than 2 m on the date of the first crack for all years of data. The first crack at Sousa Creek near High Level (SCHL) and Hay River near Meander River (HRMR) occurred in the narrowest ranges of gauge heights. These were 1.2 m (between 1.3 and 2.5 m) and 1.2 m (between 5.4 and 6.5 m), respectively. The first crack at the Chinchaga River near High Level station (CRHL) occurred within a 1.5 m range, between 0.9 and 2.4 m. However, identifying the thresholds at which the first crack occurred in the headwaters to within 1.5 m was not particularly significant. This was because the gauge heights at Chinchaga River (CRHL) and Sousa Creek (SCHL) near High Level did not fluctuate more than 2 m over the entire breakup period over all years of record. Similarly, gauge heights at Steen River (SRSR) and Meander River (HRMR) did not fluctuate by more than 4 m in all years of record.

A 2 m range of threshold at which breakup stages occur was more meaningful at the gauge stations located in the study reach. This was because water levels at the gauge stations on the lower Hay River fluctuated much more than did those in the headwaters, and as such ranges of less than 1 m were considered to be the most promising indicators. Table 3.17 summarizes the sites in the study reach with the most consistent gauge heights during each stage of breakup, while Appendix G contains the hydrographs for the six WSC and EMO water level gauge stations in the Hay River study reach, annotated with the dates of the first crack (D_c), local ice jam (D_j) and ice jam release (D_r), when known.

The most significant finding from this analysis of gauge heights was the range of heights during the first transverse crack (H_c) at Alexandra Falls (*km 1032.0*), ranging 0.7 m (between 0.3 and 1.0 m) in three years of data. The next closest range in gauge heights on the date of first was at the WSC gauge near Hay River (HRHR) at *km 1095.2*. Here, the cracks occurred in a 1.1 m range, between 3.2 and 4.3 m. The WSC Border gauge (HRNWTAB) had a 1.9 m range in gauge heights when cracks occurred, between 0.4 and 2.3 m.

As previously mentioned, the WSC gauge station near Hay River (HRHR) at *km 1095.2* had the longest available record of all the water level gauge stations in the Hay River basin, from 1964 to 2010. The dates of the first transverse cracks and water levels at which these occurred have been extracted for use in a predictive modeling study done by Zhao *et al.* (2010). These dates and water levels were determined by analyzing the water level hydrographs, and were taken at the first erratic fluctuations in the water levels. The applicability of these dates and water levels was confirmed with photographs from 2005, and 2007 to 2010. The range in gauge heights associated with the first crack (H_c) over this historical period is considerably larger than that indicated when only the 2005, and 2007 to 2010 data is used. Over the lengthier record, the first transverse crack occurred when the gauge heights (H_c) were between 1.9 to 5.2 m, a 3.3 m range. These gauge heights were color coded by severity and ranked from largest to smallest (Figure 3.30). When these were compared to the range established from gauge heights when the first crack occurred from 2005 to 2010 (range of H_c from 3.2 to 4.3 m), 17 out of 36 years of data fell within this range. Of the seven years when significant flooding occurred, the water levels associated with the first crack at the WSC near Hay River gauge (HRHR) fell within this range for five years. The first cracks at this gauge station occurred within this range of gauge heights for five of the 10 years when some flooding occurred and for 6 of 24 years when no flooding occurred. This indicated that the water level at which the first crack occurs at the WSC near Hay River (HRHR) station is not a consistent indicator of the severity of flooding to be expected.

Water level thresholds during local ice jam formation (H_j) were also considered. The gauge heights at Alexandra Falls (*km 1032.0*) and the West Channel Bridge (*km 1108.3*) during the peak stage events ranged by 1.6 m (between 1.3 and 2.9) and 1.5 m (between 3.8 and 5.3), respectively. These large ranges of water levels at which breakup stages occurred were not precise enough to be useful in forecasting. No sites had water level ranges of less than 2 m when the ice jam releases occurred (H_r). The EMO water level gauge at Paradise Gardens (*km 1067.9*) was re-installed every spring without being calibrated or standardized to a known elevation. Therefore, the gauge height during breakup stages at this site was quite variable, and it was the water level rise between stages that was analyzed at this site.

3.3.2 Changes in Water Levels Between Breakup Stages

The change in gauge heights between the first transverse crack, local ice jam and ice jam release were also examined for consistency at all five sites, and defined as:

- ΔH_{cj} – the increase in water levels (gauge heights) between the first transverse crack and local ice jam.
- ΔH_{cr} – the increase in water levels (gauge heights) between the first transverse crack and ice jam release.

- ΔH_{jr} – the increase in water levels (gauge heights) between local ice jam formation and ice jam release.

Table 3.18 summarizes the most consistent of these water level increases between stages of breakup. Three sites exhibited particularly consistent water level increases between the transverse crack and ice jam (ΔH_{cj}). At Alexandra Falls (*km 1032.0*), water levels ranged by 0.85 m, from 0.05 to 0.85 m. At the WSC gauge near Hay River (HRHR) at *km 1095.2* and the Pine Point Bridge at *km 1098.0*, the gauge heights increased by 0.7 to 2.0 m and 0.3 to 1.9 m, respectively. The site with the most consistent increases in water levels between the crack and ice jam release (ΔH_{cr}) was the NWT/AB border at *km 945.5* (1.9 to 3.7 m). The most consistent increases in water levels between local ice jam formation and release (ΔH_{jr}) occurred at the NWT/AB border at *km 945.5* (0.0 to 0.4 m) and Paradise Gardens at *km 1067.9* (0.0 to 1.3).

The broader ranges of water level increases were used as general representation of the water levels during past breakup stages. However, they were too variable to be used for forecasting. Appendix V contains a summary of the ranges of water levels during, and between, all stages of breakup at the six gauge sites.

3.3.3 Rate of Water Level Increase Preceding the First Transverse Crack

In addition to examining the gauge height thresholds during, and increases between, stages of breakup, the rate of increase of water levels immediately preceding the occurrence of the first transverse crack were investigated. For the sites and years where the dates of the first transverse crack were known, the rates of rise preceding this date were determined. Transverse cracks did not occur at the West Channel Bridge (*km 1108.3*), so the increase in water levels preceding the onset of breakup *(D_o)* was used in its place. In some cases (particularly Alexandra Falls at *km 1032.0*), the diurnal fluctuation in water levels can be misleading when considering the water levels during only one or two days. However, on a larger scale (over several days), the general trend of the rate of increase could be systematically determined.

The rates of increase in water levels preceding the first transverse crack, period over which this rate occurred, and total increase in water level over the period are summarized in Table 3.19. Alexandra Falls (*km 1032.0*) exhibited the greatest consistency in rates of increase in water levels preceding the first transverse cracks. However, there were only 2 years of available data at this site. With more years of data for comparison, this could be a promising indictor. The ranges in rates of increase at the NWT/AB border (HRNWTAB) at *km 945.5*, WSC gauge near Hay River (HRHR) at *km 1095.2*, the Pine Point Bridge at *km 1098.0* and West Channel Bridge at *km 1108.3* were comparable, from 0.004 m/hr to 0.030 m/hr. There was a slightly larger range at Paradise Gardens (*km 1067.0*), from 0.004 m/hr to 0.047 m/hr over the duration of the steady increase.

The duration of constant rate of increase in water levels varied by site. The most consistent duration of rate of rise was at Alexandra Falls (*km 1032.0*), ranging from 5.6 to 5.8 days. However, this is merely a promising potential at this point, since it was based on only 2 years of data. At the NWT/AB border (HRNWTAB) (*km 945.5*) and Paradise Gardens (*km 1067.9*), the duration of constant rate of increase in water levels before the transverse cracks occurred ranged from 1 to 4 days. This range was largest at the WSC near Hay River gauge (HRHR) at *km 1095.2*, the Pine Point Bridge (*km 1098.0*) and West Channel Bridge (*km 1108.3*), from approximately 1 to 6 days.

When the total increase in water levels over the duration of constant rate of increase preceding the first transverse cracks was considered, all sites ranged less than 2 m. The most consistent of these were the 0.5 m range at both Alexandra Falls (*km 1032.0*) and the West Channel Bridge (*km 1108.3*). There was an 0.8 m range at the NWT/AB border station (HRNWTAB) at *km 945.5*). The total water level increases at the WSC near Hay River station (HRHR) at *km 1095.2*, the Pine Point Bridge (*km 1098.0*) and Paradise Gardens (*km 1067.9*) over the duration were 1.0, 1.1 and 1.1 m, respectively.

The rates of water level increase preceding the transverse cracks at most sites were not consistent enough to be used to predict the timing of the first crack, nor were the durations of these constant rates of rise. The exception was Alexandra Falls (*km 1032.0*), which exhibited remarkable consistency in rate of increase, duration of increase and total water level increase preceding the first crack in two years of data. Additional years of data are strongly recommended, to validate or disprove these findings.

The overall increase in water level over the duration of steady increase was relatively consistent at all sites. When monitoring the water level gauges during breakup, constant rates of increase in water levels lasting more than one day should be identified. The first transverse crack (or the onset of breakup in the case of the West Channel Bridge at *km 1108.3*) has occurred once the water levels have risen between 0.3 to 0.8 m at the NWT/AB border (HRNWTAB) at *km 945.5*, Alexandra Falls (*km 1032.0*) and the West Channel Bridge (*km 1108.3*) or between 0.1 and 1.1 m, 0.2 to 2.2 m or 0.5 to 1.6 m at Paradise Gardens (*km 1067.9*), the WSC near Hay River station (HRHR) at *km 1095.2* and the Pine Point Bridge (*km 1098.0*), respectively.

In summary, the analysis of available historical data has revealed a number of promising indicators regarding the sequence and timing of breakup progression along the Hay River. Among these are several that are consistent across all years of available data. The historical record demonstrates that there was a huge variability in timing, temperatures and water levels during breakups of any flood severity. Examining single pre-breakup conditions in isolation has revealed important indicators, as discussed in this chapter. However, considering the combination of numerous pre-breakup conditions takes into consideration the cumulative effects of these conditions. Concurrent research at University of Alberta is investigating examining these relationships (e.g. Zhao *et al.* 2010).

3.4 Discussion of Results

Based on the analysis and synthesis of data discussed in the previous chapters, numerous indicators as to the timing and severity of breakup along the study reach were identified. This study was most successful in finding indicators as to when the first transverse crack (D_c), local ice jam (D_j), and ice jam release (D_r) occurred along the study reach, as well as when the onset of breakup (D_o), peak stage (D_p) and jam melting out (D_m) occurred in the Hay River delta. The typical breakup sequence was discussed in Section 2.2.1 and after interpreting all available data, detailed indicators and timing sequences were determined for the ten steps of breakup.

The indicators as to when D_c, D_j, D_r, D_o, D_p and D_m were grouped into three categories, as follows:

A. Cases where the available historic record confirmed the patterns determined through the analysis of the detailed data from 2005 to 2010.
B. Cases where there was no historic record available to confirm the patterns determined through the analysis of data from 2005 to 2010.
C. Cases where the available historic record did not confirm the patterns determined through the analysis of data from 2005 to 2010.

Case A indicators are consistent across all available data (consistent), while Case B indicators require a longer record to validate the findings (promising). Although Case C indicators appeared promising, there were discrepancies when the available historical record was considered. These should be monitored in the future, but prioritized after Cases A and B indicators.

A quantitative description of the sequence of breakup and the indicators preceding each stage of breakup are as follows:

Stage 1. ***Melting in the headwaters:*** The southern portion of the basin experiences warmer temperatures and an increase in snowmelt and subsequent discharge. This runoff wave lifts the intact ice cover (Figure 2.4a) downstream.

- Although Stages 1 and 2 really initiate the breakup process along the Hay River, they are not discrete events. Because of this, they were not considered when determining the timing sequence of breakup.

Stage 2. ***Thermal deterioration:*** Intermittent warm spring weather initiates snowmelt on the ice cover and ice melt along the channel margins. Small open leads may develop, but the ice cover remains competent.

Stage 3. ***Transverse cracking:*** Snowmelt runoff from the basin headwaters in the south lifts and breaks the strong, intact ice cover further north (downstream). The best indicators of the timing of the first transverse cracks at all locations were:

Case A Indicators: confirmed by the available historical record

- Transverse cracks occurred at Mink Creek (*km 1027.0*) within 1 day the ice clearing immediately upstream of Alexandra falls (*km 1034.0*).
- Transverse cracks occurred at the WSC near Hay River (HRHR) gauge (*km 1095.2*) between 22-Apr and 3-May, as per data since 2005[9]. Of the 19 years of known flooding events, the dates of transverse cracks at this site fell within this range for 16. In years when flooding occurred, the most common date of cracks was 29-Apr. Transverse cracks occurred at this site within 1 day of cracks and jams forming at Mink Creek (*km 1027.0*), when water levels were between 3.2 and 4.3 m[10], or when the total increase in water levels during the constant rate of rise was between 0.2 and 1.2 m.

---

[9] The available historic record indicates that 7 out of 7 significant floods, 9 out of 12 some flooding, and 13 of 23 non-flood events fell within this range of dates of transverse cracks.

[10] The available historic record indicates that 5 out of 7 significant, 6 out of 10 some, and 6 of 10 no flooding events fell within this range of water levels.

- Transverse cracks occurred at the Pine Point Bridge (km 1098.0) within 1 day of jamming at Alexandra Falls (*km 1034.0*).

Case B Indicators: no historical records available to confirm

- Transverse cracks at Meander River (HRMR) occurred between 2 and 5 days after cracking at Steen River (SRSR).
- Transverse cracks at Steen River (SRSR) happened within 2 days of cracking at Sousa Creek (SCHL).
- Transverse cracks occurred at the WSC Steen River near Steen River gauge (SRSR) when water levels were between 1.3 and 2.5 m.
- Transverse cracks occurred at the WSC near Meander River gauge (HRMR) when water levels were between 5.4 and 6.5 m.
- Transverse cracks at the WSC near Meander River (HRMR) gauge in Reach 1 did not necessarily precede transverse cracks in Reach 2. In fact, it occurred on the same day or even after transverse cracking begins in Reach 2.
- Transverse cracks occurred earliest in the upper reaches. In four out of five years, the entire study reach has cracked essentially from upstream to downstream.
- In Reach 2 it tended to occur first at the NWT/AB border (*km 945.5*) and Alexandra Falls (*km 1032.0*), though in no consistent order. However, once the first transverse crack occurred in Reach 2, the rest of the sites in the reach cracked within 3 days.

- Transverse cracks occurred at the NWT/AB border (*km 945.5*) when TDD_c was between 36 and 102˚C-days, and when the total water level rise during the constant rate of rise preceding the first crack was between 0.3 and 1.1 m.
- Transverse cracks occurred at Mink Creek (*km 1027.0*) within 2 days of crack formation at Alexandra Falls (*km 1034.0*) and Escarpment Creek (*km 1040.5*).
- Transverse cracks occurred at Alexandra Falls (*km 1032.0*) between 22-Apr and 30-Apr, and when water levels were between 0.3 and 1.0 m. Other indicators for cracks at this site include the rate of increase in water level of 0.002 to 0.005 m/hr for between 135 and 140 hr, resulting in a total rise in water level of 0.3 to 0.8m.
- Transverse cracking tended to occur in Reach 3 within 1 to 3 days of transverse cracking in Reach 2.
- Transverse cracks occurred at Escarpment Creek (*km 1040.5*) between 23-Apr and 1-May.
- Transverse cracks occurred at Paradise Gardens 2 to 4 days after cracking at Alexandra Falls (*km 1034.0*) and Escarpment Creek (*km 1040.5*), and after there was a total water level increase between 0.1 and 1.1 m during the constant rate of rise.
- When the ice cracked at Alexandra Falls and the reach just upstream of the falls cleared (between *km 1031.9* and km *1034.0*),

water was released from storage. This created a wave that propagated downstream, resulting in ice cracking between the WSC gauge at Hay River and the Pine Point Bridge (*km 1095.2 to 1098.0* in lower Reach 4), where the ice was weakest. The ice in the Reach 4 sites upstream of the bridge remained intact at this time. This typically followed the crack at Alexandra Falls by 1 to 3 days and the jam (reach upstream of the falls clearing) by 0 to 1 days.

- First transverse cracking in Reach 4 (typically at the Pine Point Bridge (*km 1098.0*)) tended to occur 2 to 4 days after transverse cracking in Reach 2.

Case C Indicators: disagreed with available historical record

- Transverse cracks occurred at the Pine Point Bridge (km 1098.0) between 1 and 3 days after the first transverse crack occurred at any location in the study reach. Cracks at this site also occurred within 1 day of transverse cracks at Mink Creek (*km 1027.0*)[11].
- Jam formation at Escarpment Creek (km 1040.5) preceded transverse cracking at Paradise Gardens by 1 to 2 days.

Stage 4. ***Sheet accumulations:*** Once the ice is broken into discrete sheets, its movement is constrained temporarily by tight bends or islands in the channel, creating ‘sheet ice accumulations’.

[11] Two historical cases were available for comparison. One case agreed with this pattern, while the other disagreed.

- Steps 4 is considered an intermediate step between transverse cracking and ice jam formations, and was not examined as a breakup stage.

Stage 5. ***<u>Mini-jams:</u>*** Variations in ice thickness, as well as river alignment, slope and velocity cause breakup to progress quicker in some areas along the river compared to others. This leads to small accumulations of broken ice (~0.5 to 2 km long) upstream of intact segments of the ice cover.

- A small rubble accumulation (mini-jam) at Escarpment Creek (*km 1040.5* in Reach 3) happens at the same time as crack and/or mini-jam formation in Reach 2. This is due to small waves generated by events (ice runs and/or water waves) upstream coming over Alexandra and Louise Falls (*km 1034.0* and *km 1037.1*).
- This study did not distinguish between mini-jams and ice jams. The first local ice jam formation at each study site (whether it was mini- or not) was reported as the ice jam stage.

Stage 6. ***<u>Ice jams:</u>*** The creation and consolidation of mini-jams eventually can lead to ice accumulations about 5 to 20 km in length. The best indicators for local ice jam formation at all locations were:

<u>Case A Indicators:</u> confirmed by the available historical record

- At Escarpment Creek (*km 1040.5*), jams occurred within 1 day of jam formation at Alexandra Falls (reach clearing between *km 1032.0* and *1034.0*).

<u>Case B Indicators:</u> no historical records available to confirm

- Local ice jamming at the NWT/AB border (*km 945.5*) occurred within 2 days of transverse cracking at that site.
- Jams formed at Grumbler Rapids (*km 986.0*), Mink Creek (*km 1027.0*), Alexandra Falls (*km 1034.0*), Escarpment Creek (*km 1040.5*) and Enterprise (*km 1048.0*) within 2 days of each other.
- Jamming occurred at Mink Creek (*km 1027.0*) within 1 day of transverse cracking.
- Ice jammed at Alexandra Fall (cleared between *km 1032.0* and *1034.0*) 1 to 2 days after cracks formed at this site. Jams also occurred when water levels increased by 0.8 m (from 0.1 to 0.9 m) since the crack.
- Once the first ice accumulation occurred in Reach 2, all key sites in Reaches 2, 3, and 4 started to jam within 3 to 5 days.
- Ice jams formed at Enterprise (*km 1048.0*) within 1 day of the jam forming at Escarpment Creek (*km 1040.5*). Typically this is the same gorge jam, that is accumulating with each ice run that passes over Alexandra and Louise Falls.
- Reach 4 (except the Pine Point Bridge, where the ice had already cracked and jammed) jammed 2 to 4 days after transverse cracks occurred at Alexandra Falls.
- At the Golf Course (km 1088.5), ice jams occurred 1 to 2 days after the jam formed at Escarpment Creek (*km 1040.5*), and 1 to 2

days after transverse cracks occurred at the Pine Point Bridge. Also, jams formed here within 1 day of cracks forming at this site.

Case C Indicators: disagreed with available historical record

- Ice jams at Alexandra Falls (*km 1034.0*) preceded ice jams at Enterprise (*km 1048.0*) by 0 to 2 days[12].
- Jams at Escarpment Creek (*km 1040.5*) preceded ice jams at Paradise Gardens (*km 1071.0*) by 1 to 2 days, and occurred within 1 day of ice jamming at the Pine Point Bridge (*km 1098.0*)[13].
- Ice jamming at the Pine Point Bridge (*km 1098.0*) occurred within 1 day of ice jamming at Alexandra Falls (*km 1034.0*)[14].

Stage 7. ***Ice jam release and ice runs:*** The water and ice impounded in an ice jam exert a tremendous driving force, and some ice jams will consolidate (shove and thicken) under the pressure or let go, releasing an ice jam release wave as (javes). The best indicators for ice jam releases at all locations were:

Case A Indicators: confirmed by the available historical record

- Ice jam release at the Golf Course (*km 1088.5*) occurred within 1 day of the transverse crack occurring at this site, and on the same day as jam formation. It also released between 1 and 2 days after crack formation at the Pine Point Bridge (*km 1098.0*), and has

[12] The historical record included cases that agreed, as well as cases that did not agree with this trend.
[13] The historical record included cases that agreed, as well as cases that did not agree with this trend.
[14] The historical record included cases that agreed, as well as cases that did not agree with this trend.

occurred on the same day that the jam at Paradise Gardens (km 1071.0) released (domino effect).

Case B Indicators: no historical records available to confirm

- At the NWT/AB border (*km 945.5*), ice jams released 3 days after transverse cracks occurred at this site, 3 to 5 days after first transverse crack formation anywhere, or 1 to 3 days after cracks occurred at the Island (*km 974.0*) and Grumbler Rapids (*km 986.0*). Also, cracks occurred when water levels increased by 0.0 to 0.4 m after ice jam formation.
- At Grumbler Rapids (*km 986.0*), ice jam release occurred within 2 days of the jam formation at this site, and between 2 and 3 days after transverse cracks formed at the NWT/AB border (*km 945.5*).
- Ice jam releases at Mink Creek (*km 1027.0*) occurred within 2 days of transverse crack formation at this site, the Island (*km 974.0*), Grumbler Rapids (*km 986.0*) and within 1 day after the first crack formation at the WSC near Hay River (HRHR) gauge (*km 1095.2*) and Pine Point Bridge (km *1098.0*).
- At Escarpment Creek (*km 1040.5*), the ice jam releases (or shoves past this site to Enterprise) 1 to 3 days after jams formed at any site between the NWT/AB border (*km 945.5*) and Mink Creek (*km 1027.0*).
- At Enterprise (*km 1048.0*), the gorge jam released 2 to 3 days after jam formed at Escarpment Creek (*km 1040.5*) and 2 to 4 days after

jam formed at this site and/or Grumbler Rapids (*km 986.0*). Other indicators for the gorge jam release are that it releases 3 to 5 days after crack formation (rubble accumulation) at Escarpment Creek (*km 1040.5*), and 1 day after the jam shoved past Escarpment Creek (*km 1040.5*). In 4 out of 5 years of known record, an impeded ice run scenario occurred as this jam release passed through Reach 4.

- Ice jams released at the Pine Point Bridge (*km 1098.0*) after an increase in TDD of 4 to 8˚C-days after crack formation at this site.

<u>Case C Indicators:</u> disagreed with available historical record

- Ice jams at Grumbler Rapids (*km 986.0*) and Alexandra Falls (*km 1034.0*) preceded ice jam releases at Paradise Gardens (*km 1071.0*) by 1 to 3 days.

Stage 8. ***<u>Re-jamming:</u>*** Ice jam release events sometimes progress down the Hay River in domino fashion, with the ice runs from upstream ice jam release events instigating the release of the next downstream ice jam. In this case, the ice runs increase in size as they progress downstream. Alternatively, ice runs tends to stall at tight bends and islands. This temporarily re-jams the ice, causing water and ice pressures to build up and then release with renewed speed and magnitude.

- Stalling may last from minutes (eg. Paradise Gardens (*km 1071.0*) and the Golf Course at *km 1088.5*) to hours or days (Enterprise, at *km 1048.0*).

- The re-jamming is not sequential[15]:
    - Although the NWT/AB border site (*km 945.5*) is furthest upstream, it is often the last site in Reach 2 to release.
    - Although Mink Creek (*km 1027.0*) is the 4th of 5 sites in Reach 2, it is the first to release.
    - The jam at Paradise Gardens (km 1071.0) released within 2 days of transverse cracking.
    - Pine Point Bridge is the most downstream site in Reach 4 at *km 1098.0*, but is the first to jam and release.
    - Paradise Gardens (*km 1071.0*) and the Golf Course (*km 1088.5*) are the most upstream sites in Reach 4, but are typically the last the release, and progress in domino fashion following the release of the (gorge) jam at Enterprise (*km 1048.0*).

Stage 9. ***Jam formation in the Hay River delta*:** There are typically two stages in the ice jam formation in the Hay River delta: the onset of breakup which creates small ice accumulations and the arrival of ice runs from upstream which cause large ice jams and the peak stage. The best indicators to the timing of the onset of breakup (D_o) in the Hay River delta were:

---

[15] All patterns in re-jamming are Case B indicators, where there was no historical record available to confirm.

Case A Indicators: confirmed by the available historical record

- D_o for significant flooding events occurred between 23-Apr and 6-May, while D_o for some flooding year occurred between 23-Apr and 7-May. The most common D_o in flooding years was 2-May[16].
- when TDD_{fo} was between 135 and 205˚C-days (in 9 of 10 known significant flooding cases).

Case B Indicators: no historical records available to confirm

- 1 to 3 days after the transverse crack occurred at the WSC Meander River gauge (HRMR).
- 5 to 8 days after the first transverse crack occurred at the WSC Steen River gauge (SRSR).
- 2 to 4 days after first transverse crack formation anywhere in the study reach.
- 2 to 3 days after ice jams formed in Reach 2.
- 1 to 2 days after the crack formed at the Pine Point Bridge (*km 1098.0*).
- when there was a total water level rise of between 0.3 and 0.8 m at the EMO West Channel Bridge gauge during the constant rate of rise.

[16] These ranges were determined from the full historical record of breakup in the delta (1894 to 2010).

Case C Indicators: disagreed with available historical record

- 1 to 2 days after the ice jam formation at Alexandra Falls (*km 1034.0*).[17]
- 0 to 1 days after the jam formation in Escarpment Creek (*km 1040.5*)[18].
- 0 to 2 days after the jam formation at Enterprise (*km 1048.0*).
- 0 to 1 days after the ice jam at the Pine Point Bridge (*km 1098.0*).[19]
- Within one day of ice jam releasing at Mink Creek (*km 1027.0*).
- 1 to 2 days after transverse cracking at the Pine Point Bridge (*km 1098.0*).

The best indicators to the timing of the peak stage (D_p) in the Hay River delta were:

Case A Indicators: confirmed by the available historical record

- D_p for significant flooding events occurred between 28-Apr and 7-May, while D_p for some flooding year occurred between 25-Apr and 7-May. The most common D_p in flooding years was 7-May[20].

---

[17] The historical record included cases that agreed, as well as cases that did not agree with this trend.

[18] The historical record included cases that agreed, as well as cases that did not agree with this trend.

[19] The historical record included cases that agreed, as well as cases that did not agree with this trend.

[20] These ranges were determined from the full historical record of breakup in the delta (1894 to 2010).

- most commonly 1 day after D_o, but both significant and some flooding have occurred outside this range, but within 6 days.
- when TDD_{fp} was between 134 and 217˚C-days (in 9 of 10 known significant flooding cases).
- when the TDD_p difference between High Level and Hay River was between 68 and 98˚C-days (in 8 out of 10 known significant flooding cases).

<u>Case B Indicators:</u> no historical records available to confirm

- 2 to 6 days after the ice cracked at the WSC Meander River gauge (HRMR).
- 4 to 6 days after first transverse cracking, and 3 to 5 days after first jamming and release in Reach 2.
- 3 to 5 days after first transverse cracking, 2 to 4 days after first jamming and 0 to 4 days after first releasing in Reach 3.
- 2 to 5 days after first transverse cracking, 1 to 5 days after jamming, and 1 to 5 days after first release in Reach 4.
- 6 to 9 days after the ice cracked (D_c) at the WSC Steen River gauge (SRSR).
- 1 to 4 days after the ice jam formation at Grumbler Rapids (*km 986.0*) and Enterprise (*km 1048.0*).
- The minimum time increments between ice jam release events and the peak stage jam (D_p) in the Hay River delta were:

- Reach 2: 0 to 3 days, with the most severe flooding (2008) being associated with the same day event.
- Reach 3: 0 to 3 days; the most severe flooding (2008) was associated with one of the same day events.
- Reach 4: 0 to 2 days, with the longest duration case associated with ice the most severe flooding (2008).

- From the full descriptions of breakup in 2005 and 2007 to 2010, the active breakup period (from known first crack formation in Reach 2 to when the peak stage jam occurs in the delta) has taken between 4 and 6 days.

Case C Indicators: disagreed with available historical record

- 1 to 3 days after jam formation and 1 to 2 days after jam release at the NWT/AB border (*km 945.5*)[21].
- 2 to 3 days after jam formation at Grumbler Rapids (*km 986.0*).
- 2 to 4 days after the ice jam formation at Escarpment Creek (*km 1040.5*)[22].
- 2 to 3 days after the jam formation at Enterprise (*km 1048.0*)[23].
- 1 to 3 days after the ice cracked at Paradise Gardens (*km 1071.0*)[24].

---

[21] The historical record included cases that agreed, as well as cases that did not agree with this trend.

[22] The historical record included cases that agreed, as well as cases that did not agree with this trend.

[23] The historical record included cases that agreed, as well as cases that did not agree with this trend.

[24] The historical record included cases that agreed, as well as cases that did not agree with this trend.

- 3 to 5 days after transverse cracking at the Pine Point Bridge (*km 1098.0*).

Stage 10. ***Ice jam melting out in the Hay River delta:*** When all the ice runs from upstream have arrived and consolidated in the Hay River delta, the ice jam sits in the East Channel (and sometimes West Channel) and thermally deteriorates. The date of melt out (D_m) is the date that this jam melts out to the Great Slave Lake ice, leaving behind open water. Large quantities of ice can be left on the river banks in the form of shear walls, but once the jam melts out to the intact lake ice, the flood risk has passed. The best indicators to the timing of the ice jam melting out (D_m) in the Hay River delta were:

Case A Indicators: confirmed by the available historical record

- D_m for significant flooding events occurred between 30-Apr and 12-May, while D_m for some flooding year occurred between 28-Apr and 10-May. The most common D_m in flooding years was 7-May[25].
- most commonly 4 days after D_o, or between 2 and 8 days after D_o.
- most commonly 1 days after D_p, or within 3 days of D_o.
- when TDD_{fm} was between 135 and 217˚C-days (in 9 of 10 known significant flooding cases).

[25] These ranges were determined from the full historical record of breakup in the delta (1894 to 2010).

Case B Indicators: no historical records available to confirm

- 4 to 6 days after the first crack at the WSC Meander River gauge (HRMR).
- 8 to 12 days after the crack at the WSC Steen River gauge (SRSR).
- From the full descriptions of breakup in 2005 and 2007 to 2010, between the first known crack formation in Reach 2 (between the NWT/AB border (*km 945.5*) and Alexandra Falls (*km 1034.5*)) to when the ice and log jam in the Hay River delta has melted out to Great Slave Lake has taken between 6 and 8 days.

This general description of breakup quantified with known indicators as to the timing and sequencing of breakup summarized the major findings of this thesis. Ultimately, there is no single perfect indicator for the timing and severity of breakup. This section contains an extensive and detailed list of indicators to the patterns of breakup stages on the Hay River, and highlights the need for an expert system to incorporate these details into an operational tool for use in breakup flood forecasting.

Table 3.1: List of sites missing dates of breakup events and reasons for the gap in data.

Stage of Breakup	Year	Site	Reason for gap in data
First Crack D_o	2005	Grumbler Rapids	No flight on this day.
	2005	Alexandra Falls	Flight photos do not cover this site.
	2005	Escarpment Creek	Flights started after first crack occurred.
	2007	Grumbler Rapids	Flight photos do not cover this site.
	2007	Alexandra Falls	Flight photos do not cover this site.
	2007	Escarpment Creek	Flights started after first crack occurred.
Ice Jam D_p	2005	NWT/AB Border	Flight photos do not cover this site.
	2005	Grumbler Rapids	No flight on this day.
	2005	Escarpment Creek	Flights started after jamming occurred.
	2007	Escarpment Creek	Flights started after jamming occurred.
	2008	NWT/AB Border	This site did not jam.
Jam Release D_m	2005	NWT/AB Border	Flight photos do not cover this site.
	2005	Grumbler Rapids	Flight photos do not cover this site.
	2005	Golf Course	No flight on this day.
	2007	Escarpment Creek	No flights on the previous day.
	2009	Grumbler Rapids	Flight photos do not cover this site.

Table 3.2: Most consistent ranges of dates of breakup events at all sites.

Stage	**Site**	**Min**	**Max**	**Range**	**# Yrs Data**
First Crack, D_o	Alexandra Falls	22-Apr	30-Apr	8	3
	Escarpment Creek	22-Apr	1-May	9	3
Ice Jam, D_p	Escarpment Creek	23-Apr	3-May	10	3
Jam Release, D_m	Golf Course	25-Apr	4-May	9	4
	Pine Point Bridge	24-Apr	4-May	10	5

Table 3.3: Most consistent ranges of days between breakup events at all sites.

Range,	First Crack to Ice Jam, ΔD_{cj}				First Crack to Jam Release, ΔD_{cr}				Ice Jam to Jam Release, ΔD_{jr}			
days	Site	Min	Max	# Yrs Data	Site	Min	Max	# Yrs Data	Site	Max	Min	# Yrs Data
0 days					NWT/AB Border	3	3	3	Golf Course	0	0	4
1 day	NWT/AB Border	2	3	3	Grumbler Rapids	1	2	2	NWT/AB Border	0	1	3
	Grumbler Rapids	0	1	3	Golf Course	0	1	4	Mink Creek	0	1	5
	Mink Creek	0	1	5	Pine Point Bridge	1	2	5	Paradise Gardens	0	1	5
	Alexandra Falls	1	2	3	Alexandra Falls	1	2	3				
	Paradise Gardens	0	1	5								
	Golf Course	0	1	5								
2 days	Escarpment Creek	1	3	3	Mink Creek	0	2	5	Grumbler Rapids	0	2	3
	Pine Point Bridge	0	2	5	Paradise Gardens	0	2	5	Pine Point Bridge	0	2	5

Table 3.4: Ranges of dates of first transverse cracks (D_c) at the four WSC gauge stations in the headwaters.

Site	Date of first crack (D_c)					
	Min	Max	Range	# Years data	From	To
Sousa Creek at High Level (SCHL)	16-Apr	29-Apr	13	7	2004	2010
Chinchaga River at High Level (CRHL)	16-Apr	2-May	16	7	2004	2010
Steen River at Steen River (SRSR)	16-Apr	28-Apr	12	4	2007	2010
Hay River near Meander River (HRMR)	21-Apr	3-May	12	4	2007	2010

Table 3.5 (a): Days between first cracking at the headwaters gauge stations When numbers are positve, the event in the x-axis occurred after that in the y-axis.

Reference Site	Chinchaga	Sousa	Meander	Steen
Chinchaga River (CRHL)		-9 to 6	1 to 5	-4 to 0
Sousa Creek (SCHL)	-6 to 9		4 to 12	-1 to 2
Meander River (HRMR)	-5 to -1	-12 to -4		-5 to -2
Steen River (SRSR)	0 to 4	-2 to 1	2 to 5	

General Pattern:

- before
- mostly before
- during
- mostly after
- after
- N/A

Table 3.5 (b): Number of years of data between cracking at all locations.

Reference Site	Chinchaga	Sousa	Meander	Steen
Chinchaga River (CRHL)		7	4	3
Sousa Creek (SCHL)	7		4	3
Meander River (HRMR)	4	4		3
Steen River (SRSR)	3	3	3	

Years of Data:

- 7 years
- 4 years
- 3 years
- N/A

Table 3.5 (c): Days between first cracking at the headwaters gauge stations, color coded by years of data. When positve, the event in the x-axis occurred after that in the y-axis.

Reference Site	Chinchaga	Sousa	Meander	Steen
Chinchaga River (CRHL)		-9 to 6	1 to 5	-4 to 0
Sousa Creek (SCHL)	-6 to 9		4 to 12	-1 to 3
Meander River (HRMR)	-5 to -1	-12 to -4		-5 to -2
Steen River (SRSR)	0 to 4	-2 to 1	2 to 5	

Years of Data:

- 7 years
- 4 years
- 3 years
- N/A

Table 3.6: Historical ranges of days between breakup events at a site as compared to the site specific ranges (from 2005 to 2010).

Site	From First Crack to Ice Jam (ΔD_{cj})				From Crack to Jam Release (ΔD_{cr})				From Ice Jam to Release (ΔD_{jr})			
	‘05 to ‘10 range		Historical range		‘05 to ‘10 range		Historical range		‘05 to ‘10 range		Historical Range	
	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
NWT/AB Border	2	3	-	-	3	3	-	-	0	1	1	1
Grumbler Rapids	0	1	-	-	1	2	-	-	0	2	0	0
Paradise Gardens	0	1	0	1	0	2	0	2	0	1	0	1
Pine Point Bridge	0	2	0	0	0	2	2	-	0	1	1	-

Table 3.7: Days between breakup events determined from the reach-based analysis that were confirmed with historical data. Those that are not shaded in grey had a range of one day, while those that are had a two day range, for all years of record.

Sites and breakup events		'05 to '10 range		Historical range	
		Min	Max	Min	Max
Jam Border	Release Border	0	1	1	1
Jam Border	Release Grumb	0	0	1	1
Release Border	Release Grumb	-1	0	0	0
Release MC	Jam Esc	-1	0	0	0
Jam AF	Jam Esc	0	0	0	1
Jam Esc	Jam Ent	1	1	1	1
Jam Ent	Crack PG	0	1	0	1
Jam Ent	Jam PG	0	1	0	1
Crack PG	Jam PG	0	1	0	0
Jam PG	Release PG	0	1	0	0
Jam GC	Jam Do	-1	0	0	0
Jam Grumb	Release Grumb	0	2	0	0
Release MC	Jam AF	-2	0	0	0
Release MC	Jam Ent	-1	1	1	1
Jam Ent	Release PG	0	2	0	1
Crack PG	Release PG	0	2	0	0
Jam Ent	Jam GC	0	2	0	0
Jam PG	Jam GC	-1	1	0	0
Release PG	Jam GC	-1	1	0	0
Jam AF	Crack PPB	-1	1	0	0
Jam Esc	Crack PPB	-1	1	1	1
Crack PPB	Jam PPB	0	2	0	0
Release PG	Jam Do	0	2	0	0

Table 3.8: Days between breakup events determined from the reach-based analysis that were not confirmed with historical data. Those that are not shaded in grey had a range of one day, while those that are had a two day range, for all years of record.

Sites and breakup events		'05 to '10 range		Historical range	
		Min	Max	Min	Max
Jam Border	Jam Ent	-2	-1	1	1
Jam Esc	Crack PG	1	2	4	4
Jam Esc	Jam PG	1	2	4	4
Jam Esc	Release PG	2	2	5	5
Release MC	Jam Do	-1	0	3	3
Crack PPB	Jam Do	1	2	0	5
Jam Grumb	Jam Dp	2	3	4	4
Jam AF	Jam PG	1	3	5	5
Jam Grumb	Release PG	1	3	0	0
Jam AF	Release PG	1	3	5	5
Release MC	Jam PPB	-1	1	3	3
Jam Border	Jam Dp	1	3	5	5
Crack PPB	Jam Dp	3	5	6	6

Table 3.9: Cases where historic records both agreed and disagreed (bolded) with the reach based analysis.

Sites and breakup events		Range of days between events					
		From '05-'10	1977	1985	1987	1988	1989
Jam AF	Jam PPB	0 to 1	1			**3**	
Jam AF	Jam Do	1 to 2	1			**3**	
Jam Esc	Jam Do	0 to 1	0			**3**	
Jam PPB	Jam Do	0 to 1	0	**5**		0	
Release Border	Jam Dp	1 to 2		2			**4**
Jam Ent	Jam Dp	2 to 3	2			2	**4**
Jam AF	Jam Ent	0 to 2	**4**			1	
Jam Esc	Jam PPB	-1 to 1	0			**3**	
Jam Ent	Jam Do	0 to 2	**4**			2	0
Jam Esc	Jam Dp	2 to 4	**5**			3	
Crack PG	Jam Dp	1 to 3	**1**				**4**

Table 3.10 (a): Order of first transverse crack formation (D_c) at all sites. Refer to Figure 2.1 for a map of the study reach.

2005	2007	2008	2009	2010
1 AF	1 Border	1 AF	1 AF	1 Border
1 Border	2 PG	1 Esc	2 MC	2 Island
1 Island	3 Island	3 Border	2 Esc	2 Grumb
1 MC	3 MC	3 Island	2 PPB	3 MC
2 PG	3 GC	3 MC	3 Border	3 AF
2 GC	3 PPB	4 Grumb	3 Island	3 Esc
2 PPB		4 PPB	3 Grumb	3 PPB
		5 PG	3 GC	5 PG
		5 GC	5 PG	5 GC

Table 3.10 (b): Order of local ice jam formation (D_j) at all sites.

2005	2007	2008	2009	2010
1 AF	2 AF	3 AF	2 AF	3 Border
2 MC	2 Ent	4 Grumb	2 PPB	3 Island
2 Ent	3 Border	4 MC	3 MC	3 Grumb
2 PG	3 Grumb	4 Esc	3 Esc	4 MC
2 PPB	3 MC	4 PPB	3 D_o	4 AF
3 GC	3 PG	5 Ent	4 Grumb	4 Esc
3 D_o	3 PPB	5 PG	4 Ent	5 Ent
5 D_p	4 GC	5 GC	4 GC	5 PPB
	4 D_o	5 D_o	5 PG	5 D_o
	5 D_p	6 D_p	6 Border	6 PG
			7 D_p	6 GC
				6 D_p

Table 3.10 (c): Order of local ice jam releases (D_r) at all sites.

2005	2007	2008	2009	2010
1 AF	2 AF	3 AF	2 AF	3 Island
1 Esc	3 Grumb	5 MC	3 MC	3 Grumb
2 MC	3 MC	5 Esc	3 PPB	4 Border
2 Ent	3 Ent	5 GC	4 GC	4 MC
2 PG	4 Border	5 PPB	5 PG	4 AF
4 PPB	4 PG	6 Grumb	6 Border	5 Esc
	4 GC	6 Ent	7 Esc	5 PPB
	4 PPB	6 PG	7 Ent	6 Ent
				6 PG
				6 GC

Reach 2
Reach 3
Reach 4
Reach 5

Table 3.11: Order of known breakup stages (D_c, D_j, D_r) at all sites from 2005 to 2010. Refer to Figure 2.1 for a map of the study reach.

2005

Crack (D_c)	**Jam (D_j)**	**Release (D_r)**
1 AF	1 AF	1 AF
1 Border	2 MC	1 Esc
1 Island	2 Ent	2 MC
1 MC	2 PG	2 Ent
2 PG	2 PPB	2 PG
2 GC	3 GC	4 PPB
2 PPB	3 D_o	
	5 D_p	

2007

Crack (D_c)	**Jam (D_j)**	**Release (D_r)**
1 Border	2 AF	2 AF
2 PG	2 Ent	3 Grumb
3 Island	3 Border	3 MC
3 MC	3 Grumb	3 Ent
3 GC	3 MC	4 Border
3 PPB	3 PG	4 PG
	3 PPB	4 GC
	4 GC	4 PPB
	4 D_o	
	5 D_p	

2008

Crack (D_c)	**Jam (D_j)**	**Release (D_r)**
1 AF	3 AF	3 AF
1 Esc	4 Grumb	5 MC
3 Border	4 MC	5 Esc
3 Island	4 Esc	5 GC
3 MC	4 PPB	5 PPB
4 Grumb	5 Ent	6 Grumb
4 PPB	5 PG	6 Ent
5 PG	5 GC	6 PG
5 GC	5 D_o	
	6 D_p	

2009

Crack (D_c)	**Jam (D_j)**	**Release (D_r)**
1 AF	2 AF	2 AF
2 MC	2 PPB	3 MC
2 Esc	3 MC	3 PPB
2 PPB	3 Esc	4 GC
3 Border	3 D_o	5 PG
3 Island	4 Grumb	6 Border
3 Grumb	4 Ent	7 Esc
3 GC	4 GC	7 Ent
5 PG	5 PG	
	6 Border	
	7 D_p	

2010

Crack (D_c)	**Jam (D_j)**	**Release (D_r)**
1 Border	3 Border	3 Island
2 Island	3 Island	3 Grumb
2 Grumb	3 Grumb	4 Border
3 MC	4 MC	4 MC
3 AF	4 AF	4 AF
3 Esc	4 Esc	5 Esc
3 PPB	5 Ent	5 PPB
5 PG	5 PPB	6 Ent
5 GC	5 D_o	6 PG
	6 PG	6 GC
	6 GC	
	6 D_p	

Reach 2
Reach 3
Reach 4
Reach 5

Table 3.12: Hay River total degree days of thaw (*TDDT*) on dates of occurrence and between breakup events at all sites.

	Hay River *TDDT*, ˚C-days on dates of occurrence											
	Day of First Crack, $TDDT_c$ (Figure 3.11)				Day of Ice Jam, $TDDT_j$ (Figure 3.12)				Day of Jam Release, $TDDT_r$ (Figure 3.13)			
Site	Min	Max	Range	# Years	Min	Max	Range	# Years	Min	Max	Range	# Years
NWT/AB Border	36	102	66	5	44	128	84	3	44	131	87	3
Island at 974	37	116	80	5								
Grumbler Rapids	37	116	80	3	44	128	84	4	55	128	72	3
Mink Creek	29	128	98	5	37	131	94	5	37	131	94	5
Alexandra Falls	36	128	91	3	41	131	91	5	41	131	91	5
Escarpment Creek	29	128	98	3	37	131	94	3	42	131	90	4
Enterprise					44	131	88	5	45	131	86	5
Paradise Gardens	47	131	85	5	51	131	81	5	51	131	81	5
Golf Course	37	131	95	5	44	131	88	5	44	131	88	4
Pine Point Bridge	29	127	98	5	29	131	102	5	37	131	95	5
Onset of breakup HR					37	131	95	5				
Peak stage jam HR					45	131	86	5				

	Increase in Hay River *Δ TDDT* between events, ˚C-days between events											
	Crack to Ice Jam ($\Delta TDDT_{cj}$) (Figure 3.14)				Crack to Release ($\Delta TDDT_{cr}$) (Figure 3.15)				Jam to Release ($\Delta TDDT_{jr}$) (Figure 3.16)			
Site	Min	Max	Range	# Years	Min	Max	Range	# Years	Min	Max	Range	# Years
NWT/AB Border	7	26	19	3	7	29	22	3	0	5	5	3
Island at 974												
Grumbler Rapids	0	11	11	3	7	11	4	2	0	7	7	3
Mink Creek	0	9	9	5	0	14	14	5	0	4	4	5
Alexandra Falls	4	19	15	3	4	19	15	3				
Escarpment Creek	4	28	25	3	4	33	29	3	0	9	8	3
Enterprise									0	8	8	5
Paradise Gardens	0	8	8	5	0	13	13	5	0	5	5	5
Golf Course	0	7	7	5	0	7	7	4	0	0	0	4
Pine Point Bridge	0	4	4	5	4	8	4	5	0	8	8	5
Onset of breakup HR												
Peak stage jam HR												

Table 3.13: Most consistent ranges of total degree days (*ΔTDDT*) between breakup events at all sites.

Range,	First Crack to Ice Jam, $\Delta TDDT_{cj}$				First Crack to Jam Release, $\Delta TDDT_{cr}$				Ice Jam to Jam Release, $\Delta TDDT_{jr}$			
°C-days	Site	Min	Max	# Yrs Data	Site	Min	Max	# Yrs Data	Site	Min	Max	# Yrs Data
0.0-5.0	Pine Point Bridge	0	4	5	Pine Point Bridge	4	8	5	NWT/AB Border	0	5	4
									Grumbler Rapids	0	4	5
									Paradise Gardens	0	5	5
									Golf Course	0	0	3
5.1-10.0	Mink Creek	0	9	5	Golf Course	0	7	4	Grumbler Rapids	0	7	5
	Paradise Gardens	0	8	5					Escarpment Creek	0	9	5
	Golf Course	0	7	5					Enterprise	0	8	3
									Pine Point Bridge	0	8	3

Table 3.14: Range of total degree days (*TDDT*) and days from start to end of breakup on the Hay River.

Year	$\Delta TDDT$ ˚C-Days	Δ Days
2005	29	5
2007	33	5
2008	38	6
2009	23	7
2010	42	6

Table 3.15: Highest and lowest mean daily temperatures (*MDT*) during the Hay River breakup period.

High Temperatures		Low Temperatures	
Date	*MDT* (˚C)	Date	*MDT* (˚C)
21-Apr-10	14.7	5-May-09	-4.0
20-Apr-10	12.4	25-Apr-10	-1.3
24-Apr-07	11.4	4-May-09	-0.1
22-Apr-10	11.1	24-Apr-10	0.3
21-Apr-05	10.7	6-May-08	1.5
2-May-08	10.4	27-Apr-07	1.8
3-May-08	9.3	25-Apr-05	2.0

Table 3.16: Ranges of water levels when the first transverse crack (H_c) occurred at the four WSC gauge stations in the headwaters.

Site	Gauge height, m at first crack (H_c)			
	Min	**Max**	**Range**	**# Years data**
Sousa Creek at High Level	1.34	2.46	1.12	7
Chinchaga River at High Level	0.85	2.36	1.51	7
Steen River at Steen River	1.33	4.16	2.82	3
Hay River near Meander River	5.36	6.50	1.14	4

Table 3.17: Most consistent ranges of gauge heights during breakup events at all gauge sites.

Stage	Site	Min, m	Max, m	Range, m	# Yrs Data
First Transverse Crack (H_c)	Alexandra Falls	0.28	0.95	0.67	3
	WSC HRHR	3.17	4.25	1.08	5
	Paradise Gardens	2.19	3.76	1.57	5
	NWT/AB Border	0.38	2.34	1.96	3
Local ice jam (H_j)	Alexandra Falls	1.26	2.92	1.65	5
	D_p in Hay River	3.76	5.27	1.51	5
Ice jam release (H_r)	Alexandra Falls	1.26	2.92	1.65	5

Table 3.18: Most consistent ranges of water level increases between breakup events at all gauge sites.

Stage	**Site**	**Min, m**	**Max, m**	**Range, m**	**# Yrs Data**
First Crack to Ice Jam (ΔH_{cj})	Alexandra Falls	0.05	0.90	0.85	3
	WSC HRHR	0.69	1.97	1.28	5
	Pine Point Bridge	0.24	1.94	1.70	5
First Crack to Jam Release (ΔH_{cr})	NWT/AB Border	1.87	3.74	1.87	3
	Alexandra Falls	0.05	0.90	0.85	3
Ice Jam to Jam Release (ΔH_{jr})	NWT/AB Border	0.00	0.43	0.43	3
	Paradise Gardens	0.00	1.32	1.32	5

Table 3.19: Rates of increase in water levels, period and increase prior to first cracking for all sites and years of record.

Site	Rate of increase in water level, m/hr			Duration of constant rate of increase, hr			Total increase in water level or duration, m			Years
	Min	Max	Range	Min	Max	Range	Min	Max	Range	of data
NWT/AB Border	0.004	0.027	0.023	24.0	96.0	72.0	0.3	1.1	0.8	5
Alexandra Falls	0.002	0.005	0.003	135.3	140.6	5.3	0.3	0.8	0.5	2
Paradise Gardens	0.004	0.047	0.044	22.0	96.0	74.0	0.1	1.1	1.1	5
WSC near Hay River	0.005	0.028	0.023	35.0	122.3	87.2	0.2	1.2	1.0	5
Pine Point Bridge	0.006	0.030	0.024	20.0	157.0	137.0	0.5	1.6	1.1	4
West Channel Bridge	0.004	0.028	0.024	23.3	146.3	123.0	0.3	0.8	0.5	5

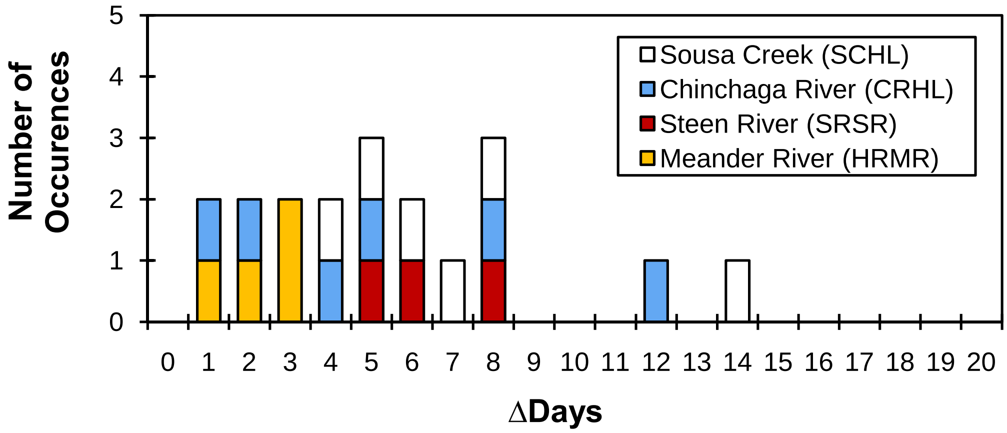


Figure 3.1: Number of days between cracking at the headwaters gauge (D_c) stations and the onset of breakup (D_o) in the Hay River delta.

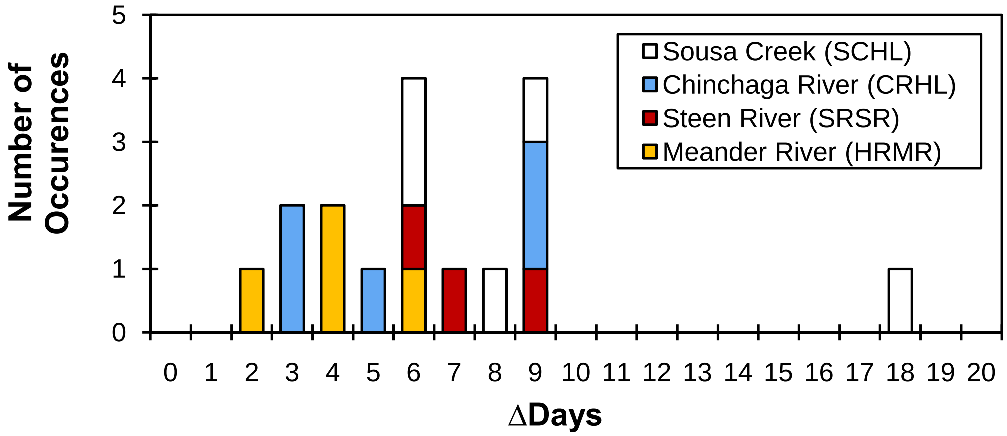


Figure 3.2: Number of days between cracking at the headwaters gauge (D_c) stations and the peak stage (D_p) in the Hay River delta.

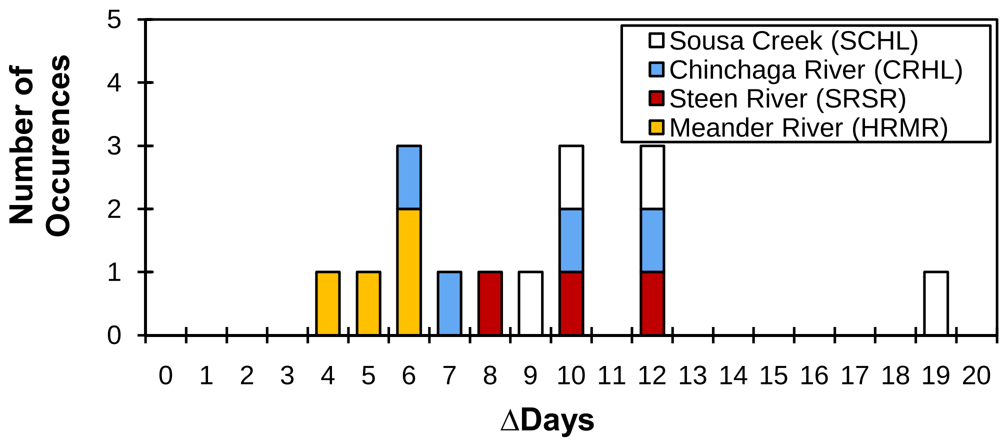


Figure 3.3: Number of days between cracking at the headwaters gauge (D_c) stations and jam melt out (D_m) in the Hay River delta.

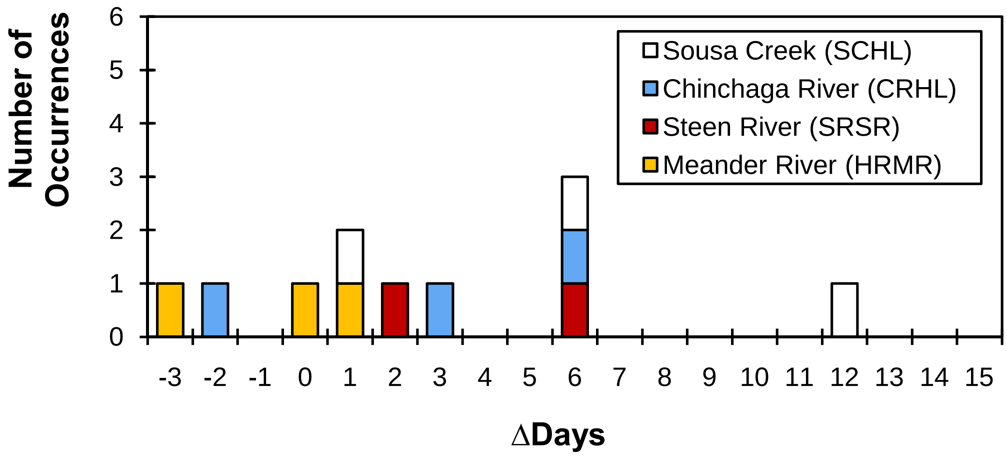


Figure 3.4: Number of days between cracks at the headwaters gauge stations (D_c) and the first transverse crack at Alexandra Falls (D_c).

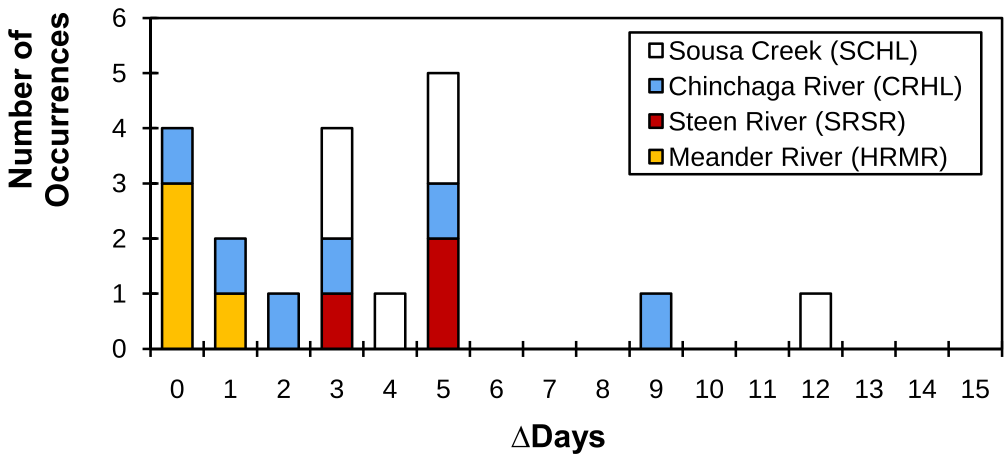


Figure 3.5: Number of days between transverse cracks at the headwaters gauges and transverse cracks (D_c) at the WSC near Hay River (HRHR) gauge.

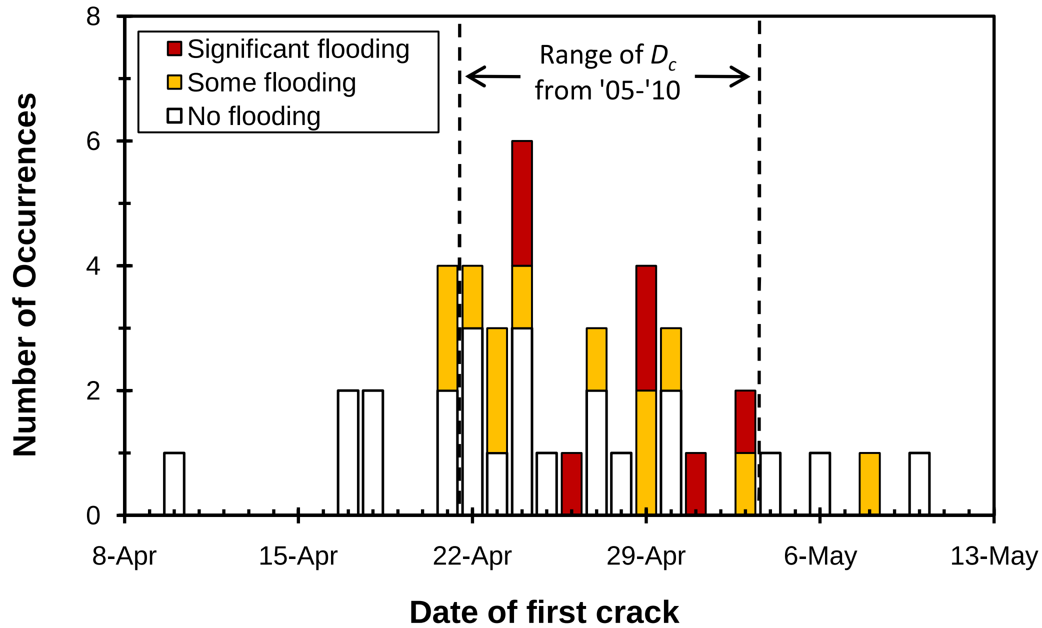


Figure 3.6: Dates of first cracking (D_c) at the WSC near Hay River (HRHR) gauge station since 1964.

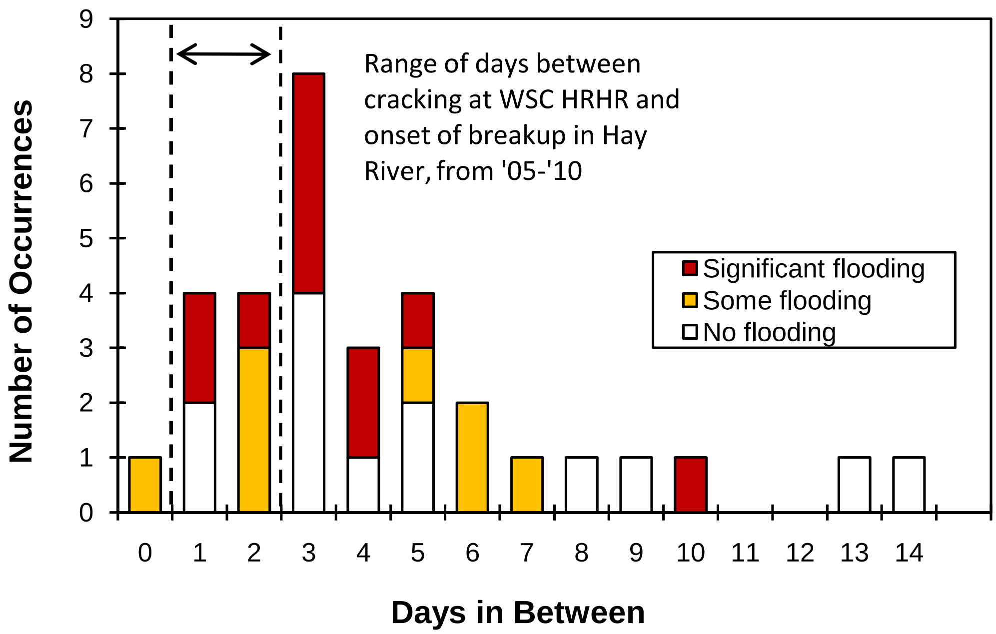


Figure 3.7: Number of days between first cracking (D_c) at the WSC near Hay River (HRHR) gauge station and the onset of breakup (D_o) in the Hay River delta, compared to the reach based range.

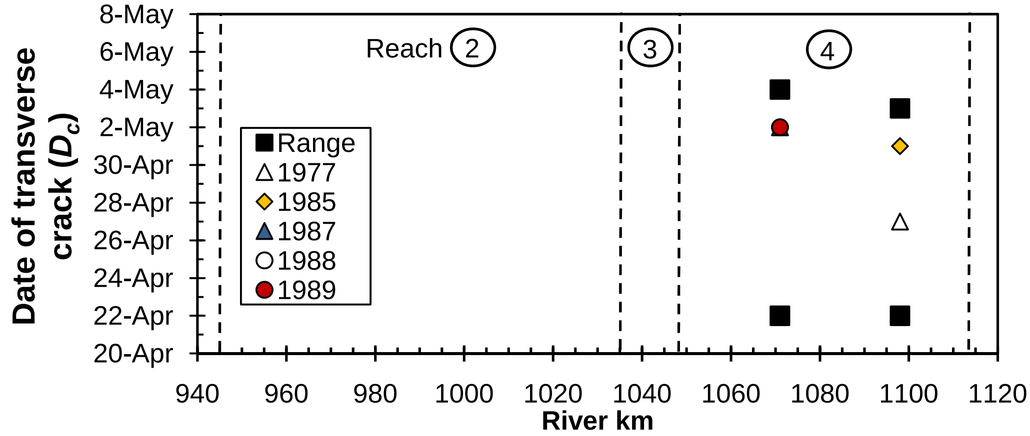


Figure 3.8: Historic dates of first tranverse cracking at Paradise Gardens and the Pine Point Bridge, compared to the range determined in the site specific analysis of 2005 to 2010 photos.

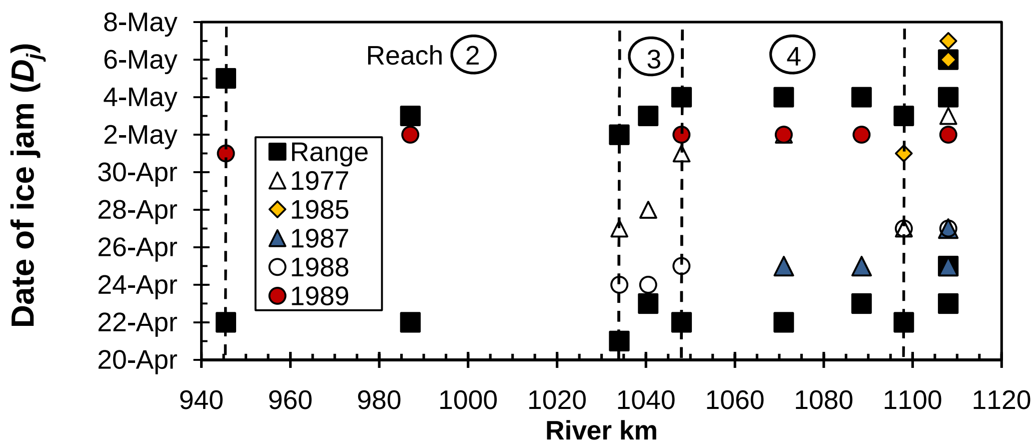


Figure 3.9: Historic dates of local ice jamming at the NWT/AB Border, Grumbler Rapids, Alexandra Falls, Escarpment Creek, Enterprise, Paradise Gardens, the Golf Course, Pine Point Bridge and in the Hay river delta, compared to the range determined in the site specific analysis of 2005 to 2010 photos.

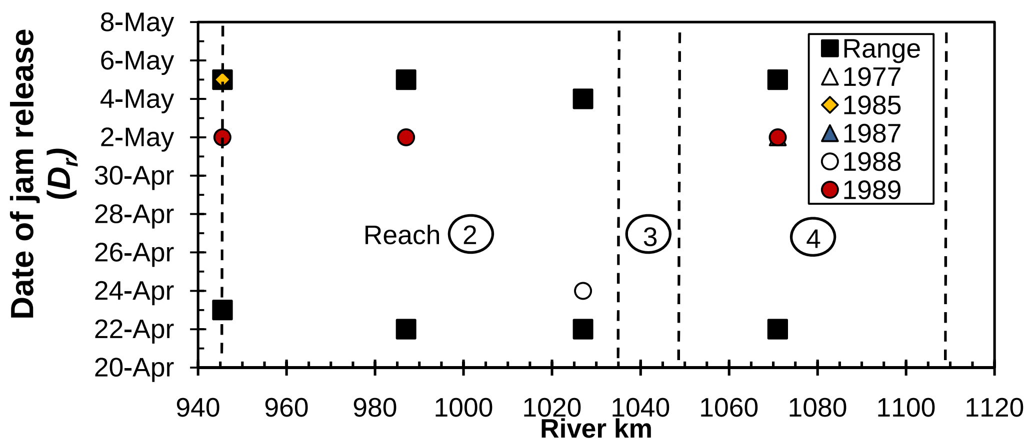


Figure 3.10: Historic dates of ice jam releasing at the NWT/AB Border, Grumbler Rapids, Mink Creek and Paradise Gardens, compared to the range determined in the site specific analysis of 2005 to 2010 photos.

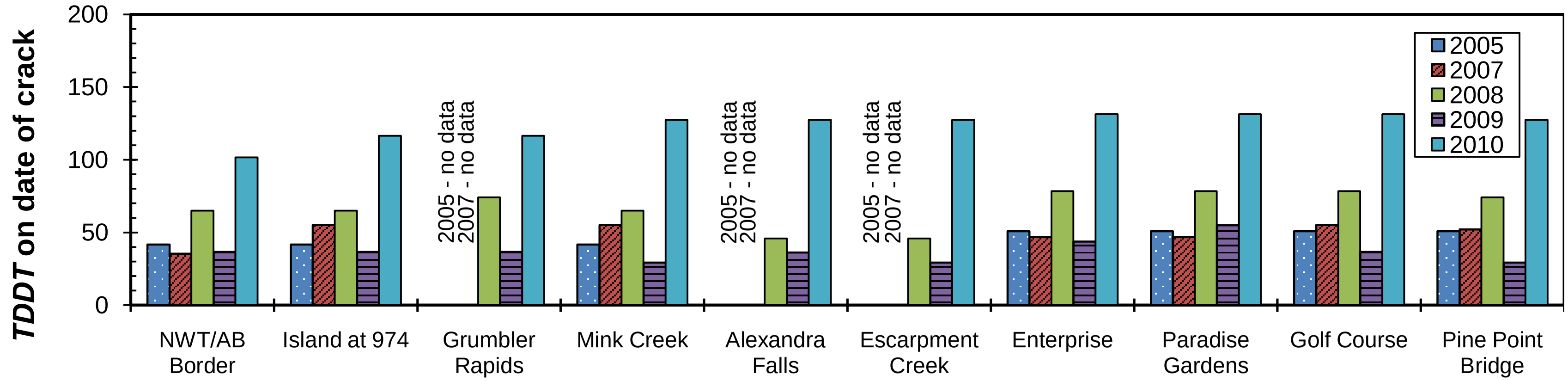


Figure 3.11: Total degree days of thaw ($TDDT_c$) on dates of first transverse cracking at all sites from 2005 to 2010.

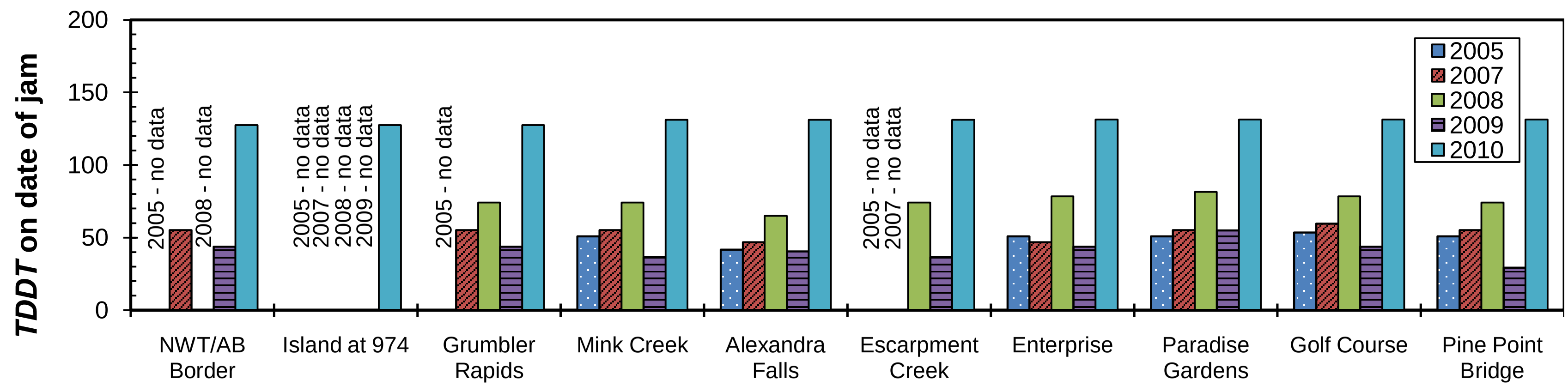


Figure 3.12: Total degree days of thaw ($TDDT_j$) on dates of local ice jamming at all sites from 2005 to 2010.

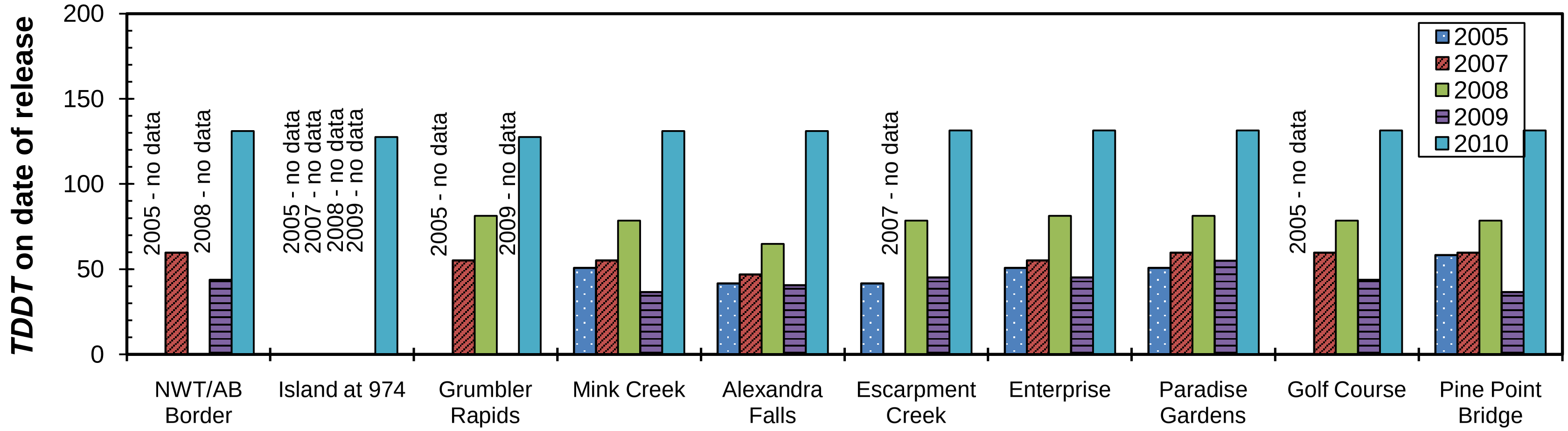


Figure 3.13: Total degree days of thaw ($TDDT_r$) on dates of ice jam releasing at all sites from 2005 to 2010.

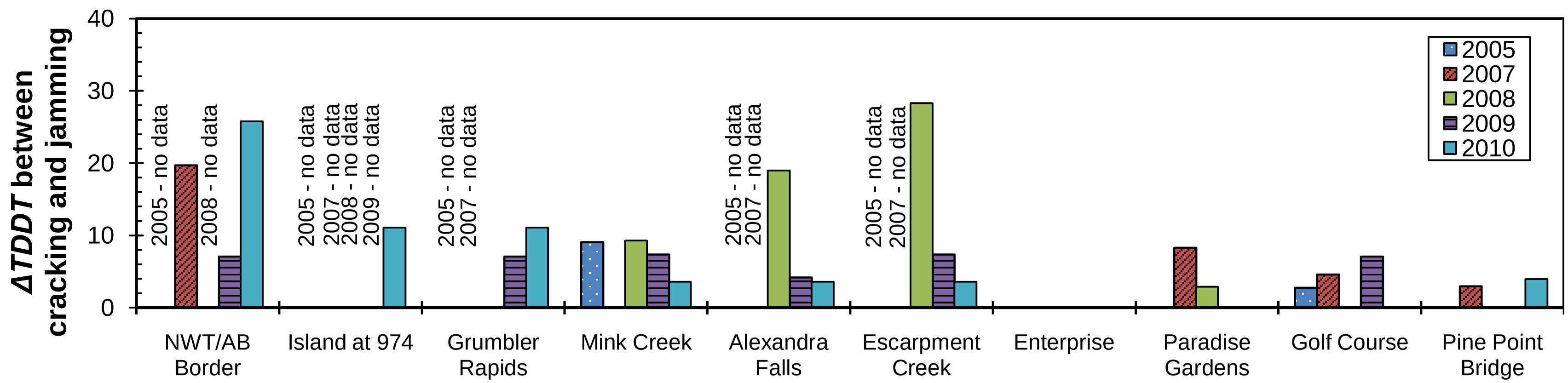


Figure 3.14: Increase in total degree days of thaw ($\Delta\ TDDT_{cj}$) between first cracking and local ice jamming at all sites from 2005 to 2010.

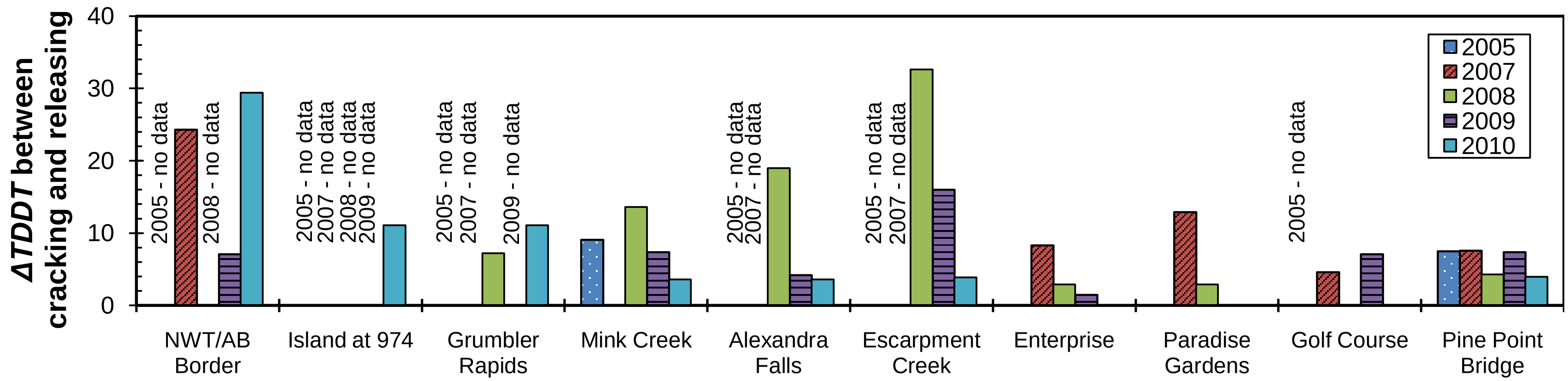


Figure 3.15: Increase in total degree days of thaw ($\Delta\ TDDT_{cr}$) between first cracking and jam releasing at all sites from 2005 to 2010.

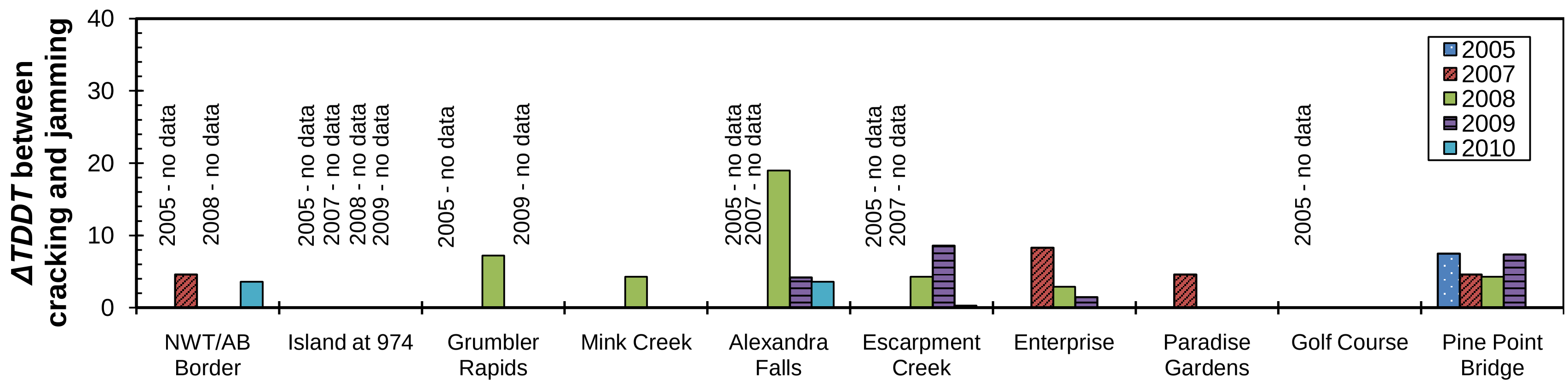


Figure 3.16: Increase in total degree days of thaw ($\Delta TDDT_{jr}$) between local ice jamming and ice jam releasing at all sites from 2005 to 2010.

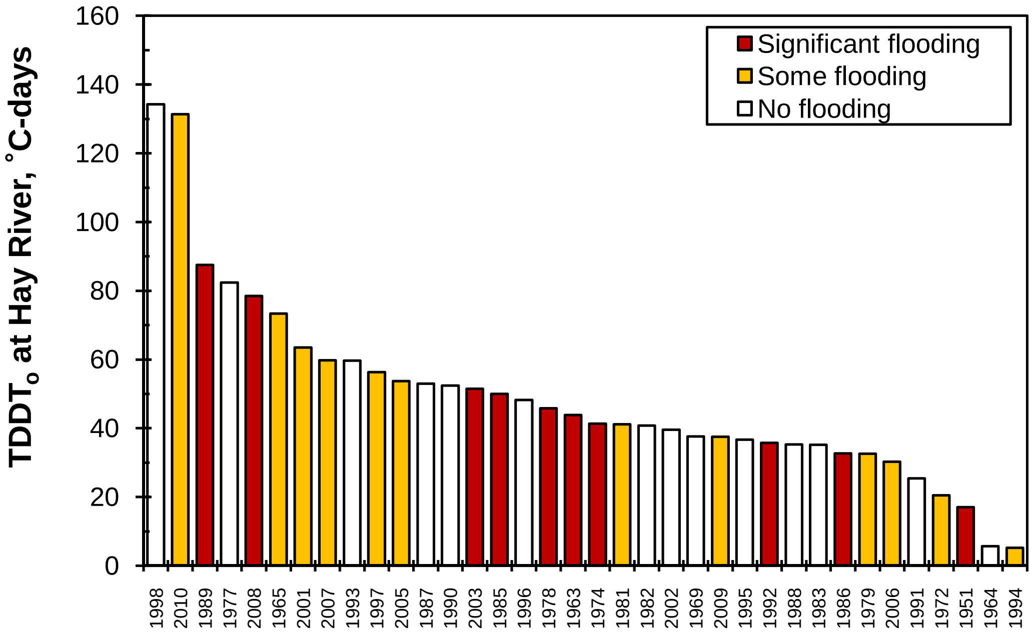


Figure 3.17: Total degree days of thaw on dates of historic onset of breakup ($TDDT_o$) and associated flood severity, for all known events between 1963 and 2010.

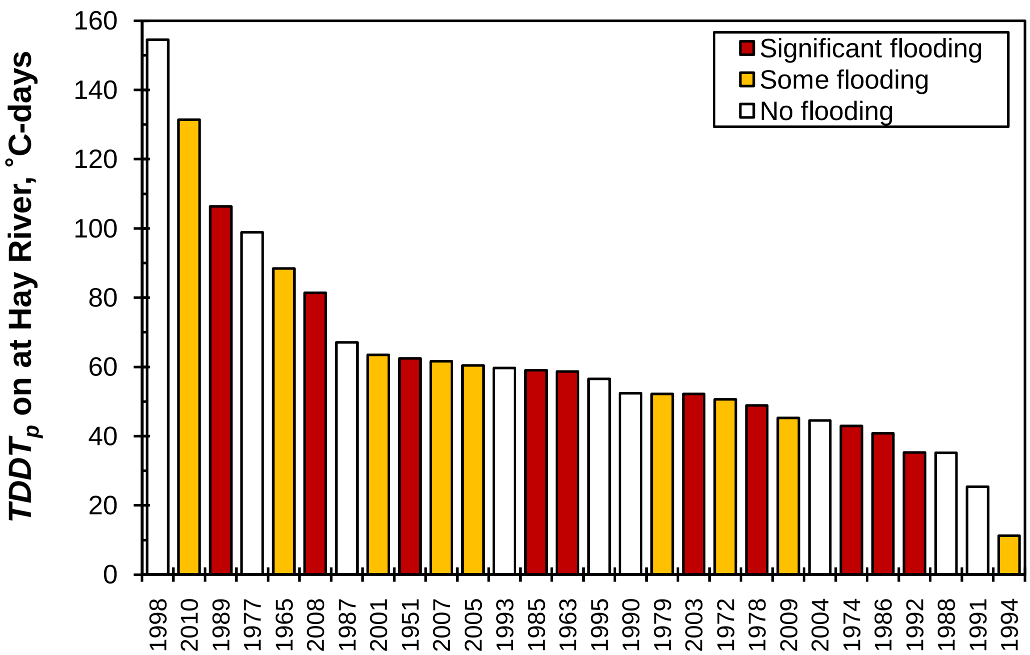


Figure 3.18: Total degree days of thaw on the dates of historic peak stage ($TDDT_p$) jam and associated flood severity, for all known events between 1963 and 2010.

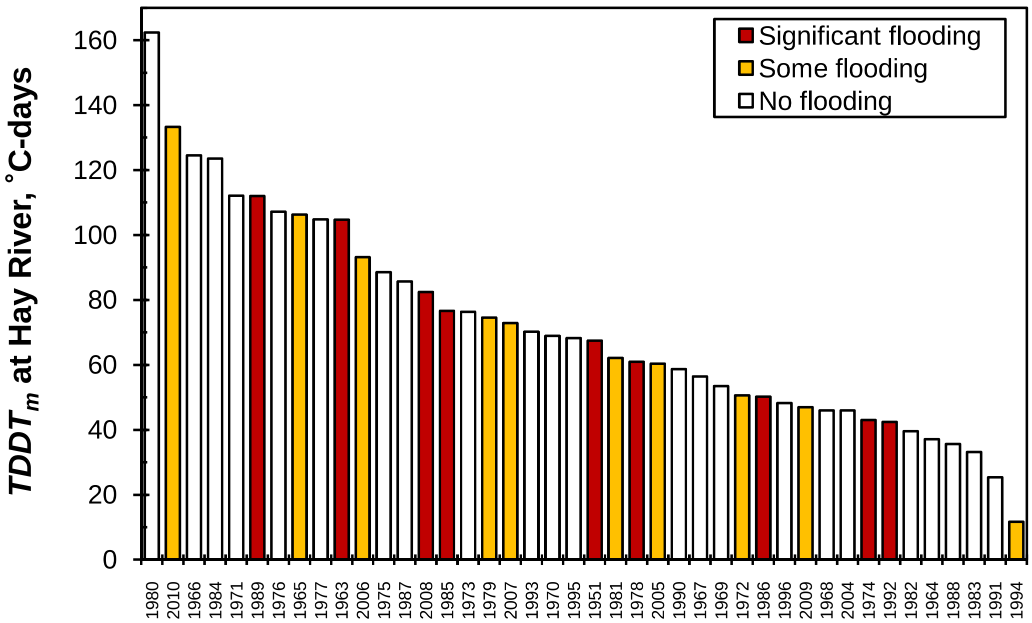


Figure 3.19: Total degree days of thaw on the dates of historic jam melt out ($TDDT_m$) and associated flood severity, for all known events between 1963 and 2010.

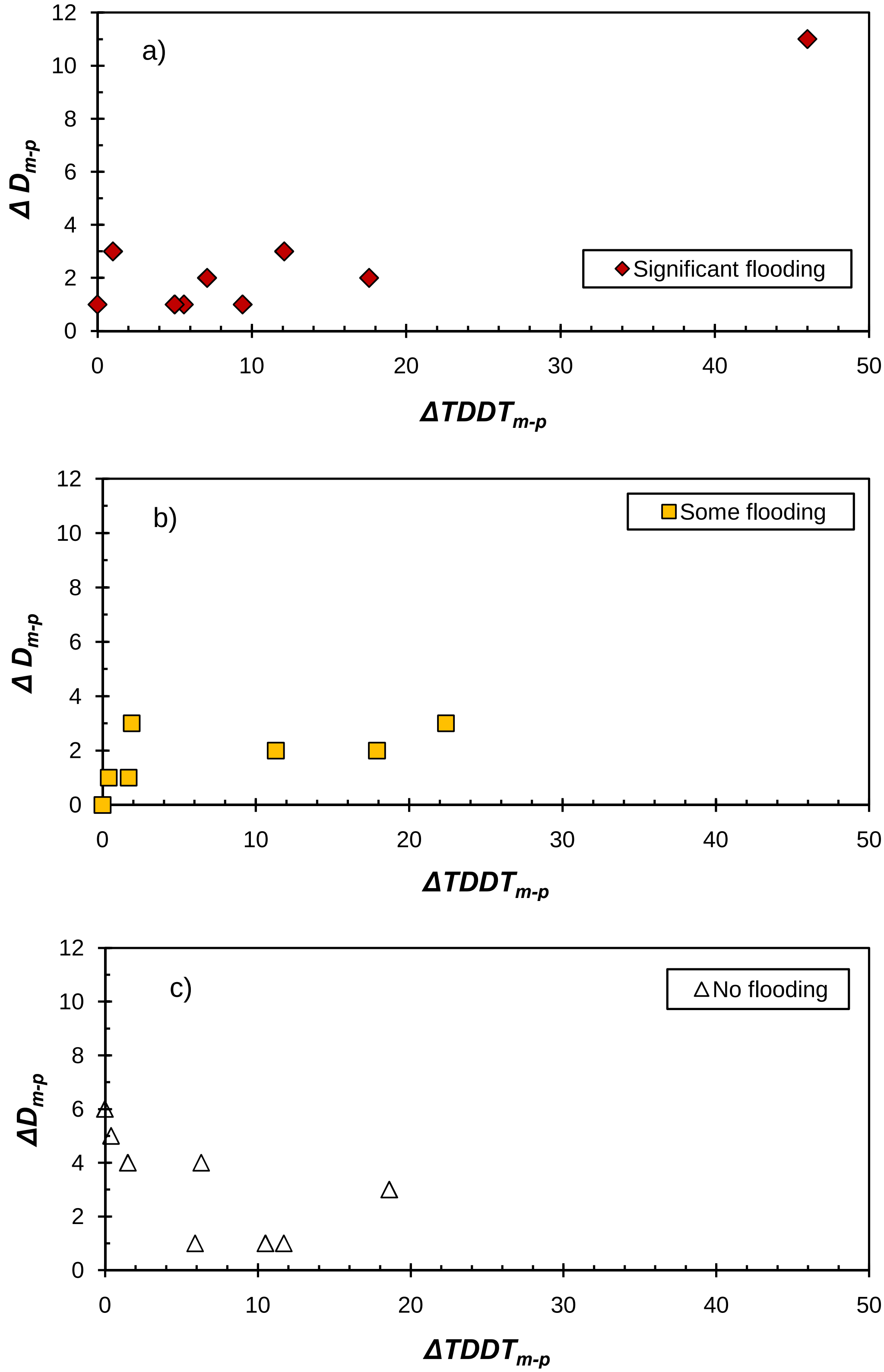


Figure 3.20: Relationship between known days of thaw and total degree days between peak stage and melt out ($\Delta TDDT_{m-p}$) for all significant (a), some (b) and no (c) flooding.

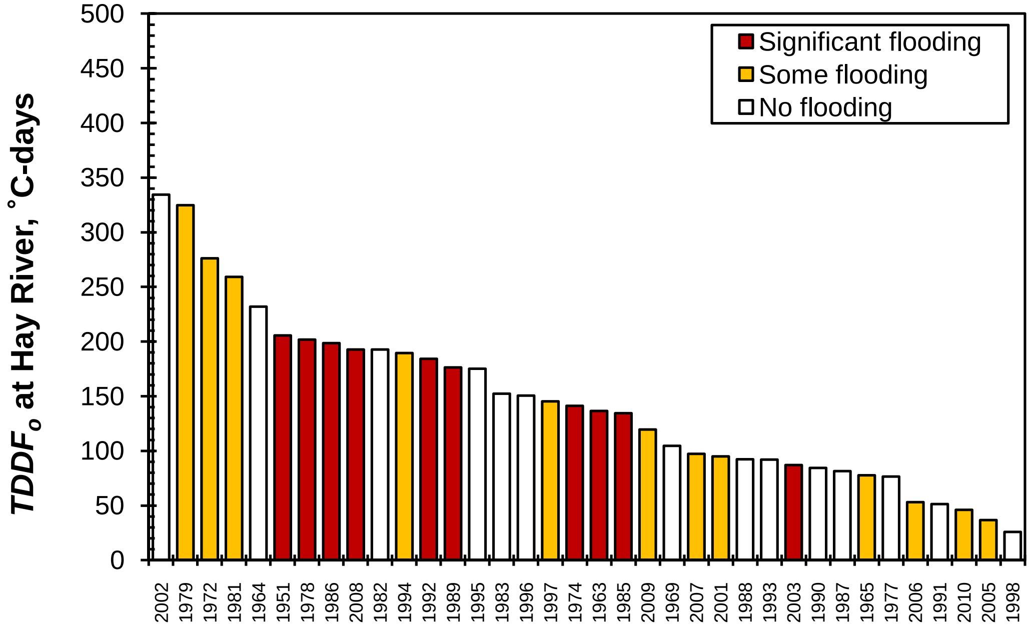


Figure 3.21: Total degree days of freezing in the pre-breakup period on the date of the onset of of breakup (*TDDF* $_o$) in the Hay River delta, for all known events between 1963 and 2010.

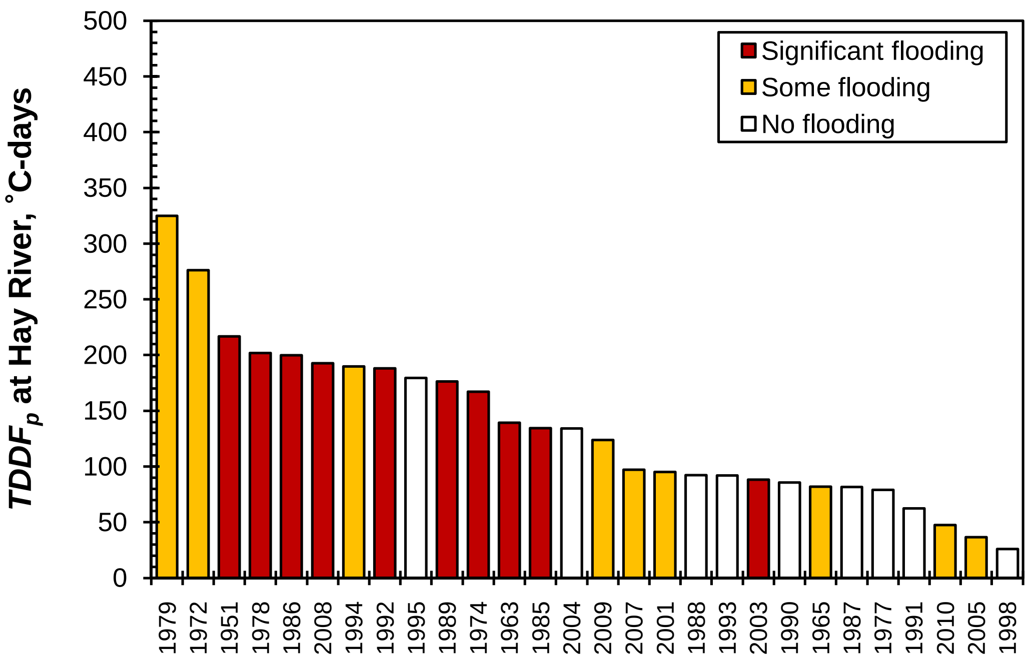


Figure 3.22: Total degree days of freezing in the pre-breakup period on the date of the peak stage jam (*TDDF* $_p$) in the Hay River delta, for all known events between 1963 and 2010.

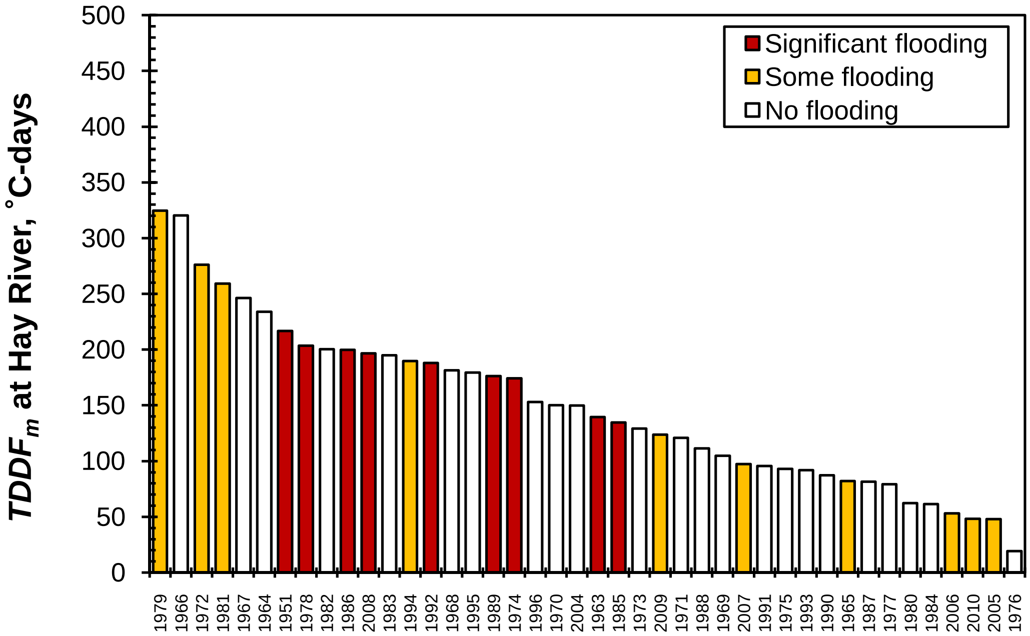


Figure 3.23: Total degree days of freezing in the pre-breakup period on the date of ice jam melt out ($TDDF_m$) in the Hay River delta, for all known events between 1963 and 2010.

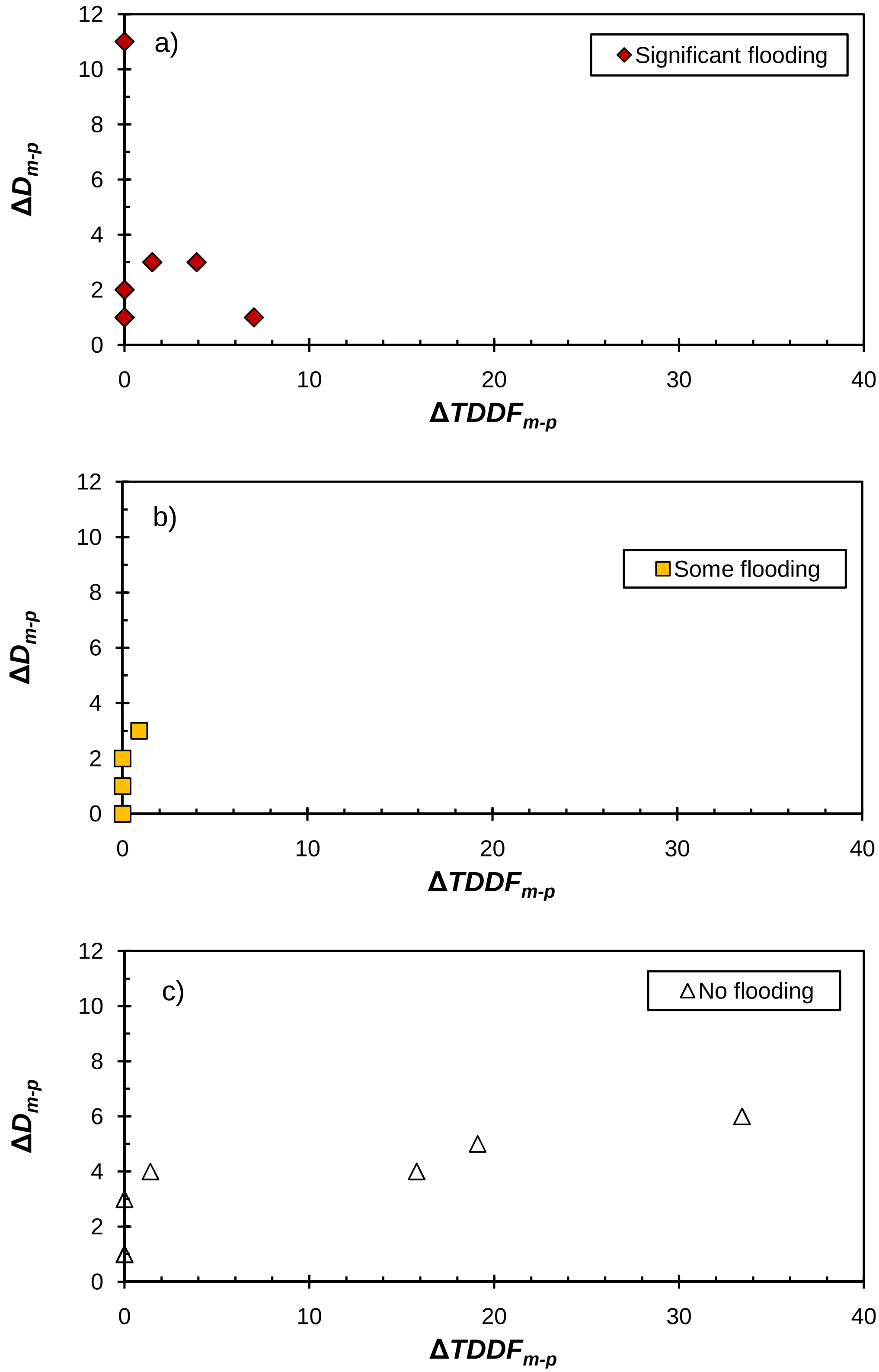


Figure 3.24: Relationship between known days and total degree days of freezing between peak stage and melt out (TDD_{Fm-p}) for significant (a), some (b) and no (c) flooding.

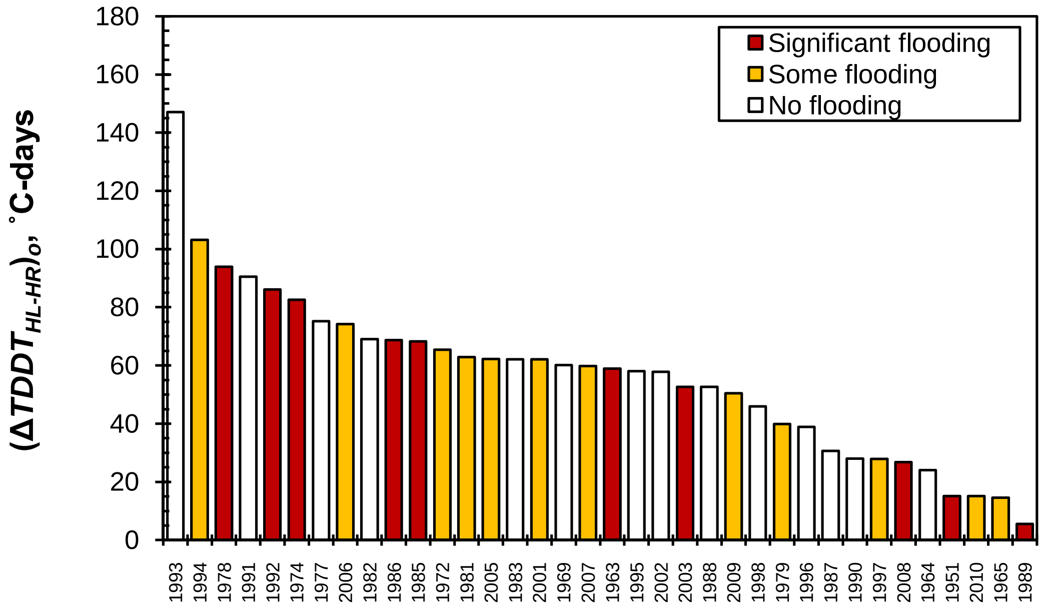


Figure 3.25: Difference in total degree-days of thaw between High Level and Hay River on the known dates of onset of breakup in Hay River (D_o).

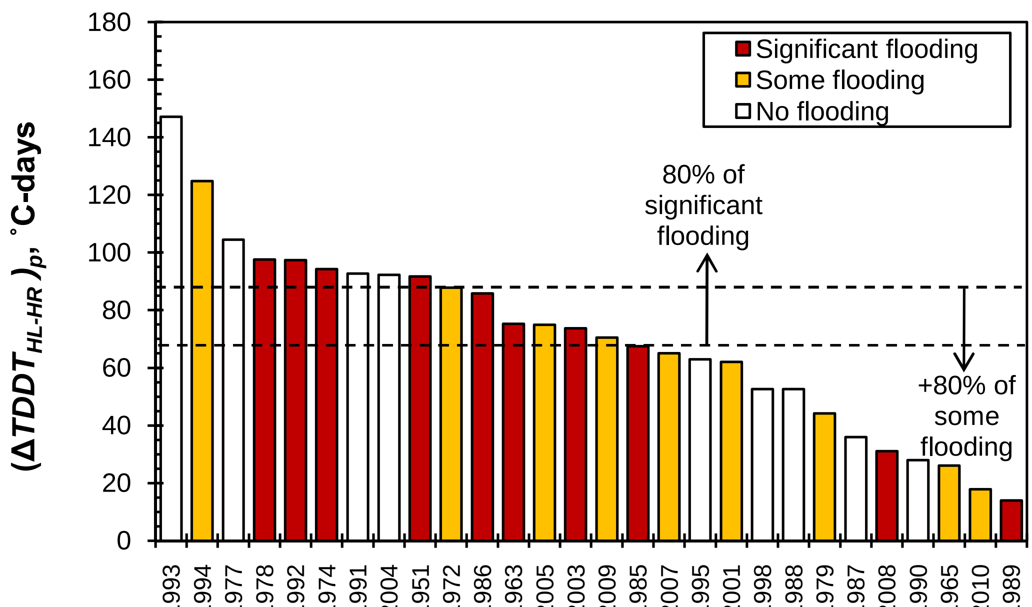


Figure 3.26: Difference in total degree-days of thaw between High Level and Hay River on the known dates of peak stage in Hay River (D_p).

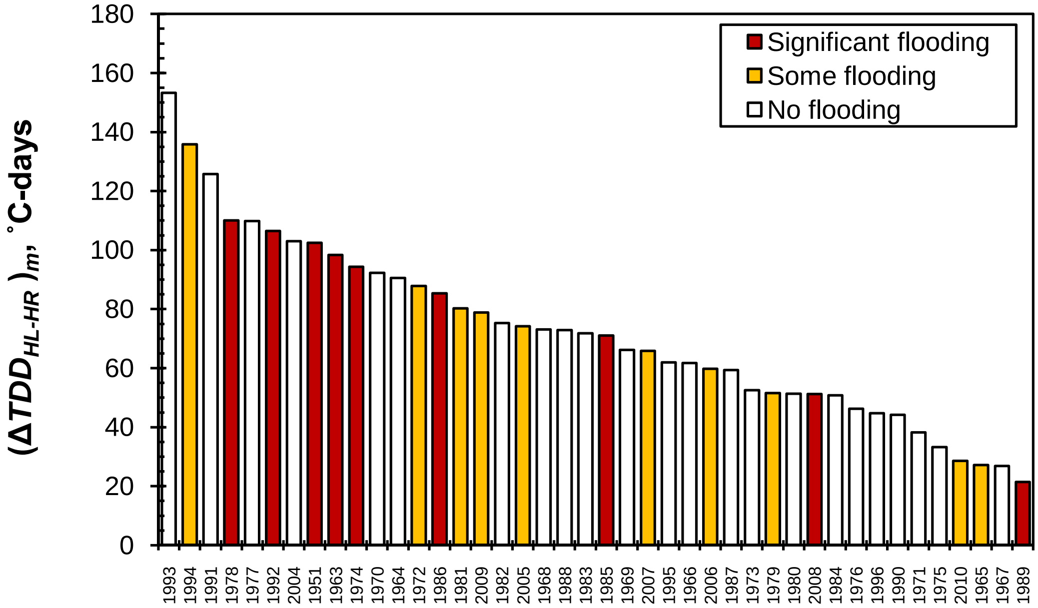


Figure 3.27: Difference in total degree-days of thaw between High Level and Hay River on the known dates of jam melt out in Hay River (D_m).

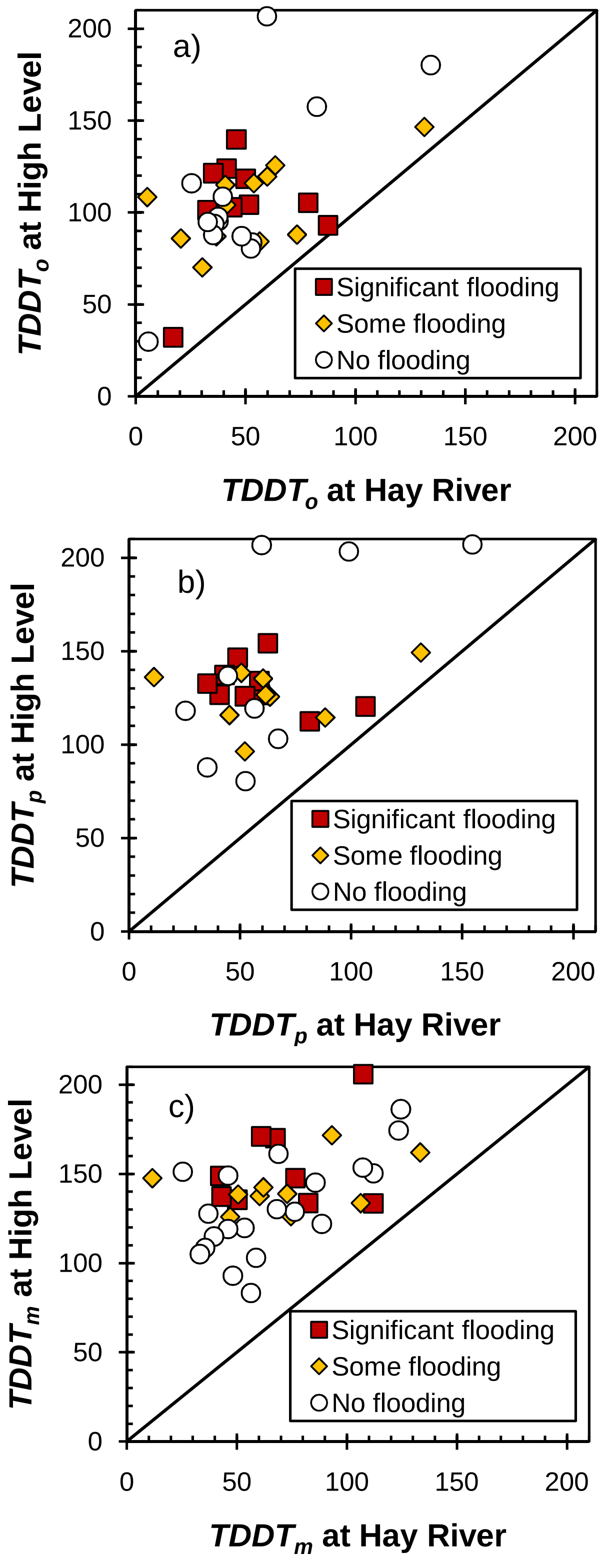


Figure 3.28: Total degree days of thaw at High Level versus Hay River on the known dates of onset of breakup (D_o) (a), peak stage (D_p) (b) and melt out (D_m) (c).

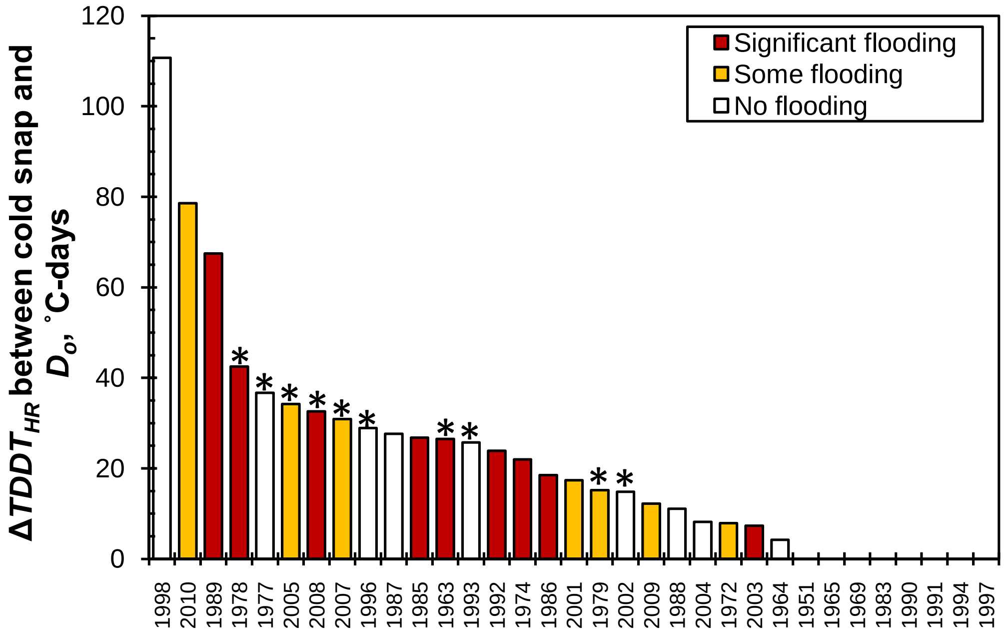


Figure 3.29: Increase in total degree days of thaw in Hay River ($\Delta TDDT_{HR}$) between the end of the cold snap and the onset of breakup (D_o). The asterisks (*) denotes a definite cold snap ending within 7 days of the initiation of breakup.

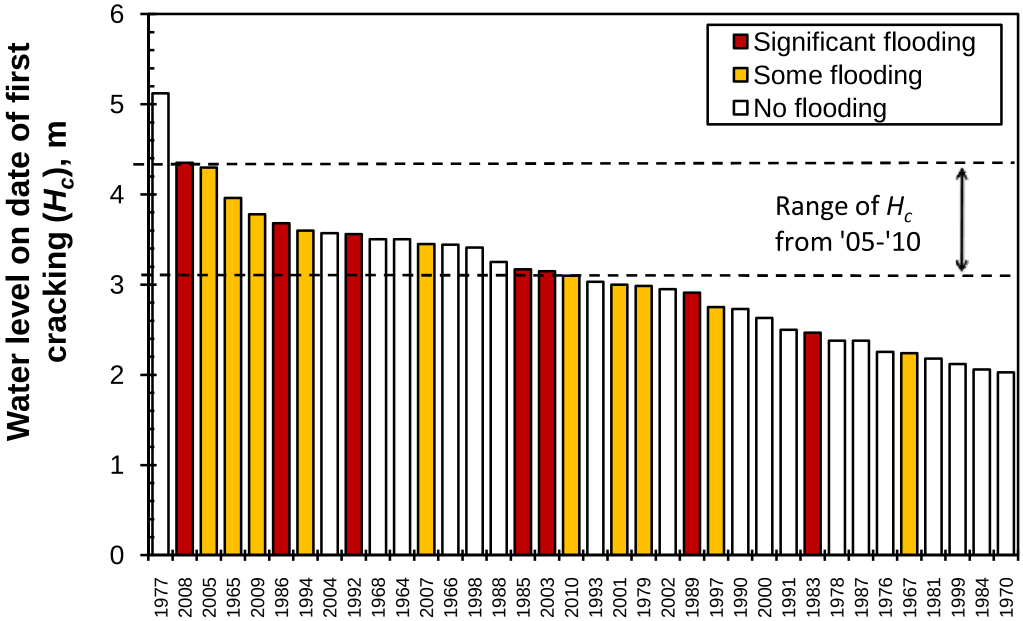


Figure 3.30: Water levels at first cracking (H_c) at the WSC near Hay River (HRHR) since 1964.

Chapter 4: Conclusions and Recommendations

Since 1894, flooding as a result of river ice jamming during breakup has occurred in 34 years (of 117 years of record). More recently, flooding has occurred in 8 of the last 10 years, and is an annual concern for residents. The analysis of this historical record, paired with 5 years of extensive breakup observations allowed for a study of the patterns in the sequence, timing and severity of breakup. The four objectives of this thesis were to:

1.) Ensure the continuity of knowledge of the key sequence and nature of breakup on the Hay River at Hay River by integrating the heuristic knowledge of local residents, academic researchers, government experts and the Town of Hay River flood watch committee.
2.) Consolidate that knowledge with quantitative hydrometeorological data to facilitate some predictive capabilities, primarily in terms of the timing of various stages of breakup.
3.) To contribute knowledge towards a flood forecasting expert system which would be of practical use to the local Flood Watch Committee.
4.) To determine the critical monitoring data required in the long term to service future (more robust) forecast model development.

The stages in breakup that were chosen to be studied were the first transverse crack (D_c), first local ice jam (D_j) and local ice jam release (D_r) at ten study sites along the reach. In the Hay River delta, the onset of breakup (D_o), peak stage (D_p) and ice jam melt out (D_m) were considered. Several types of data were interpreted in addition to the historical records of breakup stages in the delta;

water level gauge data, hydrometeorological data and aerial and ground photographs. This data was analyzed in a number of ways to determine patterns in the progression of breakup on the Hay River, including:

- A site-specific approach to consider how conditions vary at discreet sites between the various stages of breakup.
- A reach-based approach to examine how conditions change between sites during the various stages of breakup.
- An analysis of the general order in which breakup stages occur.
- An analysis of historical records of breakup stages.

The site-specific approach to dates, total degree-days of thaw and water levels did not yield narrow ranges of thresholds during breakup. The incremental changes in days, total degree-days of thaw and water levels between stages of breakup were consistent at a few sites. The reach-based method revealed a number of consistencies in days between breakup stages along the reach, but was not useful when considering degree-days. The general sequence of breakup stages was examined to identify order and timing of breakup stages along the reach. An analysis of the historical record revealed windows of dates during which significant, some and non-flood events have occurred. Considering the total degree-days of thaw, of freezing and difference between High Level and Hay River temperatures during breakup stages also allowed for an analysis of these patterns, but did not yield significant results.

Section 3.4 details the best indicators found for all stages of breakup along the study reach and the delta. The sequencing of upstream breakup stages are useful in how they relate to the timing and severity of breakup stages and flooding in the Hay River delta. Ultimately, the general overview of the sequencing of breakup and the indicators as to the timing of the first crack at Alexandra Falls, ice jam release at Enterprise and D_o, D_p, and D_m are the most valuable findings of this thesis. The first transverse crack at Alexandra Falls essentially means that breakup along the Hay River is underway. Although sites in Reach 2 may break up before Alexandra Falls, these occur in no particular order and all occur within 2 days of each other. As the EMO camera and water level gauge are installed at this location, this is the most practical site to monitor. The ice jam release at Enterprise ultimately results in the ice run that causes the peak stage D_p and possibly flooding in the Town of Hay River. This is the event that the Emergency Measures Organization (EMO) should be most concerned with, as well as how the onset of breakup (D_o), peak stage (D_p) and ice jam melting out (D_m) develop with the arrival of all ice runs from upstream.

A number of recommendations for future monitoring were developed as a result of this study.

1. The WSC gauges in the headwaters should continue to be monitored to identify the timing of the first transverse crack (erratic fluctuation in water levels). These gauges in the headwaters remain the most upstream indicators, and those that allow the most advance warning as to the timing of breakup.

2. The EMO should continue to install water level gauges at Alexandra Falls, Paradise Gardens, the Pine Point Bridge and the West Channel Bridge. The camera and gauge at the Pine Point Bridge should be installed and operational by 10-Apr to monitor thermal deterioration of the ice. The ability to monitor the ice deterioration at this site early in the breakup season will allow the EMO to identify when additional monitoring personnel (e.g. DIAND) should arrive at Hay River. At Alexandra Falls, the camera and gauge should ideally be installed by 15-Apr. Other water level gauges and any cameras should be installed and operational before 20-Apr.

3. The EMO should continue to install time lapse cameras with real-time online updating capabilities at Alexandra Falls. The breakup sequencing in Reach 2 is quite variable, but Alexandra Falls was one of the first sites to crack. This signifies that breakup in the Reach has begun, and that the onset of breakup in the Hay River delta (D_o) should be expected in as little as 2 to 4 days. This is a key breakup stage, and its timing should be documented in future years to extend the record and further develop indicators as to the patterns of timing and sequencing of breakup.

4. Key sites for future monitoring efforts include Alexandra Falls, Escarpment Creek (if possible) and Enterprise, Paradise Gardens, the WSC gauge site at Hay River (HRHR) and the Pine Point Bridge.

5. The continuous view of the river provided by aerial observation flights is unmatched by ground observations. The information gathered during daily observation flights was critical to this research. However, should budgets permit only one flight per year, the following recommendation is made as to when to time this flight to be able to garner the most information possible regarding the sequence of breakup timing. Time the observation flight to coincide with the last of the following 2 events: 2 days after the first transverse crack occurs at the EMO Alexandra Falls gauge or the day of the transverse cracking at the Pine Point Bridge.

   - By this time, most sites in Reach 2 should have cracked and formed jams, and perhaps even released. The gorge jam should be lengthening at this time. Note the presence and size of jams in Grumbler Rapids, and in the gorge. Reach 4 may or may not have broken up yet, but this reach is more visible and easily monitored from ground vantage points.
   - The gorge jam released 3 to 5 days after cracking (open lead developed) and 2 to 3 days after the jam formed at Escarpment Creek. The jam consistently released one day after the head (leading edge) shoved past km 1043.0 to 1043.5.
   - The peak stage in Hay River (D_p) occurred when the ice run caused by the release of gorge jam arrived in the delta. Although this jam typically formed at Escarpment Creek, and out of site of the road access at Enterprise, it shoved forward (stopping at the island at Enterprise) before

it released. In 5 years of record, it released after becoming visible at Enterprise.

6. Any documentation of the timing of breakup stages along the reach or in the Hay River delta will add to the current record and help with a better understanding of the sequencing and timing of breakup stages.

The site-specific and reach specific analysis of the sequencing of breakup in this thesis was done using five years of data highly detailed data. However, there was not enough years of data to warrant statistical analyses. When possible, the ranges determined using data from 2005 to 2010 (excluding 2006) were compared to the much longer historical record of breakup. Although these ranges were in large part representative, over the longer record results were more variable. Also, these five years of detailed data cover only years when some or significant flooding occurred. Additional years of data (particularly non-flood years) would add validity and confidence in the ranges of dates, water levels and total degree-days during and between breakup stages. This information should be used as a general guide to the progression of breakup on the Hay River, and not as a rule.

Chapter 5: Cited References

Beltaos, S, 2008. River Ice Breakup. Canadian Water Resources Publications, Highlands Ranch, Colorado.

Brayall, M., 2011. 2D Hydraulic Modeling of Ice Processes at Hay River, NWT. A thesis submitted to the Faculty of Graduate Studies and Research in partial fulfilment of the requirements for the degree of Master of Science in Water Resources Engineering. Department of Civil Engineering, University of Alberta, Edmonton.

Diamond Jenness, 1978. Breakup and Flooding in Hay River, NWT. Report prepared by the 1978 Social Studies Class (8C) of Diamond Jenness Secondary School as part of the Explore Canada's Heritage competition. Hay River, NWT.

EC, 1988. Flood Events in Canada: 1983-1987. Report prepared for the Water Planning and Management Branch, Inland Waters Directorate.

Gerard, R. and Stanley, S. 1988a. Documentation of Ice Regime of Hay River at Hay River NWT: Winter 1987-88. Report prepared for Indian and Northern Affairs Canada and Environment Canada, Edmonton, Alta.

Gerard, R. and Stanley, S. 1988b. Ice jams and flood forecasting, Hay River, N.W.T.: Phase 1, final report. Dept. of Civil Engineering, University of Alberta, Edmonton, Alta.

Gerard, R. and Jasek, M., 1990a. Break-up observations and ice jam flood forecast algorithm evaluation, Hay River, NWT, 1989. Report Prepared for Environment Canada and Indian and Northern Affairs Canada, Yellowknife, NWT. Engineering Report, vol. 90–3. Department of Civil Engineering, University of Alberta, Edmonton, Alta.

Gerard, R., Hicks, F., and Jasek, M., 1990b. Ice Jams and Flood Forecasting, Hay River, NWT – Phase 2 – ice jams and flood forecasting. Water Resources Engineering Report No. 90-4, Department of Civil Engineering, University of Alberta, Edmonton, Alta.

GNWT/IWD, 1984. Hay River Basin Overview. Report prepared by Environmental Planning and Assessment Division, Government of the

Northwest Territories, and Inland Waters Directorate, Department of the Environment, Yellowknife, NWT.

Hicks, F., Steffler, P. M., Gerards, R., 1992. Finite element modelling of surge propagation and an application to the Hay River, N.W.T. Canadian Journal of Civil Engineering, 19, 454-462. Department of Civil Engineering, University of Alberta, Edmonton, Alta.

Jasek, M., S. Stanley, and Gerard, R. 1993 Update of Ice Jam Flood Database, Hay River, NWT. Engineering Report, vol. 90–3. A Report Prepared for Environment Canada and Indian and Northern Affairs Canada, Yellowknife, NWT.

Jasek, M, 1993. Hay River Flood Control: Hay River, NWT. Prepared for the Town of Hay River.

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

Harrison, D.A., 1984. Nay River, NWT, 1800-1950: A geographical study of site and situation. Doctoral dissertation presented to the Department of Geography, University of Alberta, Edmonton, Alta.

Maxwell, J. and Hicks, F., 2011. 2008-2010 Breakup Observations on the Hay River, NWT. Water Resources Engineering Report 10-FH-01. Department of Civil Engineering, University of Alberta, Edmonton, Alta.

Stanley, Grimble, Roblin Ltd, 1959. Civil Engineering Report on Flooding of Hay River Townsite, NWT. Report prepared for the Department of Northern Affairs and Natural Resources, Northern Administration Branch Engineering Division, Edmonton, Alta.

Stanley, Grimble, Roblin Ltd, 1963. Engineering report on flood protection at Hay River, NWT. Report prepared for the Canadian Department of Northern Affairs and Natural Resources and Department of Public Works Canada, Edmonton, Alta.

UMA, 1978. Flood risk mapping for the Hay River, Northwest Territories. Report prepared for the Canadian Department of Fisheries and the Environment, by Underwood McLellan (1977) Ltd, Winnipeg, Man.

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

Watson, D., 2011. Observation and modelling of ice jam release events on the Hay River, NWT. A thesis submitted to the Faculty of Graduate Studies and Research in partial fulfilment of the requirements for the degree of Master of Science in Water Resources Engineering. Department of Civil Engineering, University of Alberta, Edmonton.

Zhao, L., Hicks, F. and Robinson Fayek, A., 2009. Long Lead Forecasting of Peak Flow during Breakup Using Fuzzy Logic. Proc. 15th CGU-HS CRIPE Workshop on River Ice. St. John's, NFLD.

Zhao, L., Hicks, F., Robinson Fayek, A., Kovachis, N., 2010. Forecasting the Onset of Breakup using Artificial Neural Networks. Proc. 20th IAHR International Symposium on Ice. Lahti, Finland.

Appendices

Appendix A: Consolidation historical records on breakup in Hay River.

This Appendix is a consolidation of all known historical breakup records for the Town of Hay River. All known details of breakup are described year by year from 1894 to 2010. The sources of this information include diaries from the local Anglican and Catholic Missions, consultant reports, EMO files, academic research and newspaper articles.

Appendix A: A Summary of Historical Records of Hay River Breakup[1]

The recorded history of Hay River dates back to 1868, when the Hudson's Bay Company established a fur trading post in the Old Village (Stanley, Grimble and Roblin Ltd. 1959, Harrison 1984 and UMA 1979). A variety of sources allow for a semi-continuous record of breakup events in the Hay River Delta to be established. There is no information on breakup or related flooding in the period from 1868 to 1893 (Gerard and Stanley 1988a and b). Reasons for this gap in the historic record include the closure of the Hudson's Bay Company trading post in 1875 (Stanley *et. al* 1959 and UMA 1979). It was subsequently re-opened in 1895 (UMA 1979). Likewise, St. Anne's Roman Catholic Church was abandoned in 1870, and re-opened in 1900 (UMA 1979).

The continuous historic breakup record begins in 1893, when St. Peter's Anglican Mission was established in the Old Village (Stanley *et al*. 1959, Diamond Jenness 1978, Harrison 1984 and Gerard and Stanley 1988a and b). Gerard and Stanley also report that "since 1894, a relatively continuous record of the dates of breakup in the East channel exists in the form of St. Peter's and St. Anne's Mission diaries. Only for years of significant flooding is there mention of more than the breakup date, and even then it is descriptive in nature". The community at Hay River consisted of these Missions and the trading post until St. Peter's Anglican Mission closed in 1937 (Harrison 1984) and settlement began on Vale Island in 1939 (Stanley *et. al* 1959). The Roman Catholic Mission records (as reported in Stanley *et al.* (1959)) provided records from 1904 to 1947. During the 1940's, the settlement of Hay River underwent rapid changes, with the construction of an airstrip in 1942, and the completion of the Mackenzie Highway in 1948 (Harrison 1984). The development of Old Town begun in the 1940's, and fishing companies established the West Channel Fishing Village in 1948 (Harrison 1984).

---

[1] This compendium of historical information is built on preliminary drafts by Liming Zhao and Fay Hicks.

Since the closure of the Missions, breakup records were obtained from Hay River Emergency Measures Organization (EMO), engineering consultant reports and newspaper articles. These records of spring breakup provide more detail and insight into past breakup events than the Mission diaries' accounts. Complete descriptions of breakup in the Hay River delta were recorded for a number of years ((Stanley *et. al* (1959), Stanley *et. al* (1963), Diamond Jenness (1978), UMA (1978), Jasper (1983), Gerard and Stanley (1988), Wedel (1988), Gerard and Jasek (1990), Gerard *et. al* (1990), Jasek *et. al* (1993) and Jasek (1993)). These reports were typically published following years in which significant flooding occurred and the subject matter and emphasis varied greatly. They could generally be grouped into the following categories:

- Characterization of the Hay River as it pertains to breakup, including:
    - general overviews of the Hay River's basin and channel characteristics;
    - river cross sections and bathymetry surveys;
    - breakup observations; and
    - studies of water temperature variation during breakup.
- The development of ice jam flood forecasting algorithms and procedures, including:
    - breakup flood elevation analyses and hydraulic model calibration;
    - ice jam release event analyses;
    - probability analysis of flood risk; and
    - peak stage prediction during flooding events.
- Flood control mitigation studies, including:
    - channel modification options;
    - ice control structures; and
    - economic analysis of these options.

The documentation of breakup from 1987 to 1993 was performed by researchers from the University of Alberta and supplemented with other reports when possible. Information regarding spring breakup from 1994 to 2003 came from

Hay River's independent weekly newspaper, The Hub. Little supplementary information was available for these years. Breakup monitoring and research efforts by the University of Alberta were resumed in 2004 and continued until 2010.

For all years of record, the available information regarding breakup was detailed in the following document. When possible, all relevant detail and records of breakup were consolidated and reported for all years since 1894. In addition to the qualitative descriptions of breakup presented in the Mission Diaries and the previously mentioned topics of interest in the engineering reports, additional emphasis has since been placed on identifying the severity of flooding, dates of the onset of breakup, peak breakup stage and melt out, and any documentation relating to the progression of breakup upstream of the Town of Hay River.

All ice jam high water marks caused by flooding and profiles available in the historic records were also consolidated in Figures 2.25 and 2.26 of this thesis and listed in Table 1.

Table 1: Available flood profiles in the Hay River delta.

Year	Source
1947	Stanley, Grimble and Roblin, Ltd. (1959)
1951	Stanley, Grimble and Roblin, Ltd. (1959)
1963	Stanley, Grimble and Roblin, Ltd. (1959)
1985	Underhill Engineering Ltd., as reported by Gerard and Stanley (1988a and b)
1989	Gerard and Jasek (1990)
1992	Jasek et al. (1993)
2008	University of Alberta/DIAND
2009	University of Alberta/DIAND
2010	University of Alberta/DIAND

Jasper (1983) provided a range of potential high water mark elevations based on the Mission Records descriptions. Similarly, Gerard and Stanley (1988a and b) surveyed these locations to establish a definitive high water mark elevation. It is important to note that there are difficulties and uncertainties associated with surveying in the delta. This is because this area is located in the zone of discontinuous permafrost (GNWT/IWD 1984). The delta is more susceptible to frost heave, and this often shifts benchmarks, affecting the accuracy of surveyed points. Combined with the qualitative descriptions of breakup in the early records, these profiles and high water marks helped to categorized by flood severity classes of events for years since 1894.

A number of sources report years when significant flooding and some flooding occurred. Gerard and Stanley (1988a and b), Jasper (1983) and Wedel (1988) all report the years when significant flooding occurred in the Hay River Delta. Jasper (1983) and Wedel (1988) also report several years were some overbank flooding occurred (Table 2 on the following page).

In addition to this, Wedel (1988) also included another list noting the eight most significant floods in Hay River: 1904, 1911, 1934, 1947, 1951, 1963, 1974 and 1985. In several instances, there is disagreement between sources regarding the dates of breakup events, the severity of ensuing flooding and the resulting high water marks due to localized flooding. Each of these instances was considered individually once all relevant historic information was gathered and considered.

All known information for each year's breakup is consolidated in the following document. The conflicting historic records are described, as are the assumptions made in selecting the breakup dates and severities for our interpretation of events. Table 2 also reported the years of significant and some flooding as defined by this thesis. Please note that more than 20 years of additional record is available since Jasper (1983), Wedel (1988) and Gerard and Stanley (1988a and b) were published.

Table 2: Years of significant and some flooding, as reported by several sources.

Significant Flooding				Some Flooding		
Jasper (1983)	Wedel (1988)	Gerard & Stanley (1988)	Kovachis (2011)	Jasper (1983)	Wedel (1988)	Kovachis (2011)
	1887				1904	1904
1904		1904		1911	1911	1911
		1911		1923		1923
	1914	1914	1914	1933		1933
1934	1934	1934				1934
		1947		1947	1947	1947
1951		1951	1951		1951	
1963	1963	1963	1963	1952		1952
1974	1974	1974	1974			1957
			1978			1965
		1985	1985			1972
			1986			1979
			1989			1987
			1992			1994
			2003			1997
			2008			2001
						2005
						2007
						2009
						2010

Each individual flood affected the communities that make up the Town of Hay River differently. Jasek *et al.* (1993) reported that the worst flooding occurred in the West Channel Fishing Village in 1985, 1974 and 1992. The three worst ice jam floods on record occurred in East Channel (affecting the Old Village and Old Town) in 1914, 1963 and 1992 (Jasek *et al.*1993). Note that flood protection berms were constructed in the West Channel Fishing Village after the 1992 flood (Gerard and Stanley 1988a and b). The three highest peak stages due to ice jams at the Forks occurred in 1951, 1963 and 1985 (Jasek *et al.*1993).

Ranges of historic breakup dates at Hay River were presented in several of the historic reports. Harrison (1984) suggested the window of breakup in the Town of Hay River to be between 22-Apr and 21-May. Gerard and Stanley (1988a and b) surmised that the average date of the initial ice run to arrive in Hay River (onset of breakup) was 30-Apr, with a standard deviation of five days. GNWT/IWD (1984) found that breakup occurred between 3-Apr and 30-Apr, resulting in a mean breakup date of 16-Apr with a standard deviation of eight days. This was based on inspection of the WSC Hay River gauge hydrographs between 1969 and 1982. The first and second ranges indicated when breakup in the Town of Hay River occurred, while the third referred to the WSC Hay River gauge at *km 1095.2*.

Ranges of historic melt out dates at Hay River were also presented in several of the historic reports. Harrison (1984) suggested that the earliest, average and latest dates that melt outs of any flooding type occurred were 28-Apr, 8-May and 12-May, respectively. The earliest, average and latest dates of melt out reported in Wedel (1988) were 22-Apr, 7-May and 23-Apr. These three ranges show relative commonality. Wedel (1988) also noted that the eight largest floods between 1900 and 1985 (mentioned previously) all experienced ice melting out to the lake between 2-May and 10-May.

The following document contains the consolidated record of all available breakup dates and descriptions from 1894 to 2010.

1894: No flooding

Source: Diamond Jenness (1978) and Gerard and Stanley (1988a and b).

Diamond Jenness (1978) reported that on 9-May, “the ice moved in the river just in front of the house this evening, and on 15-May the ice all moved off this afternoon in front of us (Diaries of St. Peter’s Anglican Mission).” Gerard and Stanley (1988a and b) reported that “records mention the dates of breakup but no significant flooding was recorded.”

1895: No flooding

Source: Diamond Jenness (1978) and Gerard and Stanley (1988a and b).

Diamond Jenness (1978) reported that on 3-May, “the ice in the river broke and moved away today. Water is very low and no force with the ice whatsoever (Diaries of St. Peter’s Anglican Mission).” Gerard and Stanley (1988a and b) noted that “records mention the dates of breakup but no significant flooding was recorded.”

1896: No flooding

Source: Diamond Jenness (1978) and Gerard and Stanley (1988a and b).

Diamond Jenness (1978) reported that on the morning of 11-May, “the ice in the river broke up and moved away (Diaries of St. Peter’s Anglican Mission).” Gerard and Stanley (1988a and b) noted that “records mention the dates of breakup but no significant flooding was recorded.”

1897: No flooding

Gerard and Stanley (1988a and b).

Gerard and Stanley (1988a and b) reported that "records mention the dates of breakup but no significant flooding was recorded."

1898: No flooding

Gerard and Stanley (1988a and b).

Diamond Jenness (1978) reported that on 29-Apr, "the ice broke in the river today the earliest that I have ever seen it as yet (Diaries of St. Peter's Anglican Mission)." Gerard and Stanley (1988a and b) noted that "records mention the dates of breakup but no significant flooding was recorded."

1899: No flooding

Gerard and Stanley (1988a and b).

Gerard and Stanley (1988a and b) reported that "records mention the dates of breakup but no significant flooding was recorded."

1900: No flooding

Source: Diamond Jenness (1978) and Gerard and Stanley (1988a and b).

Diamond Jenness (1978) reported that on 22-Apr, "the ice broke in the river the earliest that I have ever seen it break yet (Diaries of St. Peter's Anglican

Mission)." Gerard and Stanley (1988a and b) noted that "records mention the dates of breakup but no significant flooding was recorded."

<u>1901: No flooding</u>

Source: Gerard and Stanley (1988a and b).

Gerard and Stanley (1988a and b) reported that "records mention the dates of breakup but no significant flooding was recorded."

<u>1902: No flooding</u>

Source: Diamond Jenness (1978) and Gerard and Stanley (1988a and b).

Diamond Jenness (1978) reported that on 13-May, "the river broke (Diaries of St. Peter's Anglican Mission)." Gerard and Stanley (1988a and b) noted that "records mention the dates of breakup but no significant flooding was recorded."

<u>1903: No flooding</u>

Source: Diamond Jenness (1978) and Gerard and Stanley (1988a and b).

Diamond Jenness (1978) reported that on 19-May, "the river broke here (Diaries of St. Peter's Anglican Mission)." Gerard and Stanley (1988a and b) noted that "records mention the dates of breakup but no significant flooding was recorded."

1904: Significant flooding

Source: Stanley et. al (1959), Harrison (1978), Jasper (1983), Wedel (1988) and Gerard and Stanley (1988a and b)

The diaries from St. Anne's Catholic Mission reported that "there was a great flood which covered the point of the East settlement and high waters reached the mission house" (Stanley *et. al* 1959). A copy of notes made from the translation of the Catholic Mission records from French stated that "breakup occurred on 27-Apr to 28-Apr. Great flood, broke fence, covered field to few steps from house, but no water in cellar. The Point flooded to the cemetery. Channel broke on 29-Apr and water dropped, but ice took 15 days to melt" (Blench's notes as reported in Stanley *et. al* 1959).

The following account is taken from the Diamond Jenness (1978) report. "During our first spring, without any foretelling by the locals, for it was April, the cracking of ice awakened all the settlement and in less than two hours the homes were filled with water up to the windowsills. There were great slabs of ice floating in our potato fields and men were paddling skiffs over the top of our garden fence attempting to rescue livestock. To our great relief at about 02:00, and outlet opened in the lake and the water that had steadily been flowing upstream and spreading all over the land, turned to resume its natural course. When daylight came we could see the banks of the river laden with ice and could also see tons of ice and driftwood surrounding our buildings. This made it difficult to go from one house to another, especially to our reserve supply shack where the summer clothes that we had brought in in September were located" (Article by Miss Winona Orr Carruthers who was a teacher at the Residential School from 1903 to 1909).

Also from Diamond Jenness (1978): "On 27-Apr: Yesterday the river opened, the ice going out quietly, with no driftwood. But shortly after midnight the water began to rise fast, the mouth of the river being blocked with ice. By the morning, both banks and a great deal of the Mission clearing were under water and most of the village. The men rescued skiffs and tied them to the house while others cleared the cellars. But at two o'clock in God's goodness, the water began to subside.

On 30-Apr, water was drying fast on shore, but the river bed is a desolate sight full of huge slabs and blocks of ice in a dry muddy channel. On 5-May, water began to appear in the river again and rose to almost its usual level: in a few hours the ice was all gone and the canoes were out (Diaries of St. Peter's Anglican Mission)."

Jasper (1983) reported that on 27-Apr, "the floodwaters rose to St. Anne's Catholic cemetery, and covered the potato fields and gardens. It was deep enough to allow people to paddle over a fence. Much of the Old Village was flooded. The ice jam pushed to the mouth of the East Channel. Peak water levels of 158.7 to 159.3 were reported.

Wedel (1988) classified this year as a noteworthy flood, but not a major one.

Gerard and Stanley (1988a and b) also reported that "on 27-Apr the ice began to breakup in front of St. Peter's Anglican Mission. On 28-Apr, by a.m. both banks and a great part of the mission clearing were under water and most of the village… But by 14:00, the waters began to subside. At St. Anne's Mission, breakup was the 27 or 28-Apr. Great flood, broke fence, covered field to a few steps from the house, but some water in the cellar. The point flooded to the cemetery." The high water elevation was taken as 159.1 m, which was the ground elevation in front of the house steps at St. Anne's Mission.

Stanley *et. al* (1959), Jasper (1983) and Gerard and Stanley (1988a and b) all described significant flood events in 1904. However, the high water marks recorded at the Missions were comparable to 1947, which Jasper (1983) and Wedel (1988) classified as a noteworthy year experiencing some flooding. As such, some flooding (not significant flooding) was considered to have occurred in 1904.

There was some discrepancy in the dates of the onset of breakup and peak stage. Stanley *et. al* (1959), Gerard and Stanley (1988a and b) and Jasper (1983) reported these dates as 27-Apr and 28-Apr, respectively. The Diamond Jenness report noted these dates as 26-Apr and 27-Apr, respectively. This study takes these dates as 27-Apr and 28-Apr, respectively. The date of melt out was reported as 13-May (Stanley *et. al* 1959) and as 5-May (Diamond Jenness 1978, Wedel 1988). Based on the agreement between Diamond Jenness (1978) and Wedel (1988) and the fact that all but one melt out on record occurred within 7 days of the peak stage (not 14 days, as reported in Stanley *et. al* (1959)), the date of melt out is taken to be 5-May.

<u>1905: No flooding</u>

Source: Stanley et. al (1959), Diamond Jeness (1978) and Gerard and Stanley (1988a and b).

Stanley *et. al* (1959) and Gerard and Stanley (1988a and b) and reported that "records only contain breakup dates." The St. Anne's Catholic Mission diaries as reported in Stanley *et. al* (1959) also noted that there were "no other reports of anything remarkable." Diamond Jenness (1978) reported that on 4-May, "the river broke during the night and the ice flowed freely (Diaries of St. Peter's Anglican Mission)."

<u>1906: No flooding</u>

Source: Stanley et. al (1959), Diamond Jenness (1978) and Gerard and Stanley (1988a and b).

Stanley *et. al* (1959) and Gerard and Stanley (1988a and b) reported that "records only contain breakup dates." The St. Anne's Catholic Mission diaries as reported in Stanley *et. al* (1959) also noted that there were "no other reports of anything remarkable." Diamond Jenness (1978) noted that on 26-Apr, "the river broke quietly and ran out (Diaries of St. Peter's Anglican Mission)."

<u>1907: No flooding</u>

Source: Stanley et. al (1959), Diamond Jenness (1978) and Gerard and Stanley (1988a and b).

Stanley *et. al* (1959) and Gerard and Stanley (1988a and b) reported that "records only contain breakup dates." The St. Anne's Catholic Mission diaries as reported in Stanley *et. al* (1959) also noted that there were "no other reports of anything remarkable."

Diamond Jenness (1978) reported that on 12-May, "the river has begun to open at the sides, a little space of water running at the foot of each bank, while above the second island the ice is all broken up. On 21-May, the river opened very quietly (Diaries of St. Peter's Anglican Mission)."

<u>1908: No flooding</u>

Source: Stanley et. al (1959), Diamond Jenness (1978) and Gerard and Stanley (1988a and b).

Stanley *et. al* (1959) and Gerard and Stanley (1988a and b) reported that "records only contain breakup dates." The St. Anne's Catholic Mission diaries as reported in Stanley *et. al* (1959) also noted that there were "no other reports of anything remarkable."

Diamond Jenness (1978) reported that on 8-May, "water began to rise this afternoon and ice came down the river rumbling under the covering and breaking it up. On 9-May, ice in the river moved out very quietly, a little drift wood came down, but not very much (Diaries of St. Peter's Anglican Mission)."

However, a report appended to Stanley *et. al* (1959) mentioned that there was a flood in this year of comparable magnitude to 1951. As there was no report of anything remarkable during this year in the Mission diaries, this thesis reports no flooding in 1908.

<u>1909: No flooding</u>

Source: Stanley et. al (1959), Diamond Jenness (1978) and Gerard and Stanley (1988a and b).

Stanley *et. al* (1959) and Gerard and Stanley (1988a and b) reported that "records only contain breakup dates." The St. Anne's Catholic Mission diaries as reported in Stanley *et. al* (1959) also noted that there were "no other reports of anything remarkable."

Diamond Jenness (1978) reported that on 18-May, "First rain of all the season. Water has been rising and falling in the river, but the ice is still fast. On 20-May, water running quite freely along the river sides, but ice is still firm. On 21-May, water rising rapidly began to crack. Water backing from mouth of river this morning, raining a little. Water looks dangerous, all preparations are made to battle with a flood if it came. This afternoon, ice is beginning to move out. Current is very strong, and much ice is coming this way. The worst is over by 23:00 and the water fell a foot or two. The ice jammed at the mouth of the other branch. This was the cause of the ice and drift wood coming this way (Diaries of St. Peter's Anglican Mission)."

<u>1910: No flooding</u>

Source: Stanley et. al (1959), Diamond Jenness (1978) and Gerard and Stanley (1988a and b).

Stanley *et. al* (1959) and Gerard and Stanley (1988a and b) report that "records only contain breakup dates." The St. Anne's Catholic Mission diaries as reported in Stanley *et. al* (1959) also noted that there were "no other reports of anything remarkable."

Diamond Jenness (1978) noted that on 7-May, "the ice broke in the river at 03:00, and went out very quietly (Diaries of St. Peter's Anglican Mission)."

1911: Some flooding

Source: Stanley et. al (1959), Diamond Jenness (1978), Jasper (1983), Wedel (1988) and Gerard and Stanley (1988a and b).

Diamond Jenness (1978) reported that on 3-May, "at 20:30, the ice in the river began to show signs of going out. Later, it broke up and caused us a good deal of anxiety as it overflowed the bank. On 4-May, the water is still very high in the river and looks quite threatening. The ice is not pushing under the lake ice, but is being forced on top of it and extends fully a mile out on the lake (Diaries of St. Peter's Anglican Mission)." The list of dates of the East Channel clearing reported in Diamond Jenness (1978) noted the date of melt out to be 6-May.

Jasper (1983) noted that breakup initiated in the early morning of 4-May. Limited flooding was reported, as water rose to the fence at St. Anne's Catholic Mission. The range of peak level elevations is from 158.0 to 158.5 m.

Wedel (1988) reported noteworthy, but not severe flooding in 1911. Stanley et. al (1959) noted that there was "no reports of anything remarkable" for this year.

Gerard and Stanley (1988a and b) cited that at 22:30 on 3-May at St. Peter's Anglican Mission, "the ice in the river began to show signs of going out. Later, it broke up and caused us a good deal of anxiety as it overflowed the bank in some places and caused our skiffs to float. The high water elevation was taken as that just over the banks at the Mission: 158.6 m".

The date of onset of breakup is taken as 3-May, as reported by Diamond Jenness (1978) and Gerard and Stanley (1988). This date was chosen as opposed to 4-May (as presented by Jasper (1983)), due to the detailed breakup description available in Diamond Jenness (1978) and Gerard and Stanley (1988a and b).

The descriptions of breakup reported in Jasper (1983), Gerard and Stanley (1988a and b) and Wedel (1988) describe limited overbank flooding. While Stanley *et. al* (1959) reported no flooding, the elevation of flood high water marks provided in both Jasper (1983) and Gerard and Stanley (1988a and b) also support some flooding (not significant flooding) having occurred.

1912: No flooding

Source: Stanley et. al (1959), Diamond Jenness (1978) and Gerard and Stanley (1988a and b).

Diamond Jenness (1978) reported that 13-May was "a very hot day, max 28˚C. Ice in the river melted away, a small quantity only from above, leaving the water quite clear. No rise of water appeared (Diaries of St. Peter's Anglican Mission)."

"This year was recorded as especially mild, with descriptions indicating thermal breakup" (Gerard and Stanley 1988a and b). The St. Anne's Catholic Mission diaries as reported in Stanley *et. al* (1959) also noted that there were "no other reports of anything remarkable."

1913: No flooding

Source: Stanley et. al (1959), Diamond Jenness (1978) and Gerard and Stanley (1988a and b).

The St. Anne's Catholic Mission diaries as reported in Stanley *et. al* (1959) noted that there were "no other reports of anything remarkable."

Diamond Jenness (1978) reported that on 8-May, "the ice went out of the other branch of the river today. On 10-May, the ice melted in the river (Diaries of St. Peter's Anglican Mission)."

"This year was recorded as especially mild, with descriptions indicating thermal breakup" (Gerard and Stanley 1988a and b).

<u>1914: Significant flooding</u>

Source: Stanley et al. (1959), Diamond Jenness (1978), Jasper (1983), Wedel (1988) and Gerard and Stanley (1988a and b).

The St. Anne's Catholic Mission diaries as reported in Stanley *et. al* (1959) reported that "ice jams causing water levels and a flood at the East Settlement which covered the floor of the church. This is the church in the Old Village on the East bank of the main channel." The copy of notes made from the translation of the Catholic Mission records from French stated that "the first push of ice occurred at 03:00 on 30-Apr. Ice jammed, water rose, flood occurred. Church full of water to above floor, water and ice around the house. On 2-May, locals were preparing to leave the community as the flood continued." (Blench's notes as reported in Stanley *et. al* 1959).

Diamond Jenness (1978) reported that on 30-Apr, "water began to rise at about 17:45 and began to rapidly break up the ice and jammed so as to dam up the water. Water rose and overflowed the river banks and flooded a good part of our grounds, it reached nearly to the flag pole. Skiffs were floating about and steamers in the water, but not floating. All was quiet just before midnight, but we were awakened at 02:30 as water rose very quickly and assumed a very threatening aspect. It came into the Mission house, the floors of the dining room, kitchen and girls' play room were flooded half-way across. Children were ordered up and dressed but kept upstairs. Water reached to the stable, then rapidly receded. Water in a menacing condition all day. Steamers and scow pushed about but not crushed or stove in. Our garden fence and most of the other fences were destroyed by the ice. Cannot get to nets and ice and water still threatening as they are on the River banks and half way up to the garden. On 2-May, locals became alarmed as the water again rose high about 05:30 and later in the day they left their houses and went to live on the lake shore. Ice moved out this afternoon, and now all danger is passed (Diaries of St. Peter's Anglican Mission)."

Jasper (1983) cites that breakup began at the Mission on the evening of 30-Apr. "Water overflowing river banks and flooding Anglican Mission grounds. At 02:30 on 1-May, water rose quickly into the Mission house (halfway across the floor) and across the grounds to the stable and fish shed and flooded the Roman Catholic Church above floor level. After the water receded on 2-May, it rose again at 05:30 and then was released as the West Channel broke up [and pushed through to the lake]" (Jasper, 1983). Flooding of the lower parts of the village was reported, and the high water elevations ranged from 158.5 to 159.3 m.

Wedel (1988) reports that significant flooding occurred this year, and that the ice melted out of the East Channel on 2-May.

Gerard and Stanley report that "ice began to push on 30-Apr, with breakup starting early on 1-May. At the Anglican Mission on 1-May, it water came into the Mission house; the floors of the dining room, kitchen and girls' play room were flooded halfway across. Water also reached the stable and then receded" (Gerard and Stanley 1988a and b). Late in the day on 2-May, the ice cleared out of the East Channel. At the Catholic Mission, the church flooded to above the floor and water and ice surrounded the house. Gerard and Stanley (1988a and b) also report that "the high water was estimated as 159.8 m, based on the floor elevation of the Catholic Mission and the ground elevation of the stable area at the Anglican Mission."

Stanley *et. al* (1959), Diamond Jenness (1978), Jasper (1983) and Gerard and Stanley (1988a and b) report slightly different dates of the onset of breakup. While Stanley et. al (1959) reported "the first push of ice occurred at 03:00 on 30-Apr", Diamond Jenness (1978) noted that "ice began to break up on 30-Apr", Jasper (1983) notes that "breakup started in the evening on 30-Apr" and Gerard and Stanley (1988a and b) cite "ice beginning to push on 30-Apr, with breakup beginning early on 1-May". These sources are clearly referring to the same event. The source that Gerard and Stanley (1988a and b) referenced appeared to have begun reporting further into the evolution of breakup. For our purposes, the date of onset of breakup was taken to be 30-Apr.

The elevation of high water estimates provided in Jasper (1983) and Gerard and Stanley (1988a and b) differ. For this thesis, the high water elevation used is 159.8 m as Gerard and Stanley (1988a and b) obtained consistent elevations based on two locations; the floor of St. Anne's Catholic Mission and the ground elevation of the stable at St. Peter's Anglican Mission.

1915: No flooding

Source: Diamond Jenness (1978) and Gerard and Stanley (1988a and b).

Diamond Jenness (1978) reported that on 22-Apr, "ice in the river broke up very quietly and most of it floated out of the river today (Diaries of St. Peter's Anglican Mission)." Gerard and Stanley (1988a and b) reported that "no flooding was recorded in this period (1915 to 1922)."

<u>1916: No flooding</u>

Source: Diamond Jenness (1978) and Gerard and Stanley (1988a and b).

Diamond Jenness (1978) reported that on 2-May, "ice began during last night gradually to move down the river on the other side of the little island. On 3-May, ice left our short of this river this morning (Diaries of St. Peter's Anglican Mission)." Gerard and Stanley (1988a and b) report that "no flooding was recorded in this period (1915 to 1922)."

<u>1917: No flooding</u>

Source: Diamond Jenness (1978) and Gerard and Stanley (1988a and b).

Diamond Jenness (1978) reported that on 14-May, "the ice moved out of the river on Saturday (12-May) with the exception of a little along the shores (Diaries of St. Peter's Anglican Mission)." Gerard and Stanley (1988a and b) noted that "no flooding was recorded in this period (1915 to 1922)."

<u>1918: No flooding</u>

Source: Stanley et al. (1959), Diamond Jenness (1978) and Gerard and Stanley (1988a and b).

The St. Anne's Catholic Mission diaries as reported in Stanley *et. al* (1959) reported that "ice exited from the West Channel and breakup occurred peacefully in the East Channel." The copy of notes made from the translation of the Catholic Mission records from French stated that "Ice block upstream of the island on 7-May and ice went out from the West Channel. The Ice went out peacefully at Mission on 9-May" (Blench's notes as reported in Stanley *et. al* 1959).

Diamond Jenness (1978) reported that on 9-May "the river went out today – pretty tame. River rose quite a lot. Charlie was anxious but all went out safely (Diaries of St. Peter's Anglican Mission)."

"No flooding was recorded in this period (1915 to 1922). In 1918, there is mention in the Mission diary of ice going out on the West Channel on 9-May" (Gerard and Stanley 1988a and b).

Please note that during this period, World War I occurred. Although no flooding was recorded, it could be that there was little focus on local events at this time.

1919: No flooding

Source: Stanley et al. (1959), Diamond Jenness (1978) and Gerard and Stanley (1988a and b).

The St. Anne's Catholic Mission diaries as reported in Stanley *et. al* (1959) reported that "there were no references to ice or flooding. Some of these years (from 1919 to 1931) no records were kept."

Diamond Jenness (1978) reported that on 1-May "ice broke up in the river and very quietly moved out on the other side of the small island this afternoon. On 2-May, ice moved out of our branch of the river going very quietly and slowly today (Diaries of St. Peter's Anglican Mission)."

Gerard and Stanley (1988a and b) noted that "no flooding was recorded in this period (1915 to 1922)."

<u>1920: No flooding</u>

Source: Stanley et al. (1959), Diamond Jenness (1978) and Gerard and Stanley (1988a and b).

The St. Anne's Catholic Mission diaries as reported in Stanley *et. al* (1959) reported that "there were no references to ice or flooding. Some of these years (from 1919 to 1931) no records were kept."

Diamond Jenness (1978) reported that "the ice broke in river on the evening of 15-May. The morning of 16-May was bright. Ice began to move again after the jam of last night. It moved off quietly all day but left large pieces on the river banks from the raise last night (Diaries of St. Peter's Anglican Mission)."

Gerard and Stanley (1988a and b) noted that "no flooding was recorded in this period (1915 to 1922)."

<u>1921: No flooding</u>

Source: Stanley et al. (1959), Diamond Jenness (1978) and Gerard and Stanley (1988a and b).

Diamond Jenness (1978) reported that on 24-Apr, "villagers fearing the flooding of the river have gone to the lake shore. On 25-Apr, river ice began to move out tonight. Water was quite high, it backed up the water pipe into the cellar to a depth of a few inches over the floor. The main body of ice now gone but some remains on 26-Apr. On 27-Apr, the remaining ice moved out of the river except that on shore. We filled ice cellar yesterday (Diaries of St. Peter's Anglican Mission)." Although some flooding was mentioned here, it was due to the water pipe backing up, not overbank flooding. As such, no flooding is said to have occurred in 1921.

The St. Anne's Catholic Mission diaries as reported in Stanley *et. al* (1959) reported that "there were no references to ice or flooding. Some of these years (from 1919 to 1931) no records were kept."

Gerard and Stanley (1988a and b) noted that "no flooding was recorded in this period (1915 to 1922)."

<u>1922: No flooding</u>

Source: Stanley et al. (1959), Diamond Jenness (1978) and Gerard and Stanley (1988a and b).

The St. Anne's Catholic Mission diaries as reported in Stanley *et. al* (1959) reported that "there were no references to ice or flooding. Some of these years (from 1919 to 1931) no records were kept."

Diamond Jenness (1978) reported that on 7-May, "the ice broke up and very quietly moved out during this pm and night (Diaries of St. Peter's Anglican Mission)." The date of the onset of breakup was taken as 7-May, and melt out 8-May.

Gerard and Stanley (1988a and b) noted that "no flooding was recorded in this period (1915 to 1922)."

1923: Some flooding

Source: Stanley et al. (1959), Diamond Jenness (1978), Jasper (1983) and Gerard and Stanley (1988a and b).

The St. Anne's Catholic Mission diaries as reported in Stanley *et. al* (1959) reported that "there were no references to ice or flooding. Some of these years (from 1919 to 1931) no records were kept."

Diamond Jenness (1978) noted that on 29-Apr, "Hunters report ice gone out of other branch of river. On 1-May at 16:00, ice broke up in the river and water overflowed the banks. Only part of the ice moved out, and water remained over the banks on the potato grounds. On 2-May, the water remained high, but no further movement of ice. Some residents left their houses. Water remains high until it rose even more 02:00 on 7-May. Ice jam was close, very swift current. Ice cut away at a great deal of the bank. We shall have to move a house now as it is unsafe so close to the waters' edge. River has dropped this pm and all danger of flood is past.   (Diaries of St. Peter's Anglican Mission)."

Jasper (1983) reported that the West Channel ice broke up on 29-Apr. On 1-May, "the ice broke up around 16:00, jammed and the water rose over the banks on the Anglican potato grounds" (Jasper 1983). No high water elevations were reported for this year.

As reported by Gerard and Stanley (1988a and b), the Anglican Mission diary notes that "hunters report ice gone out of other branch of river" on 29-Apr. This marked the onset of breakup. On 1-May, at "about 16:00, ice broke up in the river and water overflowed the banks... Water remains over the banks on potato grounds. On 4-May, the river was still up even on the banks. By 7-May, the river has dropped this p.m. and all danger of the flood is past. The high water elevation was reported to be 158.8 m, based on the ground elevation at the potato field" (Gerard and Stanley 1988a and b).

Although no flooding was noted in Stanley et al. (1959), Diamond Jenness (1978), Jasper (1983) and Gerard and Stanley (1988a and b) all reported details of some overbank flooding. For the purposes of this thesis, some flooding occurred in 1923.

<u>1924: No flooding</u>

Source: Stanley et al. (1959) and Gerard and Stanley (1988a and b).

The St. Anne's Catholic Mission diaries as reported in Stanley *et. al* (1959) reported that "there were no references to ice or flooding. Some of these years (from 1919 to 1931) no records were kept." Gerard and Stanley (1988a and b) also reported that "no flooding was recorded in this period (1924 to 1931)."

<u>1925: No flooding</u>

Source: Stanley et al. (1959), Diamond Jenness (1978) and Gerard and Stanley (1988a and b).

The St. Anne's Catholic Mission diaries as reported in Stanley *et. al* (1959) reported that "there were no references to ice or flooding. Some of these years (from 1919 to 1931) no records were kept." Gerard and Stanley (1988a and b) reported that "no flooding was recorded in this period (1924 to 1931)." Diamond Jenness (1978) noted that on 6-May, "ice went out of the river (Diaries of St. Peter's Anglican Mission)."

1926: No flooding

Source: Stanley et al. (1959), Diamond Jenness (1978) and Gerard and Stanley (1988a and b).

The St. Anne's Catholic Mission diaries as presented in Stanley *et. al* (1959) reported that "there were no references to ice or flooding. Some of these years (from 1919 to 1931) no records were kept." Gerard and Stanley (1988a and b) reported that "no flooding was recorded in this period (1924 to 1931)."

Diamond Jenness (1978) reported that on 25-Apr, "during this late pm, the ice broke on the river about 3 km south of us and a portion came down a short distance. On 26-Apr, ice broke on the other side of Vale Island and is opening a channel to the lake. During 27-Apr, ice in front of the Mission is showing signs of breaking. Overnight from 28-Apr to 29-Apr: the ice cleared a way through to the lake on our side of the channel this night (Diaries of St. Peter's Anglican Mission)."

1927: No flooding

Source: Stanley et al. (1959), Diamond Jenness (1978) and Gerard and Stanley (1988a and b).

The St. Anne's Catholic Mission diaries as reported in Stanley *et. al* (1959) reported that "there were no references to ice or flooding. Some of these years (from 1919 to 1931) no records were kept." Gerard and Stanley (1988a and b) report that "no flooding was recorded in this period (1924 to 1931)." Diamond Jenness (1978) reported that on 12-May, "the ice slowly moved out of the river this am (Diaries of St. Peter's Anglican Mission)."

1928: No flooding

Source: Stanley et al. (1959), Diamond Jenness (1978) and Gerard and Stanley (1988a and b).

The St. Anne's Catholic Mission diaries as reported in Stanley *et. al* (1959) noted that "there were no references to ice or flooding. Some of these years (from 1919 to 1931) no records were kept." Gerard and Stanley (1988a and b) cited "no flooding was recorded in this period (1924 to 1931)."

Diamond Jenness (1978) reported that on 6-May, "the ice is moving today in the other branch of the Hay River. Three of our staff walked along the lake shore to view it. Also went towards Snye where there is a slight movement of ice. On 8-May, this branch of the river is out about the R.C.M.P barracks. On 9-May, part of the river moves out on side next to Residential School, and on 12-May, the river cleared (Diaries of St. Peter's Anglican Mission)."

1929: No flooding

Source: Stanley et al. (1959), Diamond Jenness (1978) and Gerard and Stanley (1988a and b).

The St. Anne's Catholic Mission diaries as reported in Stanley *et. al* (1959) noted reported that "there were no references to ice or flooding. Some of these years (from 1919 to 1931) no records were kept." Gerard and Stanley (1988a and b) reported that "no flooding was recorded in this period (1924 to 1931)."

Diamond Jenness (1978) noted that on 5-May, "the ice started to move in the river today. It has piled high further up the steep banks. On 12-May, the ice is nearly all out of the river now. A little in a few corners still abides (Diaries of St. Peter's Anglican Mission)."

1930: No flooding

Source: Stanley et al. (1959), Diamond Jenness (1978) and Gerard and Stanley (1988a and b).

The St. Anne's Catholic Mission diaries as reported in Stanley *et. al* (1959) noted that "there were no references to ice or flooding. Some of these years (from 1919 to 1931) no records were kept." Gerard and Stanley (1988a and b) also reported that "no flooding was recorded in this period (1924 to 1931)."

Diamond Jenness (1978) reported that on 30-Apr, "mild and ice rising. On 9-May, the river was out, and on 10-May, the river was quite clear of ice (Diaries of St. Peter's Anglican Mission)."

A list of dates of melt out included in Diamond Jenness (1978) recorded the date of melt out to be between 10-May and 12-May. For the purposes of this study, the date of melt out is taken as 10-May, as per the Anglican diary records.

1931: No flooding

Source: Stanley et al. (1959), Harrison (1978) and Gerard and Stanley (1988a and b).

The St. Anne's Catholic Mission diaries as reported in Stanley *et. al* (1959) noted that "there were no references to ice or flooding. Some of these years (from 1919 to 1931) no records were kept." Gerard and Stanley (1988a and b) reported that "no flooding was recorded in this period (1924 to 1931)."

Diamond Jenness (1978) cited that on 27-Apr, "the river was open at the Forks. On 9-May, the river ice is beginning to go out. Same date as last year. The river has been open above the Forks for several days. On 10-May, ice all out from the river this evening (Diaries of St. Peter's Anglican Mission)." The list of dates of the East Channel clearing reported in Diamond Jenness (1978) recorded the date of melt out as 16-May.

For the purposes of this study, the date of melt out is taken as 10-May, as per the Anglican diary records.

<u>1932: No flooding</u>

Source: Diamond Jenness (1978), Jasper (1983) and Gerard and Stanley (1988a and b).

Diamond Jenness (1978) reported that on 2-May, "the ice began to move in the river. It blocked just above the barracks. It also blocked the main part of the river with the result that the water rose up quickly. We were obliged to haul our boat "the Kingfisher" higher up the bank and also to rescue four large skiffs which were partially submerged. On 3-May, the water rose up to the top of our banks here today, due to a jam at the mouth. Great quantities of drift wood are coming down; the most for years. The main river is nearly cleared now by 20:00. This branch is still blocked. The water sank a couple of feet this afternoon. The top of our wharf was removed (Diaries of St. Peter's Anglican Mission)."

Jasper (1983) did not report any overbank flooding in 1932. On 2-May, "ice broke and jammed above the [Old] Village, backing water up. On 3-May, the jam at mouth [moved to the mouth of the East Channel] and water backed up to top of banks" (Jasper 1983). The high water elevation was reported to be between 157.0 and 157.5 m.

Gerard and Stanley reported that the onset of breakup began at the Anglican Mission on 2-May when "the ice began to move in the river. It blocked just above barracks. On 3-May, the water rose to the top of [the Anglican Mission] banks here today due to a jam at the mouth... The main river is nearly cleared now by 22:00. The high water elevation was taken as 158.5 m at the top of bank at the Anglican Mission." The peak stage and melt out occurred on the same day.

The high water mark surveyed by Gerard and Stanley (1988) is 1 m higher than the one surveyed by the contractor for Jasper (1983).

<u>1933: Some flooding</u>

Source: Diamond Jenness (1978), Jasper (1983) and Gerard and Stanley (1988a and b).

Diamond Jenness (1978) reported that 9-May was "a notable day. The ice in this river began to move from above the Mission Island sometime before 16:00. It being 2.5 ft thick and white and solid at this end, began to gradually break up due to the impact from upstream. By 19:00, the whole started to move towards the mouth. The mist was heavy so that we could not see much of the main river. The river rose over 2 feet so the Mission Island and Vale Island were partly covered. Apparently, little wood came down. We labored all afternoon with the help of Barrack's tackle to pull Cameron's scow clear of the water. We got it up by 17:00 and just in time (Diaries of St. Peter's Anglican Mission)."

Jasper (1983) noted limited overbank flooding in 1933. On 9-May, "ice started to break up around 16:00, and mass movement around 19:00. Water rose to partly cover the Mission and Vale Island" (Jasper 1983). The high water elevations cited in this report were from 157.5 to 158.5 m.

Gerard and Stanley (1988a and b) cited "at the Anglican Mission on 9-May, the ice in this river began to move from above Mission Island sometime before 16:00 … The river rose over two feet so that Mission Island and Vale Island were partly covered. High water elevation was estimated at 158.5 m, the elevation that would cause Mission Island to be partly covered" (Gerard and Stanley 1988a and b).

1934: Some flooding

Source: Diamond Jenness (1978), Jasper (1983), Wedel (1988) and Gerard and Stanley (1988a and b).

Diamond Jenness (1978) reported that "the main river and ice started to move after midnight on 2-May. The water rose steadily during yesterday afternoon. At 02:00, the principal was notified that the river was threatening a dog corral, so all dogs were liberated and a new batch of puppies was rescued. The water was rushing like a rapid over the bank and into the field. The water at the third corral division was knee high. Most were kept away by dogs fighting. The river soon went down again. This morning a great mass of drift logs came down to the mouth. On 5-May, our river bank suffered much this spring by the high, strong current. The old trail between the H.B. yard and the river has disappeared. On this side of the barracks, the same has been affected (Diaries of St. Peter's Anglican Mission)." The list of dates of ice out in the East Channel in Diamond Jenness (1978) also reported 2-May as the date of ice out.

Jasper (1983) reported that breakup began at 02:00 on the morning of 2-May. Overbank flooding (not 'limited overbank flooding') occurred, covering St. Peter's Anglican Mission schoolyard. "The water was knee deep at the third dog corral and dropped quickly" (Jasper 1983). The high water elevation was reported to be 158.5 to 159.0 m.

Wedel (1988) noted major flooding in 1934, and that the ice jam melted out to the lake on 2-May.

Gerard and Stanley (1988a and b) reported that the onset of breakup began at the Anglican Mission on 2-May when "the main river began to move after midnight... the water was rushing like a rapid over the bank into the field. The water at the corral division was knee high. The elevation of the high water was estimated as 158.8 m. This would correspond with knee-high water at the corral."

Although Wedel (1983) reported major flooding in 1934, the water levels were less than during the 1904 flood event, which he considered only "noteworthy" and not "major". Based on the high water mark elevations, the flood severity in 1934 was classified as "some flooding".

1935: No flooding

Source: Diamond Jenness (1978) and Gerard and Stanley (1988a and b).

Diamond Jenness (1978) reported that on 9-May, "the river ice on this side of the Mission Island went out this evening. It started gently moving at about 20:00. The movement was hardly perceptible (Diaries of St. Peter's Anglican Mission)."

Gerard and Stanley (1988a and b) noted that "no flooding was recorded in this period" (1935 to 1946).

1936: No flooding

Source: Stanley et al. (1959), Diamond Jenness (1978) and Gerard and Stanley (1988a and b).

Diamond Jenness (1978) reported that on 7-May, "the ice began to move and to pile up over Bear Island, opposite our wood camp. Elsewhere it is still intact. On 10-May, the ice in the other river went out this morning. During the night of 10-

May and 11-May, our river ice went out quietly. The water was much lower than usual and of very moderate flow. A small amount of drift wood came down (Diaries of St. Peter's Anglican Mission)."

The St. Anne's Catholic Mission diaries as reported in Stanley *et. al* (1959) reported that "breakup started in the West Channel". This disagrees with the Anglican diary record in Diamond Jenness (1978). Gerard and Stanley (1988a and b) noted "no flooding was recorded in this period" (1935 to 1946).

For the purposes of this study, the date of melt out was taken to be 11-May.

<u>1937: No flooding</u>

Source: Stanley et al. (1959), Diamond Jenness (1978) and Gerard and Stanley (1988a and b).

The St. Anne's Catholic Mission diaries as reported in Stanley *et. al* (1959) reported that "breakup started in the West Channel, with considerable rise of water in the East Channel", but made no reference to breakup dates or overbank flooding. Gerard and Stanley (1988a and b) reported that "no flooding was recorded in this period" (1935 to 1946).

Diamond Jenness (1978) recorded that on 27-Apr, "the water is becoming dirty and it shows signs of rising. On 28-Apr, the other river ice went out today. In the early evening, the river rose several feet within an hour and then quickly lowered again. On 29-Apr, there was much piling of ice 800 m up river and in Snye (Diaries of St. Peter's Anglican Mission)." The date of ice clearing in the East Channel was reported as 2-May in Diamond Jenness (1978).

<u>1938: No flooding</u>

Source: Stanley et al. (1959), Diamond Jenness (1978) and Gerard and Stanley (1988a and b).

The St. Anne's Catholic Mission diaries as reported in Stanley *et. al* (1959) reported that "breakup cleared out the West Channel", but made no reference to breakup dates or overbank flooding. Gerard and Stanley (1988a and b) reported that "no flooding was recorded in this period" (1935 to 1946).

Diamond Jenness (1978) reported that on 8-May, "the ice in the river began moving this evening in the main river. On 9-May, the river in front of the school and the center of the main river are open and clear this am (Diaries of St. Peter's Anglican Mission)."

<u>1939: No flooding</u>

Source: Harrison (1978) and Gerard and Stanley (1988a and b).

Diamond Jenness (1978) reported that on 1-May, "the river went out very quietly (melted out). Water very low (Diaries of St. Peter's Anglican Mission)." Gerard and Stanley (1988a and b) noted that "no flooding was recorded in this period" (1935 to 1946).

<u>1940: No flooding</u>

Source: Diamond Jenness (1978) and Gerard and Stanley (1988a and b).

Diamond Jenness (1978) reported that on 29-Apr, "ice piled up in front of docks. On 1-May, the channel opened up about supper time, went out at midnight

(Diaries of St. Peter's Anglican Mission)." Gerard and Stanley (1988a and b) cited "no flooding was recorded in this period" (1935 to 1946).

1941: No flooding

Source: Diamond Jenness (1978) and Gerard and Stanley (1988a and b).

Diamond Jenness (1978) reported that on 29-Apr, "the river went out. Mac fell in it getting a log, but no serious consequences (Diaries of St. Peter's Anglican Mission)." Gerard and Stanley (1988a and b) reported that "no flooding was recorded in this period" (1935 to 1946).

1942: No flooding

Source: Diamond Jenness (1978) and Gerard and Stanley (1988a and b).

Diamond Jenness (1978) reported that on 3-May there was a "raising of water, lot of drift wood at the lake shore, Mission Wharf a bit damaged (personal letter from Father Dessy dated 26-Apr-1978)." Gerard and Stanley (1988a and b) noted that "no flooding was recorded in this period" (1935 to 1946).

1943: No flooding

Source: Diamond Jenness (1978) and Gerard and Stanley (1988a and b).

Diamond Jenness (1978) reported that on 2-May, "ice goes out at night. Morning of 3-May, river cleared, no drift wood at all (personal letter from Father Dessy dated 26-Apr-1978)." Gerard and Stanley (1988a and b) reported that "no flooding was recorded in this period" (1935 to 1946).

1944: No flooding

Source: Diamond Jenness (1978) and Gerard and Stanley (1988a and b).

Diamond Jenness (1978) reported that on 27-Apr, “the river is clear. As last year, no drift wood (personal letter from Father Dessy dated 26-Apr-1978).” Gerard and Stanley (1988a and b) noted that “no flooding was recorded in this period” (1935 to 1946).

1945: No flooding

Source: Diamond Jenness (1978) and Gerard and Stanley (1988a and b).

Diamond Jenness (1978) reported that “sometime after midnight on 18-May, the river cleared leaving edges of ice on each side (personal letter from Father Dessy dated 26-Apr-1978).” Gerard and Stanley (1988a and b) noted that “no flooding was recorded in this period” (1935 to 1946).

1946: No flooding

Source: Harrison (1978) and Gerard and Stanley (1988a and b).

Diamond Jenness (1978) reported that “during the 2-May, river free of ice (personal letter from Father Dessy dated 26-Apr-1978).” Gerard and Stanley (1988a and b) reported that “no flooding was recorded in this period” (1935 to 1946).

Note that during this period (1935 to 1946), the Great Depression ended and the Second World War occurred. Although no flooding was recorded, it could be that there was less focus on local events during this time.

1947: Some flooding

Source: Stanley et al. (1959), Diamond Jenness (1978), Jasper (1983), Wedel (1988) and Gerard and Stanley (1988a and b).

Stanley *et. al* (1959) reported that “There were high waters with an ensuing moderate flood alarm. The partially completed fill in the West Channel was washed out. This fill was begun in 1946 and filled to road grade later in 1947, remaining intact until 1951.” The copy of notes made from the translation of the Catholic Mission records from French stated that there was a “moderate scare at the Mission, with water half-way up the house. The flood washed out the fill in the West Channel. No noteworthy at Mission however, and the breakup was relatively uneventful” (Blench’s notes as reported in Stanley *et. al* 1959).

Diamond Jenness (1978) reported that on 7-May “at 3:30, I was called by someone. Water raises rapidly on the shore and gradually stops. Heard during the day that the D.O.T camp was flooded and that the fill at the junction of the river and West Channel had been washed out by the current. In the evening, we hear the breakup along the West Channel. On 10-May, around 04:00, the river gradually freed from ice, but with strength and water coming up. People started fearing flood. Fortunately, an opening formed at the mouth of the river leaving way to the torrent of water that pushed the ice on each shore and brought an abundance of drift wood. It was a nice breakup (personal letter from Father Dessy dated 26-Apr-1978).”

As reported by Jasper (1983), “jamming caused water to rise rapidly at 03:30 on 7-May. Breakup occurred in the West Channel, and the fill at head of Vale Island washed out. (“Fill D” becomes the West Channel Bridge in 1963).   On 10-May, ice is running in the East Channel around 04:00, but the jam at the mouth of the channel backed water halfway up to St. Anne’s Catholic Mission house before the jam released.” The limited overbank flooding was reported to have reached elevations of 158.4 to 159.0 m.

Wedel (1988) reported that breakup in 1947 caused less severe, but still noteworthy flooding. The same report also called 1947 one of the eight most significant breakup floods on record. Wedel (1983) reported that the ice jam melted out to the lake on 10-May.

Gerard and Stanley (1988a and b) described the 1947 breakup events as follows:

“In 1946, fills “A” (km 1110.2), “B” (km 1109.9), “C” (km 1109.4) and “D” (across the West Channel) were placed across the channels between islands to carry the road from the mainland onto Island C. It was not until the summer of 1947 that they were raised to their design heights. “It was understood that these fills were merely built to a height and width sufficient to allow machinery and motor vehicles to cross and were in all cases much lower than they were finally built” (Douglas 1952 as reported in Harrison 1978). Water levels over-topped these fills early in the breakup. Water levels were high during breakup but no significant flooding took place as no permanent building was damaged. At the Catholic Mission there was a moderate scare at Mission, with water halfway to house. No noteworthy damage at Mission however, and the breakup was relatively uneventful”.

Peak water level elevations were 161.6 m at the Forks and 158.9 m at the mouth of the East Channel (Gerard and Stanley 1988a and b). A profile of high water levels was given Stanley, Grimble and Roblin Ltd. (1959) as shown in Figure 2.25 and 2.26 of this thesis.

1948: No flooding

Source: Diamond Jenness (1978) and Gerard and Stanley (1988a and b)

Diamond Jenness (1978) reported that on 9-May, "ice moved up the river, they say. On 10-May, roaring of ice up the river is heard. Ice still solid in front of the Old Village. On 11-May, breakup. All went calmly, not a piece of driftwood. Water very low, it happened during forenoon (personal letter from Father Dessy dated 26-Apr-1978)." A list of dates of melt out reported in Diamond Jenness (1978) also recorded the date of melt out to be 9-May.

"No flooding was experienced in these periods (1948 and 1949). Fill "D" (across the West Channel) was at an elevation of 163.9 m and was not overtopped at any time in these years. In this period blasting of the ice was done to minimize flooding. The exact location of blasting in 1948 was not recorded (Douglas 1952 from Harrison 1978)" (Gerard and Stanley 1988a and b).

For the purposes of this study, what was described in the letter from Father Dessy as reported in Diamond Jenness as "breakup" on 11-May was taken as the ice jam melting out.

1949: No flooding

Source: Diamond Jenness (1978) and Gerard and Stanley (1988a and b)

Diamond Jenness (1978) reported that the "river opens up in the middle in the morning of 3-May and is gradually cleared of ice during the day. All went quietly. Next day, river all cleared and water raising (personal letter from Father Dessy dated 26-Apr-1978)."

"No flooding was experienced in these periods (1948 and 1949). Fill "D" (across the West Channel) was at an elevation of 163.9 m and was not overtopped at any time in these years. In this period blasting of the ice was done to minimize flooding. The exact location of blasting in 1949 was from km 1108.8 to km 1111.0 in the East Channel (Douglas 1952 from Harrison 1978)" (Gerard and Stanley 1988a and b).

<u>1950: Some Flooding</u>

Source: Stanley et. al (1959), Diamond Jenness (1978) and Gerard and Stanley (1988a and b).

Stanley *et. al* (1959) reported that "Some slight flooding occurred. Blasting of river ice in the East Channel was carried out." The copy of notes made from the translation of the Catholic Mission records from French stated that the "ice was fairly high on shores, some kind of boat scaffold on the opposite shore was smashed" (Blench's notes as reported in Stanley *et. al* 1959).

Diamond Jenness (1978) reported the same account, in addition to "on 4-May the river broke up to the bend at Yellowknife Transportation Co. Water and ice crossed the Department of Fisheries fill and moved in around the powerhouse and residence. On 7-May, the river broke through at the mouth at 01:30 and is back to normal (Hay River File, Emergency Measures Organization, Yellowknife)".

Gerard and Stanley (1988a and b) noted the following: "No significant flooding took place in this year but a detailed account of breakup was recorded in a "Memorandum for the Chief" by Douglas (1951) in Harrison (1978). Blasting operations began on 21-Apr and continued to 25-Apr when flow increased considerably. Two rows of blast holes were completed from km 1108.8 to km 1111.0 (close to the downstream end of Island CD).

At midnight 2-May the first rush of ice came, breaking ice to *km 1111.0*, where the toe of the jam formed. Fill "D" had a 4 ft (1.22 m) freeboard (water elevation 162.68 m), and at Fill "B" the water level was 160.99 m. The jam remained in place until early 7-May when the river opened right through to the lake, where the ice jammed again for about one hour causing the water to rise and flood that section of the town between the main street and the river (water elevation 158.5 m). The report also states that runoff was probably more than that of 1947". Both the peak stage due to breakup and the ice jam melting out occurred on 7-May.

Gerard and Stanley reported the onset of breakup occurring on 2-May, while Diamond Jenness (1978) reported the same event occurring on 4-May. As both records were detailed, this conflict in dates was not resolved. For the purposes of this thesis, the date of onset of breakup was not reported for 1950.

<u>1951: Significant flooding</u>

Source: Stanley et. al (1959), Diamond Jenness (1978), Jasper (1983), Wedel (1988) and Gerard and Stanley (1988a and b).

Stanley *et. al* (1959) reported that "the fill across the West Channel was still constructed to highway grade level. With a large spring runoff and a rapid breakup, combined with rain, a serious flood happened. Water almost reached the Mission house again [despite it being relocated to higher ground in 1917 (personal communications with Dr. David Harrison in 2011)]. The airport was flooded and out of commission, and the downtown part of Hay River was under water. The Mackenzie highway in the town site was washed out in several places." The copy of notes made from the translation of the French Catholic Mission records stated that the "On 1-May, there was lots of water in the river. On 3-May, heavy rain caused currents on the ice. On 4-May, there was some lifting of ice upstream, but firm at the Mission. This made the locals fear on account of its resistance. There was yelling at 21:00 and roaring noises from the river. Ice yielded somewhat on opposite the shore, but stopped again because of the ice in the mouth of the river. All was quiet on 5-May, but at 02:00 on 6-May, the water rose and receded. At 04:00, the jam shoved again. On 7-May, ice still drifting, water dropping, leaving high piles of ice. News that town flooded and a man drowned at the airport" (Blench's notes as reported in Stanley *et. al* 1959).

Diamond Jenness (1978) reported that on "23-Apr, the river broke and jammed to night and spilled over the Department of Fisheries fill. Considerable damage done, and one life lost. Airport flooded, all low spots in town under water. Flooded Hotel. On 26-Apr, the river broke at the lower end, bend in the river at Yellowknife Transportation Co. spilling ice all the way down the highway to Menzies plant. On 1-May, lots of water. 3-May heavy rain of previous day caused currents 10 m wide on the ice each side. On 4-May, some lifting of ice upstream, but firm at Mission. This made residents fear on account of its resistance. Yelling at 21:00 and roaring noises from the river. Ice yielded somewhat on opposite shore, but stopped again because of resistance. On 5-May, all quiet, and at 16:00, big discharge of ice. On 6-May at 02:00 water is reported 10ft from the house, but it receded. At 04:00, big jam starts to move – estimated at 25 mph. Water again 10 ft from house, recedes again. On 7-May, ice still drifting, water dropping, leaving high piles of ice (Stanley *et. al* 1959)". The list of dates of ice clearing in the East Channel noted this occurring on 6-May (Diamond Jenness 1978).

Jasper (1983) reported the following: "On 23-Apr, flooding occurred near the Fisheries fill. On 26-Apr, ice broke near the mouth of the river (YK Transportation Co. to Menzies Fish Plant). Heavy rain on 3-May opened shore leads. The main river breakup began around 21:00 on 4-May. Flooding occurred in Old Town and car horns were heard honking. The morning of 5-May was quiet, however the mail plane was unable to land at the airport at 14:00 as most of the NW-SE runway was flooded (up to 1.2 m in depth). The NE-SW runway was barely touched."

"At 02:00 on 6-May, flood waters rose to within 5 m of St. Anne's Catholic Mission. Water rose again at 04:00 (until it was 3 in away from Mission) and then receded. Most of the Old Town was flooded, and one man drowned. By 7-May, ice moved away and water dropped" Jasper (1983). This resulted in major flooding in Old Town and high water elevations of 158.5 to 159.0 m in the Old Village and 159.0 to 160.0 m in the Old Town.

Wedel (1988) listed the 1951 event as noteworthy, but not severe. However, it is also listed in Wedel (1988) as one of the eight most significant floods on record, with melt out occurring on 6-May.

Gerard and Stanley (1988a and b) contained the following description of breakup in 1951. "In 1951 no blasting was done prior to breakup. Breakup initiated on 3-May, with the ice breaking down to km 1110.7 (Island D). Water began to flow over the west Channel Fill "D" late on 4-May. This was the peak flood level in the airport vicinity. Water was flowing to a depth of 1.22 m over the runway."

"By early morning on 5-May, water was flowing over both river banks along the whole East Channel, from the East-West Channel split to the mouth of the East Channel. One man was drowned. Water going over the airport was flowing over the West Channel road over a length of some 3 km. Then, at about 03:30 on 6-May a new rush of ice and water came down the river and the East Channel jam broke through to the lake. The river cleared on 7-May" (Gerard and Stanley 1988a and b).

The melt out date was listed as 6-May in Wedel (1988) and Harrison (1978), rather than 7-May, as in Stanley *et. al* (1959), Diamond Jenness (1978), Jasper (1983) and Gerard and Stanley (1988a and b). For the purposes of this study, the date of melt out is taken as 7-May, due to the detailed description of breakup provided in Stanley *et. al* (1959), Diamond Jenness (1978), Jasper (1983) and Gerard and Stanley (1988a and b).

Peak water levels were taken as 164.0 m at the East-West Channel split and 158.7 m at the East Channel mouth (Gerard and Stanley 1988a and b). Stanley *et al.* (1959) provided a high water level profile, which is detailed in Figures 2.25 and 2.26 of this thesis. Gerard and Stanley (1988a and b) also report that "it is evident that these [high water levels] were generated by a jam with the toe located some distance upstream of the mouth. This probably limited the flooding that could have occurred in the town, as this last move was the feared one as in other years; the ice has always jammed at the lake. This was the jam which we wished the Royal Canadian Air Force would stand by for, and were very lucky that it didn't happen. Every building in the settlement would have flooded."

<u>1952: Some flooding</u>

Source: Stanley et. al (1959), Diamond Jenness (1978), Jasper (1983) and Gerard and Stanley (1988a and b).

Stanley *et. al* (1959) reported that "very little flooding occurred, water just over bank at the Mission".

Diamond Jenness (1978) reported that on "25-Apr, the river broke up down to Island above Mission Island. On 27-Apr, the river jammed at mouth flooding the flats from Hudson's Bay to mouth and entering Hotel. On 29-Apr, the jam broke during the night and river back to normal (Hay River File, Emergency Measures Organization, Yellowknife)".

Jasper (1983) described the river jamming at the mouth on 27-Apr. Subsequently, this "flooded the Old Town from the Hudson's Bay Company flats to the mouth. Water was flush with the banks at the Old Village. On 28-Apr, water rose as ice runs arrived from upstream. The jam broke on 29-Apr and the water receded." This resulted in limited flooding in the Old Village, with high water marks ranging from 157.6 to 158.1 m.

Gerard and Stanley (1988a and b) reported that "because of the flooding in 1951, an extensive blasting program was undertaken in the spring of 1952. The East Channel was blasted from km 1108.8 to the mouth, almost 5 km. Five pound charges were placed in 3 lines across the channel, with 75 feet from line to line and the holes 60 feet apart on each line. It was found as work progressed upstream that only 2.5 pound charges were needed. In total some 700 holes were blasted.

"The river began to breakup on 25-Apr. On 27-Apr, the toe of the jam was just upstream of Island A (km 1112.3). At the East-West Channel split the water reached a level of 162.8 m and at Fill "C" it reached 161.6 m. On 28-Apr this jam broke and the toe moved to the mouth of the East Channel. This peak stage caused minor flooding at the Hay River Hotel and Menzies Fish Company (near the mouth of the East Channel). By the afternoon of 28-Apr the ice was out of the East Channel.

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

There was some disagreement between Diamond Jenness (1978), Jasper (1985) and Gerard and Stanley (1988a and b) regarding the date of the onset of breakup. Jasper (1985) listed this date as 27-Apr, while Diamond Jenness (1978) and Gerard and Stanley (1988a and b) have documented 25-Apr, with the jam shoving to the mouth of the river on 27-Apr. Typically, the onset of breakup did not result in an immediate jam in the mouth of the East Channel, as Jasper (1983) reported. The jam usually formed and pushed to this location as a secondary event. It is also possible that breakup events occurred upstream of the Missions in advance of breakup being observed there. For the purposes of this thesis, 25-Apr was the reported date of onset of breakup.

Diamond Jenness (1978) and Jasper (1985) noted that the jam broke on 29-Apr. This was not the same event as an ice jam melting out. Gerard and Stanley (1988a and b) reported that the East Channel was clear on 28-Apr, which disagreed with Diamond Jenness (1978) and Jasper (1985). For the purposes of this thesis, the date of melt out was not reported due to this conflict.

1953: No flooding

Source: Stanley et. al (1959), Diamond Jenness (1978) and Gerard and Stanley (1988a and b).

Stanley *et. al* (1959) reported that "breakup conditions were very good, and little runoff appeared. Fill D across the West Channel had been lowered and some water overtopped the fill and flowed down the West Channel".

Diamond Jenness (1978) reported that on "29-Apr, the river was very low and rotten out clearing through the mouth this late evening (Hay River File, Emergency Measures Organization, Yellowknife)".

Gerard and Stanley noted that "breakup in 1953 was very quiet. From the descriptions available it was probably a thermal breakup: On 29-Apr, the "river was very low and rotted out clearing through this late evening" (EMO File). This was considered the melt out day, as no dynamic breakup was evident. The West Channel Fill "D" was lowered in the fall of 1952. Even at this low level water did not flow over it. The high water mark elevation at the Forks was documented as 158.2 m (MacQuarrie 1954 as reported by Harrison 1978)".

1954: No flooding

Source: Stanley et. al (1959), Diamond Jenness (1978) and Gerard and Stanley (1988a and b).

Stanley *et. al* (1959) reported that "the fill at the West Channel was maintained at a low level and a considerable amount of water passed over it, and it finally washed out." Also, the "West Channel went out on 13-May and the East Channel went out on 15-May" (Blench's notes as reported in Stanley *et. al* 1959).

Diamond Jenness (1978) reported that on "22-May, you will be happy to know that we had no flood at all after our expectations. The water went over the big fill on Thursday morning. On Thursday morning (18-May), all the river ice went out of the West Channel and left no current to push the ice out of the East Channel. On Sunday morning, an unexpected current came down however, and moved ice out. By Monday morning, the river was free except for a few straggling cakes" (personal letter from Miss Eileen Ramsay). "On 12-May, water and ice crossed the main fill late this evening, and on 13-May, the river was back to normal this late evening" (Hay River File, Emergency Measures Organization, Yellowknife). As these dates do not correspond with the days of the week in 1954, and are not in logical order, this record will not be considered. The list of dates of East Channel clearing reported that this occurred on 17-May (Diamond Jenness 1978).

The following account of breakup was taken from Gerard and Stanley (1988a and b).

"Prior to breakup, the East Channel was blasted from the upstream end of Island B (km 1111.5) to the mouth. Breakup began on the night of 11 to 12-May, when the stage at the West Channel fill increased by 2.75 m (Ross 1954 as reported by Harrison 1978). This increase in stage broke the ice up to the upstream end of Island B (km 1111.5), where the toe of a jam formed. During the night of 12 to

13-May, the river rose another 2.4 m at Fill “D”' and reached a peak stage of 161.9 m, at which point 2.1 m of water was flowing over the fill. This water level remained relatively constant until 15-May. During this period, the toe of the jam in the East Channel remained in place. On 16-May, the river began to clear and the ice was reduced in volume by breaking and melting to about a quarter mile in length at the mouth of the river (Ross 1954 as reported by Harrison 1976).

The West Channel fill was completely washed out. The first rush of water after the fill was over-topped fanned ice and water over the lake ice at the mouth of the West channel, due to the latter being frozen to the bottom. A cross section was taken on the West Channel approximately 400 m downstream of the fill on 14-May. Surface floats were placed on the water and were observed travelling at 1.9 m/s. From this, Ross (1954) estimated a discharge of 453 m^3/s in the West Channel by assuming that the actual velocity was 80% of the surface velocity, allowing for dead water and using the measured area of the channel. Similarity, discharge in the East Channel was estimated to be at least 700 m^3/s and perhaps as high as 1,400 m^3/s. No actual measurements were done in the East Channel. No flooding occurred at the mouth of the East Channel.” Although there was much discussion on the low-level fill washing out, there was no mention of overbank flooding.

A list of dates of melt out reported in Diamond Jenness (1978) recorded the date of melt out as 17-May, which agreed with Gerard and Stanley (1988a and b), noting that on 16-May a 400 m stretch of ice jam remained in the mouth of the East Channel.

1955: Some flooding

Source: Stanley et. al (1959), Diamond Jenness (1978), Wedel (1988) and Gerard and Stanley (1988a and b).

Stanley et. al (1959) reported that "minor flooding occurred. The West Channel ice moved out and the East Channel ice rotted."

Diamond Jenness (1978) reported that on 30-Apr, "water an ice crossed the fill this evening. On 7-May, the fill was repaired and traffic was moving again (Hay River File, Emergency Measures Organization, Yellowknife". Also in Diamond Jenness (1978), "you will be interested to know that breakup is over and we have not had a flood. The water went over the fill on 1-May and washed the highway out taking most of the ice out of the West Channel. The ice broke at the mouth in front of the Mission on 5-May and was all clear by the next morning. There was no flood water at all on the island, for which the people were very thankful" (personal letter from Miss Eileen Ramsay).

Gerard and Stanley (1988a and b) reported that "little information could be found on breakup for this year. The only account was a letter by Miss E. Ramsey, a school teacher at St. Peter's Mission: "The water went over the fill on 1-May and washed the highway out taking most of the ice out the West Channel. The ice broke at the mouth in front of the Mission 5-May and was all clear by the next morning. There was no flood water at all on the Island. Water levels at the fill must have been higher than 159.8 m, the height of the fill at this time.

From this account, the onset of breakup and peak stage ice jam occurred on 1-May. Wedel (1988) noted that the river was clear on 11-May, while the list of dates of East Channel in Diamond Jenness (1978) reported the date of melt out to be 6-May, which agreed with the account of E. Ramsay. Some flooding occurred (based on Stanley *et. al* (1959)). Although Gerard and Stanley (1988a and b) quoted Miss E. Ramsay as saying no flooding occurred on the Island, flooding could still have occurred in the Old Village.

1956: Some flooding

Source: Stanley et. al (1959), Diamond Jenness (1978), UMA (1979) and Gerard and Stanley (1988a and b).

Stanley et. al (1959) reported that "Fill D (in the West Channel) was washed out. There was no serious flooding in the town site area." Appended to this report was a description of breakup done by an engineer at Stanley, Grimble and Roblin Ltd. The following is taken from this description:

On 1-May, water was running over the full width of Alexandra Falls, and freely downstream of the falls. During the night, ice shoved down to Fill D and into the East Channel. On 4-May and 5-May, the river continued to move swiftly down the East Channel with water disappearing under the ice. During the morning of 6-May, the water at Fill D fluctuated up and down. Ice around the fill itself which had previously remained in one piece began to break due to the rise and fall of the water, indicating that the jam upstream was beginning to break. By 14:30, the river had become filled with ice, which indicated that the jam had broken loose. The ice limit in the East Channel had by this time been shoved downstream to a point opposite the middle of Island D. A new height of water was reached on 7-May. By 09:30, the ice below the Fill in the West Channel broke free and moved out towards the lake. In the afternoon of 8-May, the West Channel was clear of ice to the mouth, while the jam in the East Channel was still holding. During the afternoon of 9-May, water levels dropped rapidly. On 11-May, the ice jam in the East Channel appeared solid, but was deteriorating fast. On the morning of 13-May, the East Channel was observed to be free of all ice.

Diamond Jenness (1978) reported that on 6-May, "the river crossed outer fill today, and on 11-May, the fill is back in and traffic moving" (Hay River File, Emergency Measures Organization, Yellowknife).

As documented in Gerard and Stanley (1988a and b), a blasting program was started in late April, 1956. "The East Channel was blasted from the downstream tip of Island B (km 1112.2) to the DPW docks (km 1113.3). Because of warm weather blasting of the rest of the channel to the mouth could not be completed but the lake ice was blasted in a fan shape at the mouth (Harriot 1956 as reported in Harrison 1978)" (Gerard and Stanley 1988a and b).

"During the night of 2 to 3-May, river ice broke up to km 1108.9. It was observed that on 3-May no ice was left on the river from Alexandra Falls to the jam in the town. On the 4-May and 5-May, little change occurred in the conditions. On 6-May, the jam pushed and a new toe was formed at the middle of Island D (km 1111.0). The West Channel Fill "D" was overtopped and the water level reached a peak stage of 161.0 m. The toe of the jam remained at km 1111.0 while the pack slowly melted in place. It was not until 13-May that the river was completely free of ice." The list of dates of the East Channel clearing reported in Diamond Jenness (1978) confirmed this date of melt out.

UMA (1979) contained a water surface profile for this flood, as reported by Gerard and Stanley (1988a and b).

The dates of onset of breakup and peak stage presented in Stanley *et. al* (1959) (2-May and 7-May, respectively) disagree with those noted in Gerard and Stanley (1988a and b) (2-May and 6-May, respectively). Both reports appeared to be describing the same event, however Stanley *et. al* (1959) contained a more detailed descritpion. As such, the dates of onset of breakup and peak stage were taken as 2-May and 7-May, respectively.

1957: Some flooding

Source: Stanley et. al (1959), Diamond Jenness (1978), Jasper (1983) and Gerard and Stanley (1988a and b).

Stanley *et. al* (1959) reported that "local residents remember 1957 as a year with very high discharge during breakup. Water overflowed and caused some damage to Fill D, and also overflowed Fills A,B, and C, causing some flooding." Appended to this report was a description of breakup done by an engineer at Stanley, Grimble and Roblin Ltd. The following is taken from this description:

Water began flowing over Fill D on 29-Apr, with ice following on 30-Apr. On 3-May, the original ice held from the mouth of Hay River to the Government Wharf. There was no water in the town site, although the fisheries staff house had 15 cm on 1-May. A surge at 19:00 cast ice on and water over Fill C. Plans to dynamite the intact ice were underway. On 2-May, water ran over all fills, the Government Wharf, the transportation shipyards, and 50% of the short runway. Minor flooding occurred in the West Channel Fishing Village in the afternoon, but receded shortly after. Ice runs occurred all day, causing minor flooding in most locales, almost flooding the Warden Station, just flooded road at wharf and Signal's Corner. The majority of river side of road from Signal's to the river mouth flooded, but not over the road. Water receded from fills in the morning of 3-May, and the river mouth was clear of ice by the morning of 4-May.

Diamond Jenness (1978) reported that on 28-Apr, "water crossed outer fill this am. On 3-May, water crossed the Department of Fisheries Fill. On 4-May, ice jammed at the mouth of the river and pushed M.V. Landa off cradle" (Hay River File, Emergency Measures Organization, Yellowknife). This description seemed to only report patches of the breakup events recorded in Stanely *et. al* (1959). A list of dates of the East Channel clearing reported in Diamond Jenness (1978) recorded the date of melt out as 6-May.

Jasper (1983) recalled that on 1-May, “the fisheries staff house has 0.15 m of water in it. On 10-May, the jam causes flooding up to 1.2 m at the Government Docks and YK Transportation Co. shipyards and over half of the short airport runway. Minor flooding occurred in the West Channel, as well as near the Fisheries fill. On 11-May, the road flooded at Sharf and Signal’s Corner. The river-side of the road flooded from Signal’s Corner to the mouth of the East Channel. Water levels were in excess of 160.3 m at Fill “D” (now the West Channel Bridge).”

Gerard and Stanley (1988a and b) reported that “water began to flow over Fill “D” early on 29-Apr. In the East Channel, ice broke to the downstream end of Island D, where the toe of a jam formed. On 3-May, blasting was done on the solid ice below the toe, from km 1112.4 to the mouth of the channel. Water levels at Fill “D” reached a peak on 3-May with a level of 161.1 m. This elevation was obtained from the description that water was flowing over the fill at a depth of approximately 2.4 m (Anonymous (1957) as reported in Harrison (1978).

“On 5-May, some minor flooding occurred in the West Channel. Late on 6-May the jam in the East Channel began to move downstream. Water just reached the road at Royal Canadian Corps of Signals Corner (km 1112.4), an elevation of 158.7 m. By 7-May, the river was clear” (Gerard and Stanley 1988).

There was some disagreement in breakup accounts between Stanley *et. al* (1959), Jasper (1983) and Gerard and Stanley (1988a and b). For the purpose of this thesis, breakup dates described in the Report for Spring Breakup as described in Stanley *et. al* (1959) (D_o = 30-Apr, D_p = 2-May and D_m = 4-May) were used, and some flooding occurred.

1958: No flooding

Source: Stanley et. al (1959), Diamond Jenness (1978) and Gerard and Stanley (1988a and b).

Appended to Stanley *et. al* (1959) report was a description of breakup done by an engineer at Stanley, Grimble and Roblin Ltd. The following is taken from this description:

Blasting operations took place from 13-Apr to 22-Apr, when the onset of breakup occurred in the Hay River delta. Water which had been rising all day began to spill over and washed out the top portion of the West Channel Fill. The mouth of the West Channel jammed around midnight, but the water levels dropped such that no flooding occurred. On the afternoon of 23-Apr, ice runs arrived from an ice jam release upstream and pushed clear through to the lake. Fills C and D were overtopped and D was washed out. On 30-Apr, the water level at Fill D dropped.

Diamond Jenness (1978) reported that on 22-Apr, "ice and water crossed outer fill today, and on 30-Apr the fill is back in and traffic moving once more" (Hay River File, Emergency Measures Organization, Yellowknife). The list of dates of East Channel clearing in Diamond Jenness (1978) also reported the channel clearing on 30-Apr.

According to Gerard and Stanley (1988a and b), "much work was done in 1958 prior to breakup. A pressure ridge had formed 800 m to 1200 m offshore opposite the West Channel. This ridge was about 3.7 m high and ran parallel to the shore (Harriot 1958 as reported in Harrison 1978). In the East Channel a 9 m wide strip was blasted from km 1111.0 to the mouth".

Breakup began on 22-Apr, as "water began to rise and by midnight a jam had formed at the mouth of the West Channel. No flooding occurred in that area.

Early on 23-Apr, the discharge dropped, probably because of an upstream jam. That afternoon, a large surge of ice and water arrived in the delta, breaking the jam in the West Channel and moving the ice out onto the lake. This surge created the peak stage, and also broke up the East Channel to the downstream end of Island D, where a jam formed. The toe stayed in this location until 30-Apr when the ice moved out into the lake. No flooding occurred in East Channel (Gerard and Stanley 1988a and b)."

<u>1959: No flooding</u>

Source: Diamond Jenness (1978) and Gerard and Stanley (1988a and b).

Diamond Jenness (1978) reported that on 12-May, "the river is clear of ice down to the Department of Fisheries this evening. On 14-May, river cleared to mouth and did not go over fill" (Hay River File, Emergency Measures Organization, Yellowknife).

Gerard and Stanley (1988a and b) reported that "breakup was very mild, with no water going over the West Channel fill (EMO Files)."

<u>1960: No flooding</u>

Source: Harrison (1978) and Gerard and Stanley (1988a and b).

Diamond Jenness (1978) reported that on 24-Apr, "at 20:30, water and ice crossed the outer fill. On 1-May, the fill is completed and traffic is moving again" (Hay River File, Emergency Measures Organization, Yellowknife). The date of ice clearing in the East Channel was also listed as 1-May

Gerard and Stanley (1998a) documented that “breakup started on 24-Apr with the water and ice going over Fill “D”. To be conservative, this was taken as having an elevation greater than 160.5 m. The river was completely clear by 1-May (EMO File). No mention of significant flooding could be found.”

<u>1961: No flooding</u>

Source: Diamond Jenness (1978) and Gerard and Stanley, 1988a

Diamond Jenness (1978) reported that on 8-May, “ice and water spilled over the outer fill. On 12-May, water dropped late this evening. On 13-May, the fill is replaced and traffic is moving again” (Hay River File, Emergency Measures Organization, Yellowknife). The date of ice clearing in the East Channel was also listed as 12-May.

As reported by Gerard and Stanley (1988a and b), “breakup began as ice and water began to spill over Fill "D" on 8-May. By 12-May, the river was clear of ice (EMO File). The peak water level was taken as greater than 160.5 m.”

<u>1962: No flooding</u>

Source: Diamond Jenness (1978) and Gerard and Stanley (1988a and b).

Diamond Jenness (1978) reported that on 30-Apr, “Hay River broke up from Mile 8 to its headwaters as we flew the entire river this day” (Hay River File, Emergency Measures Organization, Yellowknife).

Gerard and Stanley (1988a and b) and Diamond Jenness (1978) reported that the “river was clear of ice between 16-May and 18-May (EMO File).” As no other information was available for this year, the date of melt out was assumed to be 17-May, the middle of the range suggested.

1963: Significant flooding

Source: Diamond Jenness (1978), Jasper (1983), Wedel (1988) and Gerard and Stanley (1988a and b).

Diamond Jenness (1978) reported that on 27-Apr, "River run across the outer fill at 19:30 for the first time. Hay River was flooded from 30-Apr to 5-May when the water receded to normal" (Hay River File, Emergency Measures Organization, Yellowknife).

Jasper (1983) provided the following details regarding breakup in 1963: "Breakup started on 27-Apr. By 30-Apr, some flooding occurred in Old Town as the ice jam located [37 km] upstream broke. On 1-May, the flood crest hit Hay River and communications were cut off at 07:40. The evacuation began around 15:00. From 2-May to 5-May, the evacuation order continued. Several rises occurred in the water levels, with water reaching at least 161.5 m at the Hay River Hotel and 160.0 m further inland (St. Paul's School). The entire point flooded at the Old Village, with residents seeking refuge at Sandy Creek Camp, Great Slave Lake. Major flooding occurred in the Old Town and Old Village, with water levels reaching 106.0 to 161.5 m in the Old Town".

Gerard and Stanley reported that "little information could be found on the progression of breakup; most records concentrated on the effects of the flooding of the Town. On 27-Apr, water levels began to increase with water running over Fill "D" at 19:30. A jam had formed in the East Channel in the area of Island D. Flooding in the Old Town area started early on 30-Apr, when the jam moved downstream and the toe lodged at the mouth of the East Channel. At 16:00 on 30-Apr, a jam 35 km upstream broke sending a surge downstream. This surge hit

Hay River at about 07:40 on 1-May, creating the peak levels. Peak levels for the East-West channel split and near the mouth of the East Channel were 164.0 m and 160.8 m respectively. Although Fill "D" was washed out, little flooding occurred in the West Channel." Stanley *et al.* (1959) provided a high water level profile for this flood, which is detailed in Figures 2.25 and 2.26 of this thesis.

Wedel (1988) called this a major flood and reports the melt out date as 12-May, while the list of dates the East Channel clearing reported in Diamond Jenness (1978) recorded this occurring on 5-May. For the purposes of this thesis, the melt out date is taken to be 12-May, as a drop in water level does not mean the ice jam melted out (Diamond Jenness 1978).

1963 is considered to be the definitive significant flood in Hay River history.

<u>1964: No flooding</u>

Source: Diamond Jenness (1978), Wedel (1988) and Gerard and Stanley (1988a and b).

Diamond Jenness (1978) reported that on 27-Apr, "water moving through the West Channel under the bridge this day. On 1-May, there was insufficient water to raise ice and clear it out into the lake. On 10-May, the little water that came down had to melt the ice in the river and it completed this late this pm and the Hay River is clear of ice to the mouth of the river" (Hay River File, Emergency Measures Organization, Yellowknife).

Gerard and Stanley (1988a and b) reported that "breakup was relatively quiet in 1964. Flood control measures were taken prior to breakup and included plowing snow off the river ice and blasting. The West Channel fill had been removed as the bridge across the channel was completed. Breakup began on 28-Apr and by 30-Apr ice had pushed out the West Channel and into the lake. It was not until

10-May that the river was completely clear of ice (EMO Files). Most accounts attribute the lack of problems to lower than normal runoff."

Wedel (1988) also agreed that the river was clear of ice on 10-May.

<u>1965: Some flooding</u>

Source: Diamond Jenness (1978), Wedel (1988) and Gerard and Stanley (1988a and b).

Diamond Jenness (1978) reported that on 26-Apr, "the river broke up down to mile 6. On the 28-Apr, the river broke up and pushed down through the West Channel at 14:30. On 2-May, a sudden crest of water pushed down through the East Channel, raising the ice in the Snye by Fisheries and Yellowknife Transportation Co. considerable damage was done to a number of vessels in the Snye. Approximately 3 days later, the ice was clear through the East Channel river mouth" (Hay River File, Emergency Measures Organization, Yellowknife). The list of when the East Channel cleared noted that this occurred on 4-May in 1965.

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

The date of the onset of breakup is taken as 28-Apr as reported in Diamond Jenness (1978). Wedel (1988) also reported that the ice melted on out on 4-May.

<u>1966: No flooding</u>

Source: Diamond Jenness (1978), Wedel (1988) and Gerard and Stanley (1988a and b)

Diamond Jenness (1978) reported that on 12-May, "the East Channel was clear to its mouth" (Hay River File, Emergency Measures Organization, Yellowknife).

According to Gerard and Stanley (1988a and b), "breakup was extremely quiet. "Warm spring weather, with temperatures in the mid seventies helped to disintegrate the thin, rotten ice that remained on the surface of the river (TAPWE 1966). Discharge was reported to be very low and ice was completely clear of the river by 12-May."

Wedel (1988) also reported the date of melt out as 12-May.

<u>1967: No flooding</u>

Source: Diamond Jenness (1978), Wedel (1988) and Gerard and Stanley (1988a and b).

Diamond Jenness (1978) reported that on 13-May, "the East Channel was clear to the lake" (Hay River File, Emergency Measures Organization, Yellowknife).

Gerard and Stanley (1988a and b) noted that "early indications were that flooding was a good possibility (TAPWE 1967). Above average snow depths existed in the basin, and the river and lake ice was thick with a heavy snow cover. Flood control measures included plowing the snow off the river and for a distance out into the lake. Blasting of the ice was done in the East Channel from km 1110.0 out into the lake for a distance of 500 m.

"On 8-May, levels at Indian Cabins were reported to be up to the 1963 levels (TAPWE 1967). Although the peak discharge was very high in Hay River, the ice had deteriorated greatly by the time it arrived and no flooding occurred. The river was completely clear by 13-May (Gerard and Stanley 1988a and b)." Wedel (1988) also confirmed this melt out date.

1968: No flooding

Source: Diamond Jenness (1978), Wedel (1988) and Gerard and Stanley (1988a and b).

Diamond Jenness (1978) reported that on 4-May, "the East Channel was clear" (TAPWE papers, 1963 – 1977, Hay River, NWT).

Gerard and Stanley (1988a and b) noted that "the East Channel was blasted prior to breakup (TAPWE 1968). By 20-Apr, it was reported that the river was open for a distance below Louise Falls. It was not until 4-May that the river was completely out. No "push" of water and ice came from upstream. The ice that did come was so slushy it simply ran under the intact ice at the mouth (TAPWE 1968)."

Wedel (1988) also reported that the ice melted on out on 4-May.

1969: No flooding

Source: Diamond Jenness (1978), Wedel (1988) and Gerard and Stanley (1988a and b).

Diamond Jenness (1978) reported that on 29-Apr, “the East Channel was clear” (TAPWE papers, 1963 – 1977, Hay River, NWT).

Gerard and Stanley (1988a and b) noted that “the ice was very rotten by the time discharges started to increase. A jam formed in the East Channel on 26-Apr, but the discharge was so low that no significant increase in water levels occurred (TAPWE 1969). No blasting was done prior to breakup, but blasting was done in front of the jam that formed in the East Channel because high water was reported to the far south of the basin. The river went out on 29-Apr before any dramatic increase in discharge was experienced.”

Wedel (1988) also reported that the ice melted on out on 29-Apr.

1970: No flooding

Source: Diamond Jenness (1978), Wedel (1988) and Gerard and Stanley (1988a and b).

Diamond Jenness (1978) reported that on 7-May, “the East Channel was clear” (TAPWE papers, 1963 – 1977, Hay River, NWT).

Gerard and Stanley reported that “no blasting was carried out. Instead, the ice was perforated with 20 inch diameter holes put down on 20 foot centers (Town Flood Watch 1970). From the description, this was just done in the middle section of the East Channel. Breakup was very mild with levels below normal. The river was clear by 7-May (TAPWE 1970).”

Wedel (1988) agreed that the jam melted out on 7-May.

1971: No flooding

Source: Diamond Jenness (1978), Wedel (1988) and Gerard and Stanley (1988a and b).

Diamond Jenness (1978) reported that on 30-Apr, "the East Channel was clear" (TAPWE papers, 1963 – 1977, Hay River, NWT).

Gerard and Stanley noted that "levels were the lowest since 1959 (TAPWE 1971). Some sections of the East Channel simply rotted in place. The river was clear of ice by 30-Apr (TAPWE 1971)."

Wedel (1988) agreed that the jam melted out on 30-Apr.

1972: Some flooding

Source: Diamond Jenness (1978), Wedel (1988) and Gerard and Stanley (1988a and b).

Diamond Jenness (1978) reported that on 10-May, "the East Channel was clear" (TAPWE papers, 1963 – 1977, Hay River, NWT).

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

Wedel (1988) also reported that that the river was clear on 10-May.

1973: No flooding

Source: Diamond Jenness (1978), Gerard and Stanley (1988a and b) and Wedel (1988).

As Gerard and Stanley (1988a and b) reported, "no information could be found on the 1973 breakup, neither in the Town flood reports nor in the newspapers."

Wedel (1988) and the list of dates of the East Channel clearing presented in Diamond Jenness (1978) reported the date of ice out to be 2-May.

1974: Significant flooding

Source: Diamond Jenness (1978), Jasper (1983), Wedel (1988) and Gerard and Stanley (1988a and b).

Diamond Jenness (1978) reported that on 4-May, "the East Channel was clear" (TAPWE papers, 1963 – 1977, Hay River, NWT).

Japer (1983) reported that "ice broke in the West Channel before noon on 30-Apr. Jamming occurred in both channels during the day, with some flooding occurring at the back of the Hay River Hotel and to the highway in front of the pool hall, as well as in the NTCL freight yard. Flooding in the West Channel Fishing Village started late in the day on 1-May. Residents were evacuated. At 20:30 on 2-May, the jam was blasted, resulting in an immediate drop in water level. Residents were allowed to return to their homes in the morning of 3-May. In the afternoon, the East Channel ice starts to move and NTCL barges behind Island A are carried out to the lake. By 4-May, breakup is over." The high water mark in the West Channel was determined to be 159.3, as estimated from a newspaper photo published in The HUB on 8-May, 1974.

Wedel (1988) classified 1974 as a significant flood, and the jams melted out of both channels on 4-May (confirmed in Diamond Jenness (1978)). However, this source also reports WSC records indicating that the jam backwater effects were gone on 29-Apr.

The following breakup events were detailed in Gerard and Stanley (1988a and b):

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

"On 27-Apr breakup started as ice started to move through the West Channel and jammed at the mouth. In the East Channel ice broke up to Island D where the toe of the jam formed. A large jam was reported at Indian Cabins (km 920.6) on 28-Apr. This jam broke on 15:00 on 29-Apr and a surge was sent downstream. On 30-Apr, the surge hit Hay River, sending water over the banks at the new Indian Village on the East Channel (km 1110.8) and reaching a peak water level of 162.2 m at the Forks (UMA 1979). This surge moved the toe of the jam downstream in the East Channel to about km 1112.25, with water flowing over the Government Docks (km 1112.1) and reaching the highway. Ice started to move in the West Channel on 1-May and flooding started to occur there. Despite the cleared sections, ice and water could not get past the rough ice and the pressure ridge. On

2-May, it was decided to blast the pressure ridge on the West Channel as water levels reached a peak of 159.3 m (this level was a surveyed high water level obtained from the 1:2000 flood risk map for Hay River). Water levels receded after the blasting (TAPWE 1974). In the East Channel the toe of the jam began to move downstream on 3-May. As it moved water levels rose to the railroad track at Carter's Float Plane Base (km 1112.5), reaching an elevation of 156.6 m (Town Flood Watch 1974). By 07:00 on 4-May, both channels were clear of ice" (Gerard and Stanley 1988a and b).

Jasper (1988) reported the date of onset of breakup in the West Channel as 30-Apr, while Gerard and Stanley (1988a and b) listed 27-Apr. The remained of the two descriptions of breakup are similar. Based on the detailed description of breakup provided in Jasper (1988a), for the purpose of this thesis the date of the onset of breakup was 27-Apr.

1975: No flooding

Source: Diamond Jenness (1978), Wedel (1988) and Gerard and Stanley (1988a and b).

Diamond Jenness (1978) reported that on 1-May, "the East Channel was clear" (TAPWE papers, 1963 – 1977, Hay River, NWT).

Gerard and Stanley (1988a and b) noted that "breakup for this year was one of the quietest on record (TAPWE 1975). The ice was completely out on 1-May."

Wedel (1988) also reported 1-May as the melt out date.

1976: No flooding

Source: Diamond Jenness (1978), Wedel (1988) and Gerard and Stanley (1988a and b).

Diamond Jenness (1978) reported that on 27-Apr, “the East Channel was clear” (TAPWE papers, 1963 – 1977, Hay River, NWT).

Gerard and Stanley noted that “ice in both channels was perforated prior to breakup. With above normal temperatures, flooding was feared and so the ice was also blasted at the mouth of the West Channel (Town Flood Watch 1976). Breakup was complete by 27-Apr, with no flooding occurring.”

Wedel (1988) also reported 27-Apr as the melt out date.

1977: No flooding

Source: Diamond Jenness (1978), UMA (1979), Wedel (1988) and Gerard and Stanley (1988a and b).

Diamond Jenness (1978) reported that on 4-May, “the East Channel was clear” (TAPWE papers, 1963 – 1977, Hay River, NWT).

The following account of breakup was described in UMA (1979).

“By 27-Apr, the reach upstream of Alexandra Falls had cleared; the Pine Point Bridge experienced transverse cracking and local ice jamming. The onset of breakup in the Town of Hay River began with a jam forming in the East Channel. On 28-Apr, a small ice jam was reported between Louise Falls and Escarpment Creek, while ice further downstream remained intact. Over the course of 29-Apr, this jam shoved and pushed several kilometers downstream. The following day, this jam shoved to Enterprise, and continue to push through 1-May.

“On 2-May, the jam passed though Paradise Gardens in a series of starts and stops. The jam was breaking into intact ice, which was so deteriorated that it offered little resistance. On 3-May, this jam arrived in town and caused the peak stage but no flooding”. This was considered a prolonged breakup, which again suggests thermal deterioration contributions (UMA 1979).

Gerard and Stanley (1988a and b) reported that “breakup in 1977 was very mild with the river all clear by 4-May (Hub 1977). This breakup was monitored by UMA in 1979. Breakup progression was unusual in that the ice of the lower reach was the last to breakup. The ice run moved into the delta on 27-Apr, with a jam toe forming upstream of Island CD (km 1110), upstream of the mouth in the Rudd Channel (km 1111.5) and at the upstream end of the Fishing Village in the east arm (km 1112). The ice run down the West Channel moved out onto the lake ice through the mid ‘high-level’ channel at the mouth, creating the peak stage on 3-May. The jam toe in the East Channel remained in place until the jam melted out on 4-May.

“Water levels were recorded as part of the UMA (1979) study. Water levels near the mouth of the East and West Channel were 156.9 m and 158.1 m respectively. At the Forks, the peak level was 161.1 m” (Gerard and Stanley 1988a and b).

Wedel (1988) also reported 4-May as the melt out date.

The ten day period of sub zero temperatures (totaling -85˚C) before the onset of breakup in the Town of Hay River was thought to be the cause of this prolonged breakup.

<u>1978: Significant flooding</u>

Source: Gerard and Stanley (1988a and b), notes from Dr. Harrison (2011).

Gerard and Stanley (1988a and b) reported that "the first push occurred on 3-May in both the East and West Channels. By May 4-May, the toe of the jam in the East Channel was at the upstream end of Island B (km 1111.5) (Town Flood Watch 1978). This caused water levels in the Old Town (km 1110.8) to go over the road. Later 4-May, the toe moved downstream to km 1112.2, sending water over the Government docks (km 1112.1) up to the railroad tracks (Hub 1978), an elevation of 158.4 m. The river was completely clear of ice by 7-May." This melt out date was confirmed to be 7-May (D. Harrison, personal communications, February 11, 2011).

<u>1979: Some flooding</u>

Source: Gerard and Stanley (1988a and b), notes from Dr. Harrison (2011).

Gerard and Stanley (1988a and b) reported that "prior to breakup, the ice on both channels were perforated (Town Flood Watch 1979). By 10-May, the river had broken up to the NWT/AB Border (Hub 1979). On 11-May, breakup initiated in the West Channel and "plugged" at the mouth. On 12-May, the East Channel broke to the upstream end of Island B (km 1111.5). A jam that had formed at Indian Cabins broke on 13-May. The surge from the Indian Cabins jam cleared the West Channel on 14-May but not before water went over the banks at an elevation of 158.8 m. No flooding occurred in the East Channel, although water levels reached to within 0.15 m of the docks, an elevation of 157.9 m (Town Flood Watch 1979). The peak flood level of 162.7 m at the Forks was estimated from a report in the TAPWE (1979) that water levels peaked at the West Channel Bridge 16 ft (4.9 m) above the original ice level. The river was completely clear by the 15-May."

The following account of breakup was taken from the notes of D. Harrison. On 11-May, "ice began to move out the West Channel at 15:00. Had been running a little on 10-May at 22:00. On 12-May, the ice stopped flowing in the West Channel. Ice was not broken below islands C and D behind the Old Hotel. On 14-May, ice went out the West Channel in the afternoon. The ice was still solid by the Old Village on 15-May. The East Channel cleared on 17-May" (D. Harrison, personal communications, February 11, 2011).

Gerard and Stanley (1988a and b) reported the melt out date as 15-May, while the notes of D. Harrison noted the East Channel clearing on 17-May. For the purposes of this study, the date of melt out was taken to be 17-May, based on the detailed, first hand observations provided by D. Harrison.

1980: No flooding

Source: Gerard and Stanley (1988a and b), notes from Dr. Harrison (2011).

"Breakup was mild, with the river being clear by 29-Apr (Hub 1980)" (Gerard and Stanley 1988a and b). This date was confirmed in the notes of D. Harrison (D. Harrison, personal communications, February 11, 2011).

1981: Some flooding

Source: Gerard and Stanley (1988a and b), notes from Dr. Harrison (2011).

Gerard and Stanley (1988a and b) noted that "prior to breakup, ice was reported to be thinner than normal (Hub 1981). For the most part water levels were low during breakup, with some minor flooding taking place at the new Indian Village (km 1110.8), an elevation of 160.0 m. A peak level of 161.9 m was estimated at the Forks from a photo in the Hub (1981). Ice was out by 6-May."

The following account of breakup is taken from the notes of D. Harrison. "On 4-May, the river broke up and out through the West Channel. During the night of 5-May, the ice was broken up to the NTCL Islands, almost up to road level. Ice was flowing though the West Channel. During the morning of 8-May, the water level dropped and cleared of ice, broken ice in channels to the Old Hotel, but still firm at Old Village. On the morning of 9-May, the East Channel was clear of ice" (D. Harrison, personal communications, February 11, 2011).

Gerard and Stanley (1988a and b) reported the melt out date as 6-May, while the notes of D. Harrison noted the East Channel clearing on 9-May. For the purposes of this study, the date of melt out is taken to be 9-May based on the detailed first hand observations of D. Harrison.

1982: No flooding

Source: Gerard and Stanley (1988a and b), notes from Dr. Harrison (2011).

Gerard and Stanley (1988a and b) reported that "no flooding occurred in 1982 as flows were very low. Ice was out by 11-May. Again the peak water level of 160.4 m was estimated from a photo in the Hub (1982)."

The following account of breakup was taken from the notes of D. Harrison. "On 8-May, there was ice and water moving through the West Channel. On 10-May, the ice all left the river, and the East Channel was clear of ice" (D. Harrison, personal communications, February 11, 2011).

Gerard and Stanley (1988a and b) reported the melt out date as 11-May, while the notes of D. Harrison noted the East Channel clearing on 10-May. For the purposes of this study, the date of melt out is taken to be 10-May.

1983: No flooding

Source: Gerard and Stanley (1988a and b), notes from Dr. Harrison (2011).

“Breakup began at the Forks on April 28-Apr. Water levels were very low, with the ice going out between 3-May and 5-May (Hub 1983)” (Gerard and Stanley 1988a and b).

The date of melt out (Each Channel clear of ice) recorded in the notes of D. Harrison was 4-May (D. Harrison, personal communications, February 11, 2011).

1984: No flooding

Source: Gerard and Stanley (1988a and b), notes from Dr. Harrison (2011).

“Breakup was very mild with ice being thinner than normal (Hub 1984). Channels were clear of ice by 24-Apr” (Gerard and Stanley 1988a and b).

The date of melt out (East Channel clear of ice) recorded in the notes of D. Harrison was 30-Apr (D. Harrison, personal communications, February 11, 2011). The melt out date is taken to be 30-Apr, based on the first-hand observations of D. Harrison.

1985: Significant flooding

Source: Wedel (1983), EC (1988) and Gerard and Stanley (1988a and b), notes from Dr. Harrison (2011).

The following account of breakup is reported in Gerard and Stanley (1988a and b):

"Over the winter of 1984-85, the pressure ridge formed on Great Slave Lake off the West Channel was closer to the mouth than in other years. It was about 400 m offshore, and was reported to be 2 to 4 m high (Wedel 1988). No blasting or grading was done on this pressure as had been done in past years.

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

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

By early 8-May, water levels had lowered in the West Channel. Later on 8-May, ice moved through the East Channel to the mouth, but water levels downstream of Island CD did not reach flood level. Ice was completely out by 04:00 on 9-May.

Underhill Engineering Ltd. was contracted to document high water marks in Hay River. From this work peak flood levels were obtained for the mouth of the East Channel and the East-West Channel split. These were 158.5 m and 163.5 m respectively." Gerard and Stanley (1988a and b) provided a high water level profile, which is detailed in Figures 2.25 and 2.26 of this thesis.

EC (1988) confirmed the date of peak stage due to ice jamming as 7-May.

Wedel (1988) reported that major flooding occurred in 1985, and also detail the progression of breakup in the Hay River Delta as follows:

"On 20-Apr, the Emergency Measures Organization (EMO) conducted an aerial reconnaissance flight. Conditions on the Chinchaga River led to an estimate of approximately 2 weeks until breakup in Hay River. Conditions appeared right for high runoff. On 1-May, an ice jam forms at the Pine Point Bridge. On 3-May, a flood watch was instituted at 08:00. Bankfull river conditions reported at 17:30 from Indian Cabins, just south of the NWT/AB Border. A 2 m drop at 20:30 at Paradise Gardens indicated that an initial flood wave had passed through beneath the ice cover. The jam from the Pine Point Bridge arrived in town, and backed up to past the Pine Point Bridge. A state of local emergency was declared in Hay River at 21:00. On 5-May, Indian Cabins reported a huge release prior to 07:00, but river velocities soon slowed although water levels remained high along the river.

On 6-May, rapid flow was reported from Paradise Gardens at 02:30. Ice began to move in the East Channel and water levels rose at 07:00. The Old Village on Hay River Reserve was evacuated to the Community Hall in New Town, or to private residences. St. Paul's School was closed at 09:40. Water levels continued to rise slowly and at 13:00, water crossed the Mackenzie Highway at the entrance to Island D, and washed out the rail spur to the island. A helicopter survey at 16:00 showed ponding behind the pressure ridge at the mouth of the West Channel, that Island D was under water and that the new Indian Village was experiencing some flooding. Evacuation of the West Channel residents began in the evening. Approximately 3 m of ice pile-up was noted along the West Channel river banks.

On 7-May, at 00:30, a huge surge of water and ice was reported moving down the West Channel. Within 15 min, the roads in the West Channel were flooded to depths exceeding one meter. Remaining residents were evacuated by truck or front end loader. The suddenness of the event prevented siren-warnings to be given in time, and prevented firefighters from responding adequately. Ignoring his own safety, a private resident rescued several people from rooftops by canoe when he realized other means of rescue were not possible. All residents were evacuated safely within 90 min of the flood surge. On 8-May, the West Channel levels continue to fall and flows down the East Channel are below capacity."

The date of melt out (Each Channel clear of ice) recorded in the notes of D. Harrison was 8-May (D. Harrison, personal communications, February 11, 2011).

The dates of onset of breakup (6-May) and peak stage due to ice jamming (7-May) are consistent between Gerard and Stanley (1988a and b) and Wedel (1983). For our purposes, the date of melt out was taken to be 9-May. This is based on the detailed breakup description in Gerard and Stanley (1988a and b), which agrees with Wedel (1988).

1986: Significant flooding

Source: Gerard and Stanley (1988a and b).

The following account of breakup was reported in Gerard and Stanley (1988a and b).

"Prior to breakup it was reported that lake and river ice was thicker than normal. Because of the thick ice, blasting was done on the West Channel. Ice began to move in the West Channel on 2-May. In the East Channel ice broke to the downstream end of Island CD on 4-May. Later in the day the toe moved downstream a few hundred meters, stopping behind the Hay River Hotel (km 1111.7).

On 5-May, the jam that had formed at Indian Cabins released. On 6-May, some flooding was reported at the new Indian Village (km 1111) as water reached the road. On 7-May, water levels reached a peak of 163.4 m at the West Channel Bridge and water went over the banks at the Fishing Village (elevation 159.0 m). In the East Channel some minor flooding occurred below Island B as water went over the docks to reach an elevation of 158.5 m (Town Flood Watch 1986). McBryan summarized the 1986 breakup as a smaller version of 1985, the difference being a lower discharge. The river was completely clear by 8-May."

Without knowing whether this ice movement was as a result of thermal deterioration or an incoming ice run (breakup onset), the date of the onset of breakup is assumed to be 4-May, when the East Channel ice broke to the downstream end of Island CD.

1987: No flooding

Source: Gerard and Stanley (1988a and b).

Gerard and Stanley (1988a and b) reported that "prior to breakup, considerable flood mitigation work had been done on the river. This included clearing the snow from the lower portions of the East and West Channels and using a ditch witch to make long narrow longitudinal cuts in the ice in the East Channel. In the West Channel snow dykes were built out onto the lake to constrain the flow as it moved onto the lake, in the hope that it would carry ice and water out away from the mouth.

Ice began to breakup at the town site on 26-Apr. A jam was formed in the West Channel just upstream of the mouth in the Rudd Channel. In the East Channel, ice jammed at the downstream end of Island CD. A large jam at Indian Cabins gave way on 27-Apr. Over the next few days little movement occurred in the delta. Ice from the jam at Indian Cabins arrived in Hay River on 28-Apr. This caused the head of the jam to grow upstream with little movement occurring at the toes. On the 29-Apr and 30-Apr, the jam began to melt in place due to warm water coming from upstream. Ice began to move out into the lake on 30-Apr and by 1-May, the river was free of ice."

Peak water levels at the mouths of the East and West Channels and the Forks were 158.2 m, 158.1 m and 162.2 m respectively."

1988: No flooding

Source: Gerard and Stanley (1988a and b).

The following account of breakup was detailed in Gerard and Stanley (1988a and b). "On 23-Apr at 15:00, the Chinchaga River at the Highway 58 crossing (km

612.48) was open and the water temperature as 2.3 °C. On 24-Apr, the bottomfast ice in the West Channel began to release from the bed and float to the top. This created a juxtaposed ice accumulation in the West Channel. The river was open between Alexandra and Louise Falls and for about 7 km upstream of Alexandra Fall. Below Louise Falls a small 2.8 km jam was present.

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

By the morning of the 26-Apr the head of the jam had moved downstream 1.3 km so that open water existed from Louise Falls to km 1042.65. The toe of this jam had moved to km 1059.92. There was again an open water lead of about 500 m downstream of the toe. The ice cover downstream of this jam had shifted overnight.

On the early morning of 27-Apr, large scale movement began. Ice in the town began to breakup at 07:00. Ice broke down the East Channel to the upstream end of Island CD (km 1110.9), where the toe of a jam formed. In the West Channel, ice moved through the Rudd Channel and out into the lake, with the run breaking through the lake ice along the shore to the west of the mouth for about 2 km. At the end of the run, ice had fanned out on and through the lake ice for a distance of about 1 km from shore. In the east arm of the West Channel, the toe of the ice jam had formed at the mouth of the channel. The high water for this year at this location occurred due to a momentary surge as the ice run moved into this arm and was stopped at the mouth. The head of the jam was located at km 1098.4, close to the Pine Point Bridge. Above this jam the river was open all the way to the falls.

On 28-Apr, there was no change. Air temperature decreased such that the mean daily temperature for 28-Apr was below zero. The discharge also decreased, causing the water level in the town to fall steadily. Over the night of 28-Apr to 29-Apr, the head of the jam moved upstream to km 1097.6. Although air temperatures were cold in Hay River, they seemed to be the result of cold north winds off the lake because in the upper catchment air temperatures remained above zero. This caused water temperatures to increase a little from 0.0˚C to 0.3˚C at the head of the jam by 09:00 on 29-Apr. This was followed by a relatively rapid increase over the next 29 hours to 2.8˚C at 13:50 on 30-Apr, after which it leveled off. Due to melt caused by the above-zero water temperatures, the head began to move downstream.

On 30-Apr at 22:00, the head moved to km 1104.46. The jam continued to melt over night and by the morning of 1-May, the head was below the split. The toe had still not moved in either channel, but a large open water lead about 700 m long and 150 m wide had formed in front of the toe in the East Channel. At 22:45 the toe in the East Channel moved, filling this open water lead. It stopped at the solid ice at the front of the lead. By this time, with the warm water continuing to melt the ice, the ice jam in the East Channel was less than 500 m long.

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

In addition to this, Gerard and Stanley (1988a and b) also reported several details regarding the progression of breakup. On 24-Apr, Alexandra Falls and Mink Creek had cleared of ice. There was a small jam in place near Escarpment Creek. There was a small section of open water at the Pine Point Bridge. On 25-Apr, the jam near Escarpment Creek shoved to Enterprise. There was a small jam upstream of Paradise Gardens, and intact ice downstream of this jam to the Pine Point Bridge. Breakup initiated in the Town of Hay River on 27-Apr.

1989: Significant flooding

Source: Gerard and Jasek (1990), The Hub (10-May, 1989) and notes from Dr. Harrison (2011).

The following account of breakup was detailed in Gerard and Jasek (1990). This information was gathered from the Emergency Measures Organization (EMO) flood watch notes.

"On 30-Apr, the breakup front on the Hay River was some distance upstream of Indian Cabins (km 921). By late afternoon on 1-May, it had moved north of the border to about km 983 and the ice extended back to Steen River (km 889) in various stages of sheet ice, broken ice and open water. A jam had formed about 13 km upstream of Steen River and extended back to Meander River (km 799).

In the early hours of 2-May, a 25 km jam had developed downstream of Grumbler Rapids at km 996. By 09:30 this jam had released. At this time, the breakup front below the falls was at Enterprise (km 1049). At 13:58 an ice run extended from km 921 to 945 and was presumed to be the ice from the Steen River jam observed the previous evening. At 14:20, breakup at Paradise Gardens (km 1068) began and by 15:40, ice at Golf Course (km 1089) was moving. The breakup front passed the Chamber of Commerce Park (km 1103) at 16:29; and reached the ballpark (km 1106) at 16:50. The ice run moved down the West Channel at 17:13 and then East Channel at 17:17. The run stalled in the East Channel at Island CD at about 19:30, and in the West Channel at the lake at about 20:00. When the jam formed, the pack extended back to km 1083, upstream of the Golf Course, a distance of some 30 km. It is likely the whole ice run of the Hay River below Steen River was triggered by release of the Steen River jam. There was not a secondary breakup front from downstream of the falls." Gerard and Jasek (1990) provided a high water level profile, which is detailed in Figures 2.25 and 2.26 of this thesis.

Breakup 1989 kept Hay River tense and in a 'holding pattern' a full week (HUB article 10-May 1989). "In New Town, ice piled up on gardens along McBryan Drive and water flowed into the ravine on Riverview Drive. The Don Wright Ball Park was flooded. In the New Village on the Hay River Dene Reserve, some minor flooding by the Sharing Lodge (old school building) occurred. For a time the residents of the Old Village were evacuated as the waters rose and ice climbed the banks.

West Channel residents were evacuated from their homes twice, once on Tuesday night (2-May and again on Friday afternoon (5-May) as the final tremendous surge of water (approximately 1200 m^3/s) pushed through the solidly packed ice in the West Channel and caused some minor flooding along the east shore. One house suffered damage to a basement wall and water lapped across the road, but this soon receded. In the Old Town, flooding was limited to some water over Carter's floatbase dock, Strangs' Corner and water almost across the highway at the low point just before Strangs. Dr. Gerard felt the town was lucky that the ice went out as it did, as there was potential there for worse flooding than in 1963."

The following account of breakup is taken from the notes of D. Harrison. "On 2-May, ice started to move down the West Channel in the late afternoon. The ice surface broke up to about Cliff Strang's old house, near to the airport entrance. On 3-May, the ice levels were very high, onto the baseball diamond, up the ditch behind Fordhams, along the edge of bank of the nature trail, ice in woods on top of the bank, water and ice on bank in the Chamber of Commerce Park. School was cancelled on from 3-May to 5-May at Camsell School in the Old Town. On 4-May and 5-May, ice had to be bulldozed off the road to the Old Town. On 5-May, people were evacuated from the West Channel Fishing Village. There was some flooding on the river bank area. At 16:00 on 5-May, water levels dropped as water ran out through the West Channel. By 19:00, the ice was still solid by Carter's, there was a little broken ice by Camsell's old house and across the winter road to the Old Village. On 6-May, the river was flowing freely in the East Channel, and water levels dropped considerably" (D. Harrison, personal communications, February 11, 2011).

<u>1990: No flooding</u>

Source: Jasek et al. (1993) and notes from Dr. Harrison (2011).

Jasek *et al.* (1993) reported that "this breakup was largely uneventful, and 1990 and 1991 had several features in common: breakup occurred fairly quickly with all ice from the upstream reaches of the Hay River arriving all at once; there was little surge effects; the ice jam in town melted from the upstream ends as warmer water came down from upstream. "There is only minor runoff in the whole system" McBryan said.

Breakup began in the Town of Hay River on 27-Apr and all ice from upstream had arrived by 28-Apr. The pack proceeded to melt from the upstream end and reached the mouths of the East and West Channels on 1-May."

The following account of breakup is taken from the notes of D. Harrison. On 27-Apr, ice was moving down the West Channel at 18:30, stopping at 20:00. The ice was not broken at NTCL at this time. On 28-Apr, the ice was stopped, but not broken up behind the Old Hotel to the mouth of the river. On 30-Apr, ice in the West Channel was bankfull, but rotting and black in color. Ice moved by the High School at 12:45, and flowed by Alexandra Apartments at 17:00. There was some open water and the ice hadn't broken up by the Old Hotel by 15:00. The West Channel was free of ice on the morning of 1-May. By 16:00, the river was ice free down to the North side of the NTCL islands. Ice was moving slowly by

Carter's, but was not broken up and there were small patches of water with blocks of ice flowing. There was smooth, flat ice in front of the Old Village and by 21:00, there was broken ice up to the Northern top of Island A. The river was free to the mouth of the East Channel at 16:00 on 2-May. (D. Harrison, personal communications, February 11, 2011).

Jasek *et. al* (1993) and Harrison (2011) reported different dates of melt out in the East Channel: 1-May and 2-May, respectively. The dates of melt out in the West Channel agree (1-May), and the date of melt out in the East Channel is taken as 2-May, based on the more detailed, first hand observation of breakup by Harrison (2011).

1991: No flooding

Source: Jasek et al. (1993) and notes from Dr. Harrison (2011).

"Breakup began on 24-Apr. All ice from upstream had arrived by 25-Apr. The pack proceeded to melt from the upstream end and reached the mouths of the East and West Channels on 1-May" (Jasek *et al.* 1993).

The following account of breakup was taken from the notes of D. Harrison. On 24-Apr, the river ice broke up and lifted and went out into the West Channel. The 25-Apr was -14˚C, and there was no change from 24-Apr. No change from 26-Apr to 28-Apr, but on 29-Apr water started to flow by Diamond Jenness in the mid morning. By 19:00, water was moving, and ice free to the Forks. Ice was still in both channels, but the water level was down 2 ft. The ice was still solid behind the Old Hotel. On 30-Apr, water dropped 5 to 10 ft. There was loose ice in the West Channel and some open water patches, while the East Channel was open to the North end of the NTCL islands. Ice still covered the mouth of the East Channel, but by 16:30 on 1-May, the East Channel was clear of ice (D. Harrison, personal communications, February 11, 2011).

1992: Significant flooding

Source: Jasek et al. (1993) and notes from Dr. Harrison (2011).

The following account of breakup is reported in Jasek *et al.* (1993).

"Breakup began on 26-Apr at about 17:00. Some flooding occurred in the West Channel Fishing Village shortly afterwards. The snow dyke at km 1111.7 overtopped and the ice jam toe pushed through the Fishing Village Channel to the mouth (km 1113) and onto the lake. The water rose high enough to overtop roads in a few locations. The ice jam toe in the East Channel stalled at the usual position, the downstream end of Island C-D (km 1111.5).

Little change in the water levels occurred over the next 24 hrs. However, surges were expected as ice jams were still present upstream of the falls between Grumbler Rapids (km 988) and Indian Cabins (km 920). An ice jam was also present at the Golf Course (km 1090). Later in the evening of 27-Apr, at about 21:15, a surge caused the East Channel toe to move and stall at the Hay River Hotel (km 1111.7). A peak level of 162.7 m geodetic was recorded by the Town Flood Watch at the WCB (km 1108.3) at about 22:20.

On the morning of 28-Apr, a second surge caused further movement of the East Channel toe at about 10:50 hrs. While the toe in the channel on the west side of Island B remained in place, the toe in the channel on the east side of Island B advanced downstream past Carters Air Services to km 1112.8 and caused flooding. The water levels rose high enough to inhibit transportation on both sides of the East Channel; water overtopped roads near the Carters Air Services (km 1112.6) and the road leading to the Old Village. At about the same time water levels started to rise in the West Channel Fishing Village and peaked between 13:00 and 16:00. Water continued to flow 1.5 km east of the Fishing Village along Lakeshore Drive, flooding the roadway. By about 18:00 all ice from upstream had arrived in Hay River. The head of the jam was at km 1105.0, about 0.5 km upstream of the Ball Diamond. Levels continued to drop due to decreasing discharge. Levels also fell as pack melt occurred at the upstream end of the jam. By the end of 30-Apr both East and West Channels had melted out all the way to the lake and the threat of flooding had passed." *Jasek et al.* (1993) provided a high water level profile, which is detailed in Figures 2.25 and 2.26 of this thesis.

The following account of breakup is taken from the notes of D. Harrison. Breakup started early in the afternoon on 26-Apr. By 17:30, ice and water and fair amounts of logs flowing down the main channel and broke up ice to the NTCL islands. Started moving down the West Channel about 18:30 and flowing rapidly. Ice stopped flowing at the West Channel Bridge around 21:00. By the evening of 27-Apr, water levels rose to bank full. On 28-Apr, water and ice levels were high, but no overnight flooding. Flowing in mid-morning out of the West Channel. Main channel water was high, flooding over railway tracks, high along river banks, boats floating in water by Carter's but not broken up to the lake on the Main Channel. On 29-Apr, the water level was high, but dropped 4 to 5 ft from the road level. Ice was still over the river at the Synchro Lift and the Old Village. Ice jammed in mouth of the West Channel, broken ice from the West Channel Bridge to the Old Hotel and Island B. On 30-Apr, the ice left the East Channel completely and by 1-May, water levels dropped close to normal (D. Harrison, personal communications, February 11, 2011).

1993: No flooding

Source: Jasek (1993) and notes from Dr. Harrison (2011).

Jasek (1993) reports that "the 1993 breakup of the Hay River was one of the lowest events on record. Many of the residents of Hay River were quoted as saying that they had "never seen the ice go out like this before". The breakup was largely a thermal breakup as compared to the usual dynamic type experienced in Hay River. The breakup front was caused by increasing water temperatures in the headwaters, and not an increase in discharge. The jam associated with this breakup front was typically about 1 km long. The increase in stage which it produced was in the order of 1 m or less. The progression of this breakup front or melting front was much slower than the typical breakup front on the Hay River.

The maximum water levels occurred in solid ice conditions, before the arrival of the breakup front. This suggests that peak discharge was insufficient in magnitude to mechanically breakup the ice."

Jasek (1993) also mentioned that the reach immediately upstream of Alexandra Falls typically clears of ice 1 to 2 weeks prior to the onset of breakup in the Town of Hay River.

The following account of breakup is taken from the notes of D. Harrison. "On 5-May, there was a little rise in water level and ice moved out by the West Channel. There was loose ice in the river up to Island D (NTCL Island). On 6-May, ice left the main channel by the Mission and the East Channel was clear of ice" (D. Harrison, personal communications, February 11, 2011).

1994: Some flooding

Source: The Hub (3-May, 1994) and notes from Dr. Harrison (2011).

The following account of breakup was detailed in a 3-May, 1994 HUB article.

"Residents were evacuated from West Channel at 11:55, on Wednesday, 27-Apr, when the first surges of water and ice moving down the West Channel at considerable speed and great deal of force. The berm built by the Town across the West Channel held for about three to four hours, but water had been going underneath right from the start of the push and it was eventually breached. The 300 m snow berm that Ed Studney built along the bank of the West Channel succeeded in keeping out ice, although water did seep in.

After the surge on Wednesday, the river sat solid with very high levels. Some breaking occurred in the East Channel, with ice blocks pushed to the edge of the highway between the airport entrance and NTCL's Islands C and D. Over Wednesday night and Thursday, the water broke a lead along the east side of the East Channel, crossed over at Hudson Island and came down behind the Hay River Hotel and to the government docks, where it met solid ice and no more give. At the same time, a small lead continued on the east side, which allowed some relief flow.

Red McBryan of the Flood Watch committee says when the water and ice hit the thicker ice built up along the roadways on the river, especially the Old Village crossing and the tracks that were cleared for the races during Kamb'a Carnival, "She stopped dead." Clearing the snow and exposing the ice had allowed for more growth of ice in these areas.

Finally, at 05:30 on Saturday, 30-Apr, ice began to move under the West Channel Bridge. Water came up at West Point along and across various parts of Alaska Road. Water also came back up at Studney's, back along the road to Carter's old plant and behind the old Fishermen's Federation Store. In some places, it flowed across Mackenzie Drive and onto properties on the south side of the road, but there was no flooding of houses and no ice damages.

The alert status for breakup of the Hay River ended officially at noon on Saturday, 30-Apr. Levels at the Pine Point Bridge held steady between 20 and 22 feet (6.1 and 6.7 m), giving some of the highest water levels on record."

The following account of breakup was taken from the notes of D. Harrison. Water and ice started flowing into the West Channel at 10:30, and jammed by nightfall. This jam sat all day on 28-Apr, but by 29-Apr it moved out through the West Channel. On 30-Apr, water made it to the lake in the West Channel, while the ice in the East Channel was broken up across from the Airport. At the Old Hotel, the water was a little lower. The ice was out of the East Channel on 1-May (D. Harrison, personal communications, February 11, 2011).

<u>1995: No flooding</u>

Source: The Hub (2-May, 1995)

"Flooding is unlikely this year" (The HUB 2-May, 1995). No mention was made of the dates of breakup.

The following account of breakup was taken from the notes of D. Harrison. "On 2-May, the ice broke up by Diamond Jenness High School, but there was no change until 6-May, when there was still ice behind the Old Hotel, by the Government Docks, by Carter's by the Old Village and down to the mouth of the river, but all broken up. The West Channel was open to the North end of the runway. By 12:15, there was no ice in the East Channel, and was free from around St. Peter's Mission" (D. Harrison, personal communications, February 11, 2011).

<u>1996: No flooding</u>

Source: The Hub (7-May, 1996)

The following excerpt was taken from a 7-May, 1996 article in the HUB newspaper.

"Breakup in Hay River was rather uneventful this year. River levels are considered moderate, about 10 feet below major flood stage. The river broke at the NWT/AB Border at noon on 30-Apr and broke in town on 1-May. All the winter ice had broken by the morning of 2-May and the river was flowing freely. Above normal snowpack accumulations in Northern Alberta and BC this winter created the potential for significantly higher flows than experienced during the past two years, but a swift breakup resulted in no flooding."

1997: Some flooding

Source: The Hub (22-Apr, 29-Apr and 6-May, 1997)

On 22-Apr, the HUB reported that "freeze up levels on the Hay River and Great Slave Lake were the highest on record, and they've been recording since the 1930's. Ice thicknesses were average… Major property damage flooding happened in 1952, '63, '74 and '85."

Breakup occurred in town at 19:25 on 2-May (HUB article 6-May 1997). "Although breakup caused some boats to be piled up at the Government Docks. Elsewhere, damage was minimal". "A newly constructed section of berm is being credited with saving West Channel homes" (HUB article 6-May 1997). "The extension of the West Channel Berm as far as the airport directly prevented high water and ice from entering residential areas. A recent building-up of the berm near the West Point Road was also critical in preventing a flood. "If those berms hadn't been there some of the people would have gotten wet in the West Channel and we probably would have had to evacuate." Studney said if the new section had not been built this year, two or three feet of water would have flooded residential areas there. The new berm extension "should have been built 20 years ago."" (HUB article 6-May, 1997).

“In a separate matter, Hay River councilors learned Monday night that GNWT Municipal and Community Affairs (MACA) has refused a request from the Town of Hay River for finance assistance during this year’s spring breakup. Hay River wanted the money to upgrade flood berms and monitors” (HUB article 22-Apr, 1997).

1998: No flooding

Source: The Hub (14-Apr, 28-Apr and 8-May, 1998)

“The Hay River remained under 24-hour watch as The Hub went to press (HUB 28-Apr, 1998), but the risk of flooding was considered largely past. On 14-Apr, the Hub reported that “this was considered a relatively mild winter. During breakup upstream of town, ice had accumulated to depths of up to 12 m and anchored to the ground below Louise Falls. Because of the mild weather and high water levels last fall, the river didn’t freeze above the falls until December 8th. Prior to that, it was freezing up and breaking up, freezing up and breaking up. In the course of this, the river was always full of slush and pan ice going over Louise Falls. The ice proceeded down the gorge toward Hay River but started to jam. “With this much ice coming down all falling there, we have built up a tremendous amount of pack ice in the river.” This ice is anywhere from 3 to 12 m thick, bank to bank, up into the trees. Below the falls and into the Town of Hay River, we have a significant increase in the volume of ice that will come at us, coupled with whatever comes from the south. The jammed ice is anchored to the river bottom, and the big question, is whether the northbound ice will flow over top of the jammed ice or whether all of the ice will be pushed out together.”

On 28-Apr, the HUB reported that “all the ice at the bottom of Louise Falls let go after a massive push. It seemed to be advancing a 800 m to 1600 m every day. As water cut a channel right through the centre of the ice pack rather than the jam shoving to town, the jam appeared to be melting in place. The water level at the border dropped 0.35 m in the last few days, so no further surge is expected. The berm has been raised this year by 0.6 m and 85 cubic meters of soil has been stockpiled at Carter's yard."

On 8-May, the HUB reported that "the Hay River breakup started Thursday afternoon (30-Apr). By Saturday afternoon, the river was largely clear of ice."

1999: No flooding

Source: The Hub (27-Apr, 1999)

"Ice leaving us quietly. At this point, flooding is extremely unlikely" reported the 27-Apr HUB article. There was no mention of breakup dates in 1999.

2000: No flooding

Source: The Hub (25-Apr, 2000)

On 25-Apr, the HUB reported: "The tributaries running into the Hay River are practically dry, which is unusual for this time of year. McBryan said in many years, when the ice breaks at the border, it will reach Hay River in just a matter of hours. There's no sign of breakup and no sign of high water. The ice is getting very rotten now, but there's no pressure to move it." There was no mention of breakup dates in 2000.

2001: Some flooding

Source: The Hub (8-May, 2001)

The HUB reports on 8-May that "although an uneventful breakup was expected, ice and water spilled over a low spot in the berm early in the morning on 4-May. At 04:30, jammed ice in the West Channel forced water levels to rise above the berm at the West Channel Fishing Village, flooding several back yards, but causing minimal damage. By dawn, the water had dropped 1.5 m in just two hours. The water level on May 7-May was estimated to be 4.4 m, which was 4.1 m lower than the water level on 4-May. Residents credit the berm for preventing more significant flooding."

2002: No flooding

Source: The Hub (23-Apr and 22-May, 2002)

On 23-Apr, the HUB reported Red McBryan saying "there is not enough water to cause a problem, although the ice conditions in the Hay River could cause problems if there's a sudden melt.

On 22-May, the HUB cited "this year's breakup was considered late and dramatic but damage was minimal. The Coast Guard's dock was flooded and the traffic sign near Porrit Landing was knocked over, as usual. Official breakup time was determined by the Flood Watch Committee as 18:59 on May 15th, when the water reached the 10-foot mark on the West Channel Bridge. Ice pushed up on the shoulder of the Mackenzie Highway on Vale Island, and remained jammed for hours. The water kept escaping to the lake, and eventually the ice also pushed to the lake. Computer-controlled water level gauges have been installed at several points on the river again this year to give EMO volunteers "the big picture" of breakup."

2003: Significant flooding

Source: The Hub (23-Apr, 30-Apr, 4-May and 7-May, 2003)

On 23-Apr, the HUB reported that "ice near the border is nearly twice as thick as it was last year (32" versus 19"). Near the mouth of the Hay River, the ice is 1.5 m thick. Residents believed that if it remained cold and there is a slow breakup that there should be no flood. However, should there be a fast breakup, major flooding should be expected."

On 30-Apr, the HUB reported that "at 04:00 on 28-Apr, the water level gauges at the West Channel Bridge showed the water rise to and then past the 10 foot mark, marking official breakup. Later that morning, the broken ice started jamming up and remained mostly still overnight, while water levels steadily rose. The ice was still at the newspaper deadline on 29-Apr."

On 4-May, the HUB stated that "at 17:00 on 29-Apr, water and ice started spilling over the West Channel berm, flooding yards, sheds and homes." Evacuation began. Access to Vale Island was cut off for a short time. When the Mackenzie Highway was flooded, it only partially blocked the road, and cleared quickly. Also reported on 4-May: "Access to the West Channel was cut off for almost three full days. Water an ice rose more than a meter deep in many areas."

The HUB featured a day by day account of flood activities on 7-May. The following account of breakup is summarized from that article. "Mayor Duncan McNeill calls a state of emergency on 30-Apr. Twenty five residents are asked to evacuate, although people are still free to come and go. By 16:00 the river starts to wash away the road to the Old Village, and the road is closed. At 16:30, ice floes and river water rush onto the Mackenzie Highway near the airport. RCMP block off traffic in both directions on Vale Island. At 17:05, waterfalls of ice and muddy water charge over the berm in West Channel. The fire department blocks off access to the neighborhood.

At 14:30 on 1-May, the water has already washed away a meter of the newly constructed road. The road close to the Old Village is also damaged, causing 75 residents to be evacuated. The Old Village itself escaped damage.

At 10:00 on 2-May, a new surge of water lifts the ice again. There's more water coming. By 10:15, town crews have built a sandbag dike, in the ravine behind Princess Alexandra Middle School. It's holding back water that flooded into the ravine and threatens a New Town sewer lift station. At 13:30 the water rose late in the afternoon, but not as high as it was at the peak of the flood (1-May). By 09:00 on 3-May, it is determined there is little chance of further flooding."

EMO photos showed the log jam on 3-May. However, the locations of where these photos were taken were unknown.

2004: No flooding

Source: University of Alberta/DIAND research program and the Hub (28-Apr and 19-May, 2004).

Local residents told the University of Alberta research team that there was "skinny ice and little water. It looks like a non-event." On 30-Apr, the ice between Enterprise and Paradise Gardens was intact, but with some border flow. There were steep shear walls at the Golf Course, and immediately downstream there was running ice. Sheet accumulations were piling up between the Golf Course and the Pine Point Bridge, while the ice downstream of km 1101 was intact.

This accumulation shoved to Chamber of Commerce Park (*km 1103.5*) on 2-May, but did not shove into the Hay River delta. The ice between *km 1103.5* and the NTCL berm in the East Channel and the mouth of the West Channel was ridged and cracked. The accumulation extended back to the Golf Course (*km 1088.5*), with open water upstream. The ice in the upstream end of the accumulation was quite deteriorated, with water between floes and the water levels were low (point bars were visible). There was a small accumulation below Louise Falls.

On 3-May, there was no change in the ice conditions downstream of the Golf Course. The leading edge (melting front) of the accumulation had advanced 1 km. This year, there was no "onset of break" to speak of, as the accumulation melted through the delta, but did not actually experience a dynamic breakup. The peak stage in the delta during breakup occurred on 1-May. The date of melt out was obtained from the EMO West Channel Bridge water level record as 5-May (when the ice affected water levels dropped and leveled off).

On 28-Apr, the HUB reported that "flooding is unlikely this year. The river ice is just 0.55 m thick, which is substantially thinner than it was in 2003. The water levels are low. However, the town is more prepared for a flood this year, than last. The gauges to monitor ice levels have been fixed. The engineering department has built up the berm in West Channel, and repaired the gates between the river and the ravine in New Town." But, residents doubted that the water level will get to the 10-foot marker on the West Channel Bridge, the level usually used to declare the official time of breakup.

On 19-May, the HUB reported that "the Hay River broke up 1-May… and was one of the quietest breakups in memory, with the deteriorated ice slowly pushing out onto the lake. Throughout breakup, there was only a 1.3 m rise in water levels, occurring at 17:32 on 5-May.

2005: Some flooding

Source: University of Alberta/DIAND research program and the HUB (27-Apr, 2005).

The first observation flight was taken on 20-Apr, and there was thermal deterioration at the Forks (*km 1108.0*). By 21-Apr, the reach immediately upstream of Alexandra Falls was clear of ice (*km 1032.0 to 1034.0*). Ice was intact at Paradise Gardens (*km 1071.0*), Golf Course (*1088.5*) and the WSC gauge near Hay River (*1095.2*). Transverse cracking, sheet accumulations and mini-jams had formed in Reach 2 (from the NWT/AB border to Alexandra Falls). There was a jam mid-way between Escarpment Creek and Enterprise (*km 1044 to 1047*), and a mini-jam at the gravel pits (*km 1057*).

During the morning of 22-Apr, ice runs were passing over Alexandra Falls (*km 1034.0*), water levels started to spike at Paradise Gardens (*km 1071.0*) and by later in the morning there was running ice at Paradise Gardens. Overnight, the jam at Enterprise (*km 1048.0*) released and stalled between Paradise Gardens and the Golf Course (*km 1077 to 1087*). Cracking and movement began at the WSC near Hay River gauge and the Pine Point Bridge (*km 1095.2 to 1098.0*) in the morning as well.

By noon on 23-Apr, the 2 jams (one between Paradise Gardens and the Golf Course (*km 1071.0* and *1088.5*) and one between the WSC near Hay River gauge and Pine Point Bridge) shoved into one and pushed to the Chamber of Commerce Park (*km 1103.5*). This pushed into the East and West Channels. In the morning on the 24-Apr, the jam pushed through the West Channel, and the ice moved onto the lake towards the pump house. Ice runs continued to arrive throughout the day. The toe of the East Channel jam shoved to the NTCL berm (*km 1111.3*).

Around 04:00 on 25-Apr, a jam formed in the Rudd Channel, while the East Channel was full of ice to the Forks (*km 1108.0*), so all the flow went down the West Channel. The peak stage occurred on 25-Apr and some flooding occurred in the industrial areas (NTCL yard and government docks) and in the West Channel Fishing Village. Melt out occurred on 5-May.

On 27-Apr, the HUB reported that the “West Channel was overflowing with water and flood watchers Monday afternoon 25-Apr), when parts of Alaska Road got lost under water. Although the river started to breakup early Saturday morning (23-Apr) it did not reach the official 10-foot height on the WCB until 4:43 Monday morning (25-Apr).”

2006: Some flooding

Source: University of Alberta research program and the HUB (3-Apr, 2006).

The first observation flight was taken on 24-Apr. Ice was running at Paradise Gardens (*km 1071.0*) and the WSC gauge at Hay River (*km 1095.2*), while the ice upstream of Alexandra Falls was intact to the NWT/AB border (*km 945.5 to 1034.0*), other than a jam in Grumbler Rapids (*km 986.0*). Water levels were reported to be high in the creeks. Ice began to move at the Pine Point Bridge (*km 1098.0*) and shoved to the Chamber of Commerce Park (*km 1103.5*) and then into the West Channel. Ice runs continued to arrive over until 28-Apr, but the jam did not push into the East Channel.

The University of Alberta research team was unable to stay until complete melt out due to a lack of funding for the monitoring program for this year. After their departure, the peak stage and some flooding occurred in the Hay River delta, but no detailed records were kept of this. The date of melt out was obtained from the EMO West Channel Bridge water level record as 29-Apr (when the ice affected water levels dropped and leveled off).

On 3-May, the Hub newspaper reported that on “over Thursday night, flooding occurred over most of 100 St. while the the WC remained dry. It was mostly industrial areas affected. The water poured over fisherman’s Wharf, knocking a couple of fishing boats form their dry land supports. The water poured over the rail line, across NTCL’s yard and down 100 St.”

<u>2007: Minor flooding</u>

Source: University of Alberta/DIAND research program and The Hub (18-Apr and 2-May, 2007).

The first observation flight was on 19-Apr, and local ponding and flow on top of the ice cover at some locations through Town and the West Channel were noted. There was intact ice to Alexandra Falls (*km 1034.0 to 1108.0*), which was running clear water over the ice, so the Chinchaga runoff had not reached this location. Upstream of the falls for 20-30 km, ice cover is partially inundated, but has not lifted from bed/winter levels or deteriorated or cracked. A local expert thought that there would be at least 1 week until the ice run began. At the EMO meeting, several concerns were raised, including: that there was not enough warm weather, that extensive snow was in the bush which was unusual for this time of year, and if the temperatures warmed significantly, a lot of water will come.

During the observation flight on 23-Apr, transverse cracking and sheet separation was noted between Alexandra Falls (*km 1034.0*) and Meander River. On 24-Apr, there was intact ice upstream of Enterprise, and open water downstream. A 3 km jam formed between the 2 islands near the gravel pits (between *km 1062.0* and *1065.0*). There was a small accumulation at Paradise Gardens (*km 1071.0*), and the ice was intact downstream of *km 1081*.

On 25-Apr, Reach 2 was broken up and interspersed with ice runs, sheet accumulations, mini-jams and open water. Two jams had had formed in Reach 2: one 10 km downstream of Grumbler Rapids (*km 986.0*) and the other upstream of Mink Creek at *km 1023.0*. The reach between *km 1032.0* and *1034.0* (immediately upstream of Alexandra Falls) had cleared of ice and a small jam formed upstream of the island at Enterprise. Open water extended to Paradise Gardens (*km 1071.0*), where there were two jams, interspersed with open water. The ice was intact at the Golf Course (*km 1088.5*) through to the WSC gauge near Hay River (*km 1095.2*), where there was open water leading to a small jam at the Pine Point Bridge (*km 1098.0*). There was intact ice from the Pine Point Bridge to the lake, except at the Forks (*km 1108.0*) and in the West Channel, where the ice had thermally deteriorated, leaving some open water. A second observation flight on 25-Apr was taken. There was a small jam at the NWT/AB border (*km 950.0*). There were little changes in conditions in the remainder of Reach 2. The jam at Enterprise had released, and was pushing through intact ice to Paradise Gardens. The jam at the Pine Point Bridge extended back to the Golf Course.

During the morning of 26-Apr, the ice at the Pine Point Bridge (*km 1098.0*) started moving and the jam shoved to Chamber of Commerce Park (*km 1103.5*). This jam extended back to Paradise Gardens (*km 1071.0*). Ice runs were present from Mink Creek (*km 1027.0*) to Paradise Gardens (*km 1071.0*). There was an 18 km ice jam at the NWT/AB border, jammed up against intact ice from *km 957.0* to *972.0.* By 12:15, the ice jam shoved down the West Channel first, and then began pushing in the East Channel. The jam at the border was still intact.

Over the course of 27-Apr, ice continued to run down the West Channel. The jam also shoved down the East Channel to the NTCL berm (*km 1111.3*). The head of the jam was located just upstream of the Pine Point Bridge (*km 1097.0*). There were many ice runs between this jam and Grumbler Rapids (*km 986.0*). The peak stage in the delta occurred on 27-Apr and the jam melted out of the East and West Channels on 29-Apr. Some flooding occurred during this breakup.

On 2-May, the Hub newspaper reported that “flooding prompts overnight evacuation, but damage minimal. “Water backing up the Oxbow floods, over the Mackenzie Highway on Friday (27-Apr) afternoon. The road soon became impassible for small vehicles”. The river first showed signs of life on Thursday (26-Apr), with huge sheets of ice shifting behind the Hay River Court House. “We were lucky. It was thin ice and the river froze low and so the volume of ice we had to handle was not as much as normal.” “We were super lucky that the West Channel did not stop, as long as it’s flowing the water is getting away, but if it had stopped down there, it would have been pretty bad.””

2008: Significant flooding

Source: University of Alberta/DIAND research program and The Hub (7-May, 2008).

A 10 day cold snap preceded breakup, from 17-Apr to 26-Apr. The University of Alberta/DIAND research team began daily observation flights on 25-Apr. It rained overnight, between 27-Apr and 28-Apr. During the observation flight on 28-Apr, water was observed pooled on the ice cover in most of the study reach. Thermal deterioration and open leads were noted throughout the reach. On 30-Apr, the ice cracked at the EMO gauge at Alexandra Falls (*km 1032.0*). Small mini-jams had formed in Reach 2 (between the NWT/AB border (*km 945.5*) and Alexandra Falls (*km 1032.0*)) by 1-May.

On 2-May, the sail on the lip of Alexandra Falls (*km 1034.0*) released but the ice was caught by the jam in the gorge (Reach 3, *km 1032.0 to 1048.0*). Ice remained intact in Reach 4 (Enterprise (*km 1048.0*) to the Forks (*km 1108.0*)), but was thermally deteriorated and water levels were high. There was a little rain overnight, and on the morning of 4-May, the onset of breakup occurred as the ice from the WSC at Hay River gauge (*km 1095.2*) shoved into Town. The ice in

Reach 4 upstream of the WSC at Hay River gauge remained intact. The gorge jam had shoved downstream 1 km, but did not release. The jams at Grumbler Rapids (*km 986.0*) and the gorge (*km 1048.0*) released in the afternoon. By 20:00 on 5-May, both ice runs had shoved into the Hay River delta.

Significant flooding occurred on Vale Island, Old Town and in the Old Village, stranding 25 people, knocking over telephone poles and the Anglican Church off its foundations. The NTCL yards were flooded, and barges were floated out onto the lake and moved around. This jam remained in place over 6-May, while Vale Island was evacuated for 24 hours. Water levels remained high, and the ice jam melted out slowly. The log jam was in the East Channel on 7-May, and the jam melted out to the lake on 8-May. Two ice jam flood profiles were surveyed on 5-May and 6-May. The progression of the melting front was also documented.

On 7-May, the Hub newspaper reported that "floodwaters were at the highest level since 1963… Following a week of warm, sunny weather, the Hay River suddenly sprang to life late Sunday afternoon, sending sheets of thick river ice barreling through the town… both the east and west channels remained jammed with ice throughout the day Monday, before another wave of water and ice led to flooding on Vale Island.

The Hub also reported Vale Island resident Kate Osted saying that the floodwaters moved quickly. "It's my understanding this hasn't happened since 1963." Osted said her yard at the corner of 102 St. and 102 Ave. flooded in minutes as she spoke to her mother on the phone. As the water levels continued to rise, boats that had previously sat on barrels on dry land began to float freely near the Hay River Heritage Center on 110 Ave. It's probably the biggest comparable (to 1963's), and when it does happen it will happen very quickly."

2009: Some flooding

Source: University of Alberta/DIAND research program and The Hub (13-May, 2009).

A 9 day cold snap preceded breakup, from 20-Apr to 28-Apr. The University of Alberta/DIAND research team began observation flights on 26-Apr. Mini-jams were spotted in Reach 2 (between the NWT/AB border (*km 945.5*) and Alexandra Falls (*km 1034.0*)) on 26-Apr. On 30-Apr, the ice at the EMO Alexandra Falls (*km 1032.0*) gauge cracked and on 1-May, ice was spilling over the falls. By 2-May, and a jam had accumulated at Escarpment Creek (Reach 3). The onset of breakup occurred on 2-May, as the jam shoved from the WSC at Hay River gauge (*km 1095.2*) into the Hay River delta. The ice jammed in the West Channel in the mouth, and toed out at Strang's corner in the East Channel. On 4-May, several sheets broke off ice at Paradise Gardens (*km 1071.0*), and shoved into town, but ice between the gorge jam at Enterprise (*km 1048.0*) and Paradise Gardens was still intact. This pushed the toe of the jam in the East Channel to the end of Island B.

Early in the am of 6-May, the gorge jam (at *km 1048.0*) released. As this shoved in the delta, the Rudd Channel was releasing water and ice. The toe of the jam in the East Channel pushed to the lake. Some flooding occurred in the NTCL yard, the government docks, the Old Village and parts of 100, 101 and 102 St. Seven ice jam flood profiles were surveyed between 20-Apr and 7-May. The progression of the melting front was also documented. Melt out occurred on 7-May.

On 13-May, the Hub newspaper reported that "there was minimal flooding as a result of 'crummy' weather. While some flooding did occur on 100, 101 and 102 Sts, property damage was significantly lower than predicted… Hicks says relief from the flood is due to a stretch of bad weather. A cold snap just before the breakup delayed runoff from melting snow, alleviating the effects of the flood.”

2010: Some flooding

Source: University of Alberta/DIAND research program and The Hub (28-Apr, 2010)

The University of Alberta/DIAND research team began daily observation flights on 16-Apr. Thermal deterioration (hinge cracks) along the study reach had begun, but no transverse cracking had occurred. On 21-Apr, the ice went out at Meander River and mini-jams were spotted upstream of the NWT/AB border (*km 945.5*). The ice in reach 2 (from the NWT/AB border to Alexandra Falls at *km 1034.0*) had deteriorated, and transverse cracking was observed at the Island at *km 974* and a small rubble accumulation formed in Grumbler Rapids (*km 986.0*). Transverse cracking occurred at the EMO Alexandra Falls gauge (*km 1032.0*) and the WSC gauge at Hay River (HRHR) at *km 1095.2* on 22-Apr. Jams were forming in Reach 2, while a small accumulation of rubble ice had formed in the gorge (Reach 3). On 23-Apr, large jams had formed in Grumbler Rapids (*km 986.0*) and in the gorge (*km 1040.5*).

The onset of breakup occurred in the Town of Hay River on the morning of 24-Apr, as the ice from between the Pine Point Bridge *(km 1098.0*) and *km 1108.0* shoved into the delta. Over the course of the day, the jam shoved to the mouth of the West Channel, and to the NTCL berm in the East Channel. The gorge jam was still in place, but water was rushing through an open lead at the toe of the jam just upstream of the island at Enterprise (*km 1049.0*).

Just after midnight on 25-Apr, the gorge jam released and an impeded ice run occurred as it shoved its way though intact ice in Reach 4. The peak stage and some flooding occurred throughout the day. Affected areas included the NTCL yards, the government docks, and sections of 100, 101 and 102 St. Three ice jam flood profiles were surveyed; on 24-Apr, 25-Apr and 26-Apr. The progression of the melting front was also documented, and melted out to the lake on 28-Apr.

On 28-Apr, the Hub newspaper reported that “a small portion of Hay River’s Old Town was under water Monday following the breakup of the Town’s namesake river over the weekend. Town councillor Kevin Wallington said sections of 100 Street, 101 Street and 102 Street began flooding around 8 p.m. on Sunday. While water levels have since dropped, officials remain cautious as an ice jam extends from south of Chamber Park to the mouth of the river. “We’re looking at about 10 kilometers of packed ice and snow and slush between us and the mouth of the river.””

Appendix B: Melting front locations and sources for known years.

This Appendix contains the all documented melting front location information. The eleven tables in Appendix B are:

Table B.1: Melting front locations in 1987, as reported by Jasek *et. al* (1993).

Table B.2: Melting front locations in 1988, as reported by Jasek *et. al* (1993).

Table B.3: Melting front locations in 1990, as reported by Jasek *et. al* (1993).

Table B.4: Melting front locations in 1991, as reported by Jasek *et. al* (1993).

Table B.5: Melting front locations in 1992, as reported by Jasek *et. al* (1993).

Table B.6: Melting front locations in 1993, as reported by Jasek (1993).

Table B.7: Melting front locations in 2004, as reported by UA/DIAND.

Table B.8: Melting front locations in 2007, as reported by UA/DIAND.

Table B.9: Melting front locations in 2008, as reported by UA/DIAND.

Table B.10: Melting front locations in 2009, as reported by UA/DIAND.

Table B.11: Melting front locations in 2010, as reported by UA/DIAND.

Table B.1: Melting front locations in 1987, as reported by Jasek *et. al* (1993).

Channel	Date and time	River km	Channel	Date and time	River km
Main	4/28/1987 8:39	1096.38	East	4/30/1987 8:47	1108.36
	4/29/1987 14:50	1103.32		4/30/1987 13:53	1110.61
	4/29/1987 16:03	1104.12		4/30/1987 16:12	1111.27
	4/29/1987 23:45	1106.08		4/30/1987 16:36	1113.29
	4/30/1987 4:55	1107.74		4/30/1987 17:00	1114.00
			West	4/30/1987 9:19	1108.60
				4/30/1987 10:58	1109.15
				4/30/1987 12:40	1109.35
				4/30/1987 23:11	1112.00

Table B.2: Melting front locations in 1988, as reported by Jasek *et. al* (1993).

Channel	Date and time	River km	Channel	Date and time	River km
Main	4/29/1988 8:30	1097.80	East	5/1/1988 16:30	1108.05
	4/29/1988 22:00	1098.45		5/1/1988 20:15	1109.05
	4/30/1988 7:30	1101.00		5/1/1988 23:15	1109.70
	4/30/1988 11:50	1102.15	West	5/1/1988 16:30	1108.15
	4/30/1988 14:00	1102.70		5/1/1988 22:15	1109.00
	4/30/1988 16:45	1103.50			
	4/30/1988 20:00	1104.40			
	4/30/1988 22:30	1104.70			
	5/1/1988 3:20	1106.20			
	5/1/1988 6:25	1106.70			
	5/1/1988 8:29	1107.30			
	5/1/1988 8:50	1107.60			

Table B.3: Melting front locations in 1990, as reported by Jasek *et. al* (1993).

Channel	Date and time	River km	Channel	Date and time	River km
Main	4/28/1990 14:30	1094.70	East	4/30/1990 20:15	1108.30
	4/28/1990 15:00	1095.30		4/30/1990 21:10	1108.50
	4/29/1990 12:20	1095.53		4/30/1990 23:11	1109.30
	4/29/1990 16:45	1098.16		5/1/1990 11:23	1111.40
	4/30/1990 8:58	1103.40		5/1/1990 20:20	1112.20
	4/30/1990 10:35	1105.00		5/1/1990 21:10	1113.20
	4/30/1990 13:45	1105.83		5/1/1990 21:40	1113.65
	4/30/1990 13:53	1105.88	West	4/30/1990 21:05	1108.33
	4/30/1990 14:21	1106.08		4/30/1990 21:58	1108.53
	4/30/1990 19:15	1107.92		4/30/1990 23:15	1108.77
				5/1/1990 11:35	1111.00
				5/1/1990 20:39	1111.70
				5/1/1990 21:37	1111.80

Table B.4: Melting front locations in 1991, as reported by Jasek *et. al* (1993).

Channel	Date and time	River km	Channel	Date and time	River km
Main	4/25/1991 17:30	1081.50	East	4/29/1991 16:45	1108.20
	4/26/1991 16:18	1083.60		4/29/1991 20:36	1108.75
	4/27/1991 11:20	1085.80		4/29/1991 22:23	1109.35
	4/27/1991 14:30	1086.80		4/29/1991 23:00	1109.85
	4/27/1991 19:29	1089.70		4/30/1991 0:12	1110.05
	4/28/1991 10:30	1095.70		4/30/1991 0:59	1110.20
	4/28/1991 11:20	1096.25		4/30/1991 1:08	1110.40
	4/28/1991 15:14	1098.22		4/30/1991 11:33	1111.25
	4/28/1991 17:17	1098.40		4/30/1991 16:04	1111.30
	4/28/1991 22:32	1101.60		4/30/1991 19:41	1112.36
	4/29/1991 8:11	1104.70		5/1/1991 8:30	1114.20
	4/29/1991 10:55	1105.30	West	4/29/1991 16:30	1108.00
	4/29/1991 11:25	1105.90		4/29/1991 20:25	1108.00
	4/29/1991 15:30	1107.60		4/29/1991 21:29	1108.00
				4/30/1991 0:00	1108.00
				4/30/1991 1:20	1108.00
				4/30/1991 11:15	1108.67
				4/30/1991 19:00	1108.85
				5/1/1991 8:10	1110.40

Table B.5: Melting front locations in 1992, as reported by Jasek *et. al* (1993).

Channel	Date and time	River km	Channel	Date and time	River km
Main	4/28/1992 22:28	1105.00	West	4/29/1992 15:05	1108.20
	4/29/1992 8:50	1106.30		4/29/1992 15:48	1108.35
	4/29/1992 9:50	1106.40		4/29/1992 16:06	1108.50
	4/29/1992 12:50	1107.35		4/29/1992 16:47	1108.60
	4/29/1992 14:00	1107.60		4/29/1992 18:13	1108.80
East	4/29/1992 15:05	1108.20		4/29/1992 19:20	1110.40
	4/29/1992 16:16	1108.20		4/29/1992 21:00	1110.50
	4/29/1992 18:02	1108.45		4/30/1992 1:45	1111.70
	4/29/1992 19:40	1108.90			
	4/29/1992 20:00	1109.00			
	4/29/1992 21:08	1109.30			
	4/29/1992 22:18	1109.40			
	4/29/1992 23:20	1109.65			
	4/30/1992 1:45	1110.10			

Table B.6: Melting front locations in 1993, as reported by Jasek (1993).

Channel	Date and time	River km
Main	5/4/1993 17:00	1100.30
	5/5/1993 6:45	1103.80
	5/5/1993 11:36	1105.80
	5/5/1993 15:15	1108.30

Table B.7: Melting front locations in 2004, as reported by UA/DIAND.

Channel	Date and time	River km	Channel	Date and time	River km
Main	5/4/2004 19:00	1103.50	East	5/5/2004 9:00	1109.30
	5/4/2004 22:30	1105.70		5/5/2004 10:30	1111.50
	5/5/2004 2:00	1106.00	West	5/5/2004 12:00	1111.10

Table B.8: Melting front locations in 2007, as reported by UA/DIAND.

Channel	Date and time	River km	Channel	Date and time	River km
Main	4/28/2007 8:00	1100.80	East	4/29/2007 10:00	1108.30
	4/28/2007 19:45	1105.70		4/29/2007 12:30	1109.50

Table B.9: Melting front locations in 2008, as reported by UA/DIAND.

Channel	Date and time	River km	Channel	Date and time	River km
Main	5/6/2008 13:00	1105.50	East	5/7/2008 12:20	1109.20
	5/6/2008 22:00	1106.00		5/7/2008 14:48	1109.40
	5/7/2008 4:38	1107.40		5/7/2008 15:15	1109.60
	5/7/2008 7:47	1108.00		5/8/2008 21:15	1114.10
			West	5/7/2008 10:24	1108.30
				5/7/2008 14:00	1108.40
				5/8/2008 12:00	1112.40

Table B.10: Melting front locations in 2009, as reported by UA/DIAND.

Channel	Date and time	River km	Channel	Date and time	River km
Main	5/7/2009 9:48	1105.90	East	5/7/2009 21:00	1109.40
	5/7/2009 10:45	1106.00	West	5/7/2009 21:00	1110.00
	5/7/2009 11:50	1106.10			
	5/7/2009 12:04	1106.20			
	5/7/2009 12:09	1106.40			
	5/7/2009 12:12	1106.60			
	5/7/2009 12:17	1106.70			
	5/7/2009 12:25	1106.75			
	5/7/2009 13:47	1107.15			
	5/7/2009 15:03	1107.80			
	5/7/2009 16:28	1108.05			

Table B.11: Melting front locations in 2010, as reported by UA/DIAND.

Channel	Date and time	River km	Channel	Date and time	River km
Main	4/25/2010 19:45	1100.60	East	4/28/2010 10:00	1110.20
	4/26/2010 14:40	1100.69	West	4/28/2010 1:50	1108.30
	4/26/2010 20:10	1102.02		4/28/2010 10:00	1110.20
	4/27/2010 1:45	1103.30		4/28/2010 16:30	1111.20
	4/27/2010 8:30	1104.60			
	4/27/2010 12:15	1105.50			
	4/27/2010 14:00	1106.10			
	4/27/2010 16:00	1106.25			
	4/27/2010 21:30	1108.00			

Appendix C: Detailed flight photo coverage from observation flights along the Hay River.

This Appendix contains the dates of aerial observation flights from 2005 to 2010. The numbers of photographs taken per flight are also included. When a second reconnaissance flight was taken in a day, the date and number of photos taken are listed under the 2 column for each year.

Table C: Detailed observation flight photograph coverage along the Hay River (2005 to 2010).

Year	2005	2007		2008		2009		2010	
Flight	**1**	**1**	**2**	**1**	**2**	**1**	**2**	**1**	**2**
16-Apr								267	
17-Apr								341	
18-Apr								890	
19-Apr		61						828	
20-Apr								830	
21-Apr	189							959	
22-Apr	134							1115	
23-Apr	175	89						110	1,307
24-Apr						92		475	864
25-Apr	188	174	312	95		293		208	116
26-Apr		322	245			730			
27-Apr		375	64	116		711			
28-Apr				289		923			
29-Apr				295		811			
30-Apr				270		978			
1-May				543		1,157			
2-May				642		1,064	111		
3-May				587	531	1,326			
4-May				1,134	556	135	71		
5-May				924		902	760		
6-May				555		514			
Total	**686**	**1,642**		**6,537**		**10,578**		**8,310**	

Grand total flight photos: 27,753

Appendix D: Detailed descriptions of time-lapse camera stations, dates of coverage, camera operators and photograph intervals.

This Appendix lists the locations and dates of photographic coverage for each remote camera station. The organization owning the camera, the number of photographs taken per breakup season, and the interval in minutes between photographs are also listed.

Table D: Detailed list of time-lapse camera stations, dates of coverage, camera operators and photograph intervals.

Year	Site	River km	Dates	No. Photos	Photo Interval, min	Camera Owner
2007	Alexandra Falls	1034.0	Apr 20-28	3,519	5	THR/DIAND
	Paradise Gardens	1071.0	Apr 19-Apr 28	3,764	1-5	THR/DIAND
	Pine Point Bridge	1098.0	Apr 23-Apr 28	3,670	1-5	THR/DIAND
2008	Meander River	811.0	Apr 25-May 6	350	30	UA
	Alexandra Falls	1034.0	Apr 26-May 6	1,953	5	THR/DIAND
	Paradise Gardens	1071.0	Apr 26-May 6	1,971	5	THR/DIAND
	WSC Gauge @ HR	1095.0	Apr 26-May 6	1,959	5	UA
	Pine Point Bridge	1098.0	Apr 26-May 6	1,938	5	THR/DIAND
2009	Meander River	811.0	Apr 16-May 7	806	30	UA
	NWT/AB Border	945.5	Apr 16-Apr 30	1,719	15	UA
	Alexandra Falls	1034.0	Apr 26-May 7	1,946	10	THR/DIAND
	Paradise Gardens	1071.0	Apr 25-May 7	1,832	30	THR/DIAND
	Golf Course	1088.5	Apr 29-May 7	974	5	UA
	WSC Gauge @ HR	1095.0	Apr 19-May 7	3,312	5	UA
	Pine Point Bridge	1098.0	Apr 29-May 7	1,471	30	THR/DIAND
	Cambridge Hotel	1106.1	May 1-May 7	6,402	1	UA
	NTCL	1111.3	Apr 28-May 7	792	5	UA
2010	Meander River	811.0	Apr 15-Apr 29	672	30	UA
	NWT/AB Border	945.5	Apr 17-Apr 29	3,529	5	UA
	Alexandra Falls	1034.0	Apr 18-Apr 26	805	15	THR/DIAND
	Alexandra Falls	1034.0	Apr 18-Apr 26	2,243	5	UA
	Enterprise	1048.0	20-Apr	1,534	-	UA
	Paradise Gardens	1071.0	Apr 16-Apr 26	969	15	THR/DIAND
	Paradise Gardens	1071.0	Apr 15-Apr 16	2,607	5	UA
	Golf Course	1088.5	Apr 18-Apr 24	1,779	5	UA
	WSC Gauge @ HR	1095.0	Apr 17-Apr 26	875	5	UA
	Pine Point Bridge	1098.0	Apr 19-Apr 27	658	15	THR/DIAND
	Commerce Park	1103.6	Apr 22-Apr 28	1,636	5	UA
	Cambridge Hotel	1106.1	Apr 20-Apr 28	1,334	5	UA
	Forks - East Channel	1108.4	Apr 23-Apr 28	1,440	5	UA
	Forks - West Channel	1108.4	Apr 23-Apr 28	1,428	5	UA
	NTCL	1111.3	Apr 22-Apr 27	1,365	5	UA
	Government Docks	1113.4	Apr 24-Apr 28	812	5	UA

Appendix E: Names, locations, years of coverage and water level recording increments at the six WSC water level gauges.

This Appendix contains the details of six WSC water level gauge stations, including their names, locations, years and dates of data coverage and the time increment that water levels were recorded. The six tables in Appendix E are:

Table E.1: Dates of coverage and data collection increment at the Sousa Creek near High Level (SCHL 07OA001) WSC gauge station.

Table E.2: Dates of coverage and data collection increment at the Chinchaga River near High Level (CRHL 07OC001) WSC gauge station.

Table E.3: Dates of coverage and data collection increment at the Steen River near Steen River (CRHL 07OB004) WSC gauge station.

Table E.4: Dates of coverage and data collection increment at the Hay River near Meander River (CRHL 07OB003) WSC gauge station.

Table E.5: Dates of coverage and data collection increment at the NWT/AB border (HRNWTAB 07OB008) WSC gauge station.

Table E.6: Dates of coverage and data collection increment at the Hay River near Hay River (HRNWTAB 07OB001) WSC gauge station.

Table E.1: Dates of coverage and data collection increment at the Sousa Creek near High Level (SCHL 07OA001) WSC gauge station.

Year	Start of Period	End of Period	Frequency of Measurement
2004	19-Apr 13:00	10-May 00:00	60 min
2005	17-Apr 01:00	09-May 23:30	60 min
2006	17-Apr 00:00	09-May 23:30	60 min
2007	19-Apr 14:00	09-May 23:30	60 min
2008	17-Apr 00:00	10-May 00:00	60 min
2009	17-Apr 01:00	09-May 23:30	60 min
2010	01-Apr 00:00	30-May 23:30	30 min

Table E.2: Dates of coverage and data collection increment at the Chinchaga River near High Level (CRHL 07OC001) WSC gauge station.

Year	Start of Period	End of Period	Frequency of Measurement
2004	17-Apr 00:30	10-May 00:00	60 min
2005	19-Apr 14:00	10-May 00:00	60 min
2006	17-Apr 00:00	10-May 00:00	60 min
2007	20-Apr 14:00	09-May 23:30	60 min
2008	17-Apr 01:00	10-May 00:00	60 min
2009	17-Apr 01:00	09-May 23:30	60 min
2010	01-Apr 00:00	30-May 23:30	30 min

Table E.3: Dates of coverage and data collection increment at the Steen River near Steen River (CRHL 07OB004) WSC gauge station.

Year	Start of Period	End of Period	Frequency of Measurement
2007	17-Apr 01:00	09-May 22:00	60 min
2008	17-Apr 00:00	09-May 22:00	60 min
2009	17-Apr 01:00	09-May 23:00	60 min
2010	01-Apr 00:00	30-May 23:00	30 min

Table E.4: Dates of coverage and data collection increment at the Hay River near Meander River (CRHL 07OB003) WSC gauge station.

Year	Start of Period	End of Period	Frequency of Measurement
2006	08-May 12:00	09-May 23:30	60 min
2007	01-Apr 00:30	09-May 23:30	60 min
2008	01-Apr 00:30	09-May 23:30	60 min
2009	01-Apr 00:30	09-May 23:30	60 min
2010	01-Apr 00:00	30-May 23:30	30 min

Table E.5: Dates of coverage and data collection increment at the NWT/AB border (HRNWTAB 07OB008) WSC gauge station.

Year	Start of Period	End of Period	Frequency of Measurement
2003	24-Apr 21:00	10-May 23:00	60 min
2004	26-Apr 00:00	08-May 00:00	15 min
2005	12-Apr 15:00	18-May 17:00	60 min
2006	22-Apr 00:00	01-May 23:10	5 min
2007	23-Apr 00:00	03-May 00:00	15 min
2008	01-May 00:00	08-May 00:00	15 min
2009	30-Apr 00:00	09-May 00:00	15 min
2010	13-Apr 00:00	10-May 23:45	15 min

Table E.6: Dates of coverage and data collection increment at the Hay River near Hay River (HRNWTAB 07OB001) WSC gauge station.

Year	Start of Period	End of Period	Frequency of Measurement
2003	17-Apr 10:00	09-May 22:00	60 min
2004	17-Apr 01:00	09-May 23:00	60 min
2005	17-Apr 01:00	09-May 23:00	60 min
2006	17-Apr 01:00	09-May 23:00	60 min
2007	17-Apr 01:00	10-May 00:00	60 min
2008	01-Jan 00:00	01-Sep 00:00	60 min
2009	14-Apr 01:00	10-May 23:00	60 min
2010	10-Apr 00:00	10-May 07:45	15 min

Appendix F: Details of the four EMO water level gauge stations in the study reach.

This Appendix contains the details of four EMO water level gauge stations, including their locations, years and dates of data coverage and the time increment that water levels were recorded. The four tables in Appendix F are:

Table F.1: Dates of coverage and data collection increment at the EMO Alexandra Falls gauge at *km 1032.0*.

Table F.2: Dates of coverage and data collection increment at the EMO Paradise Gardens gauge at *km 1067.9*.

Table F.3: Dates of coverage and data collection increment at the Pine Point Bridge gauge at *km 1098.1*.

Table F.4: Dates of coverage and data collection increment at the West Channel Bridge station at *km 1108.3*.

Table F.1: Dates of coverage and data collection increment at the EMO Alexandra Falls gauge at *km 1032.0*.

Year	Start of Period	End of Period	Frequency of Measurement
2003	23-Apr 07:00	23-Apr 10:00	60 minute
	23-Apr 10:00	02-May 09:29	1 minute
2004	17-Apr 13:40	26-Apr 23:07	10 minutes
	26-Apr 23:07	08-May 14:50	1 minute
	08-May 14:50	07-May 14:50	10 minutes
2005	11-Apr 09:50	19-Apr 22:18	10 minutes
	19-Apr 22:18	06-May 21:20	1 minute
	06-May 21:20	07-Aug 18:10	10 minutes
2006	08-Apr 11:10	24-Apr 12:44	10 minutes
	24-Apr 12:44	30-Apr 13:10	1 minute
	30-Apr 13:10	11-Jun 19:40	10 minutes
2007	13-Apr 10:20	24-Apr 20:51	10 minutes
	24-Apr 20:51	07-May 23:00	1 minute
	07-May 23:00	19-Jun 13:00	10 minutes
2008	14-Apr 10:00	02-May 10:12	10 minutes
	02-May 10:12	09-May 13:00	1 minute
	09-May 13:00	11-Jun 13:30	10 minutes
2009	22-Apr 10:40	29-Apr 13:01	10 minutes
	29-Apr 13:01	07-May 16:39	1 minute
2010	22-Apr 12:10	26-Apr 12:10	5 minutes

Table F.2: Dates of coverage and data collection increment at the EMO Paradise Gardens gauge at *km 1067.9*.

Year	Start of Period	End of Period	Frequency of Measurement
2003	20-Apr 09:40	20-Apr 16:30	10 minutes
	20-Apr 16:30	06-May 12:10	1 minute
2004	17-Apr 13:20	26-Apr 23:10	10 minutes
	26-Apr 23:10	08-May 14:50	1 minute
	08-May 14:50	10-May 07:30	10 minutes
2005	08-Apr 14:30	19-Apr 22:17	10 minutes
	19-Apr 22:17	06-May 21:20	1 minute
	06-May 21:20	04-Jul 12:00	10 minutes
2006	05-Apr 08:00	24-Apr 12:43	10 minutes
	24-Apr 12:43	30-Apr 13:10	1 minute
	30-Apr 13:10	11-Jun 19:20	10 minutes
2007	13-Apr 11:30	24-Apr 20:51	10 minutes
	24-Apr 20:51	07-May 23:00	1 minute
	07-May 23:00	05-Jun 11:00	10 minutes
2008	14-Apr 12:10	03-May 10:11	10 minutes
	03-May 10:11	12-Jun 13:30	1 minute
2009	21-Apr 11:20	29-Apr 12:58	10 minutes
	29-Apr 12:58	07-May 16:48	1 minute
2010	22-Apr 13:05	28-Apr 13:01	1 minute

Table F.3: Dates of coverage and data collection increment at the Pine Point Bridge gauge at *km 1098.1*.

Year	Start of Period	End of Period	Frequency of Measurement
2003	20-Apr 11:00	20-Apr 16:30	10 minutes
	20-Apr 16:30	06-May 12:08	1 minute
2004	17-Apr 12:50	26-Apr 23:08	10 minutes
	26-Apr 23:08	08-May 14:50	1 minute
	08-May 14:50	10-May 07:30	10 minutes
2005	11-Apr 11:30	19-Apr 22:15	10 minutes
	19-Apr 22:15	06-May 21:20	1 minute
	06-May 21:20	04-Jul 12:00	10 minutes
2006	05-Apr 10:10	24-Apr 12:41	10 minutes
	24-Apr 12:41	30-Apr 13:10	1 minute
	30-Apr 13:10	11-Jun 19:30	10 minutes
2007	17-Apr 14:10	24-Apr 20:47	10 minutes
	24-Apr 20:47	07-May 22:50	1 minute
	07-May 22:50	19-Jun 13:00	10 minutes
2008	15-Apr 09:30	03-May 10:08	10 minutes
	03-May 10:08	10-May 13:00	1 minute
	10-May 13:00	12-Jun 13:30	10 minutes
2009	20-Apr 11:30	29-Apr 12:56	10 minutes
	29-Apr 12:56	07-May 16:46	1 minute
2010	22-Apr 13:03	28-Apr 13:01	1 minute

Table F.4: Dates of coverage and data collection increment at the West Channel Bridge station at *km 1108.3*.

Year	Start of Period	End of Period	Frequency of Measurement
2003	20-Apr 11:32	06-May 12:09	1 minutes
2004	17-Apr 12:40	26-Apr 23:11	10 minutes
	26-Apr 23:11	08-May 14:50	1 minute
	08-May 14:50	10-May 07:30	10 minutes
2005	14-Apr 13:50	19-Apr 22:13	10 minutes
	19-Apr 22:13	06-May 21:20	1 minute
	06-May 21:20	04-Jul 12:00	10 minutes
2006	05-Apr 10:00	24-Apr 12:42	10 minutes
	24-Apr 12:42	30-Apr 13:10	1 minute
	30-Apr 13:10	11-Jun 19:10	10 minutes
2007	16-Apr 15:00	24-Apr 20:48	10 minutes
	24-Apr 20:48	07-May 22:50	1 minute
	07-May 22:50	05-Jun 11:00	10 minutes
2008	15-Apr 08:40	03-May 10:09	10 minutes
	03-May 10:09	08-Jun 19:30	1 minute
2009	16-Apr 09:30	29-Apr 12:57	10 minutes
	29-Apr 12:57	07-May 16:47	1 minute
2010	21-Apr 13:04	27-Apr 13:00	1 minute

Appendix G: Hydrographs from the six EMO and WSC gauge stations located in the Hay River study reach.

The hydrographs from the six EMO and WSC gauge stations located in the Hay River study reach were analyzed. When known, the dates of first transverse cracking, local ice jamming and ice jam releasing were annotated on each hydrograph. The years and site of each hydrograph figure are specified as follows:

Figures G.1 to G.8: WSC Hay River near the border (HRNWTAB) gauge station, from 2003 to 2010.

Figures G.9 to G.16: EMO Alexandra Falls gauge station, from 2003 to 2010.

Figures G.17 to G.24: EMO Paradise Gardens gauge station, from 2003 to 2010.

Figures G.25 to G.32: WSC Hay River near Hay River (HRHR) gauge station, from 2003 to 2010.

Figures G.33 to G.40: EMO Pine Point Bridge gauge station, from 2003 to 2010.

Figures G.41 to G.48: EMO West Channel Bridge gauge station, from 2003 to 2010.

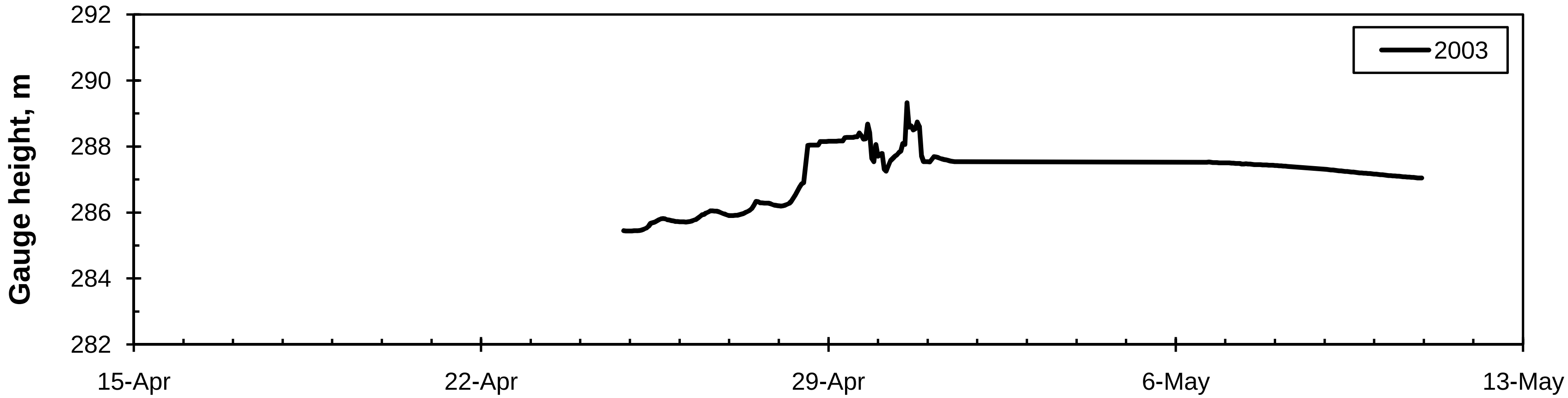


Figure G.1: Water levels and known breakup dates at the NWT/AB border station (WSC 070B008) during breakup in 2003.

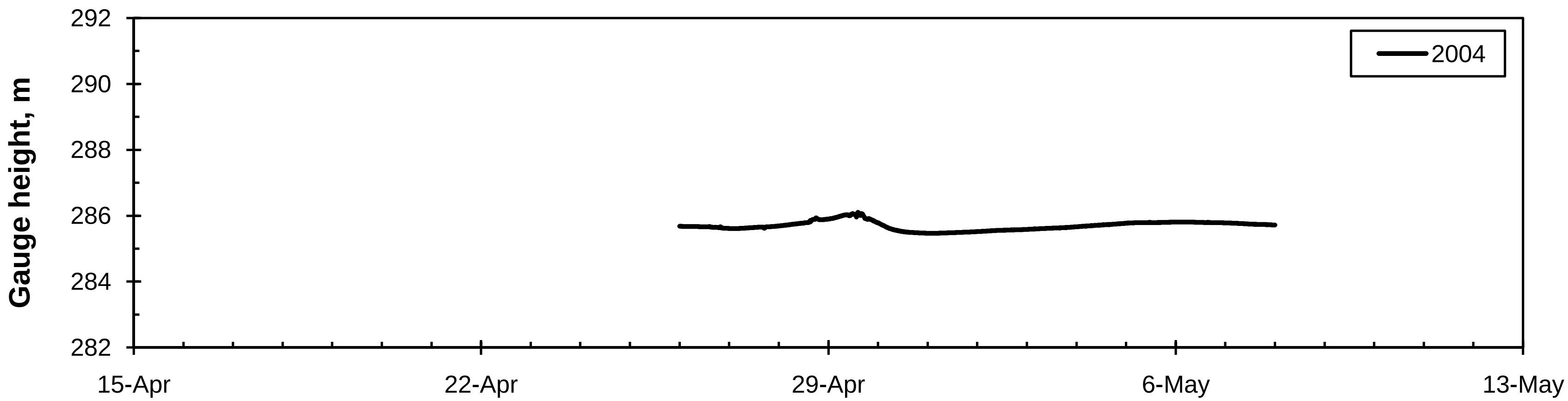


Figure G.2: Water levels and known breakup dates at the NWT/AB border station (WSC 070B008) during breakup in 2004.

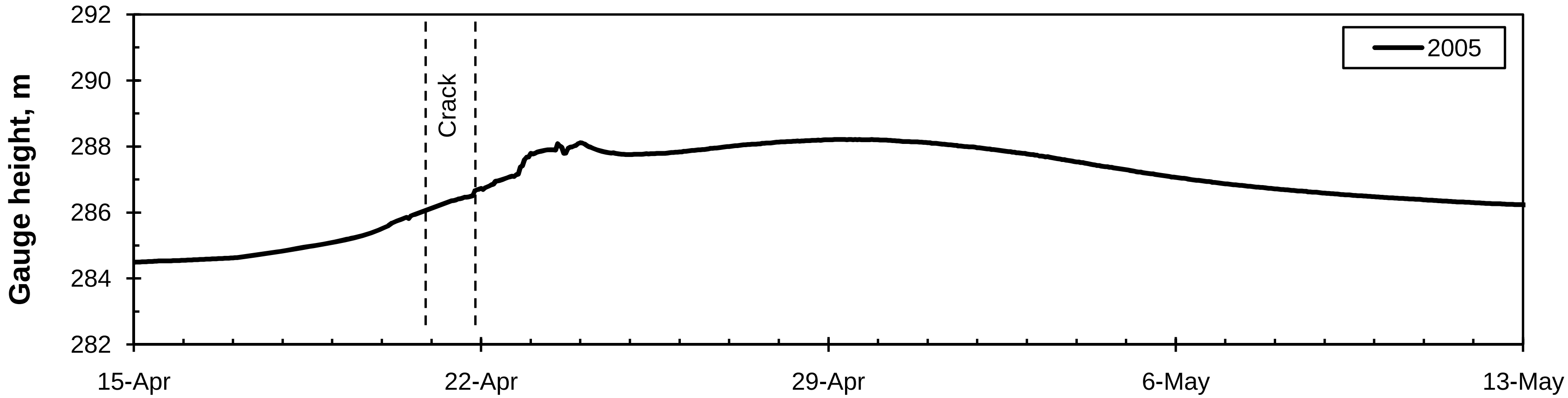


Figure G.3: Water levels and known breakup dates at the NWT/AB border station (WSC 070B008) during breakup in 2005.

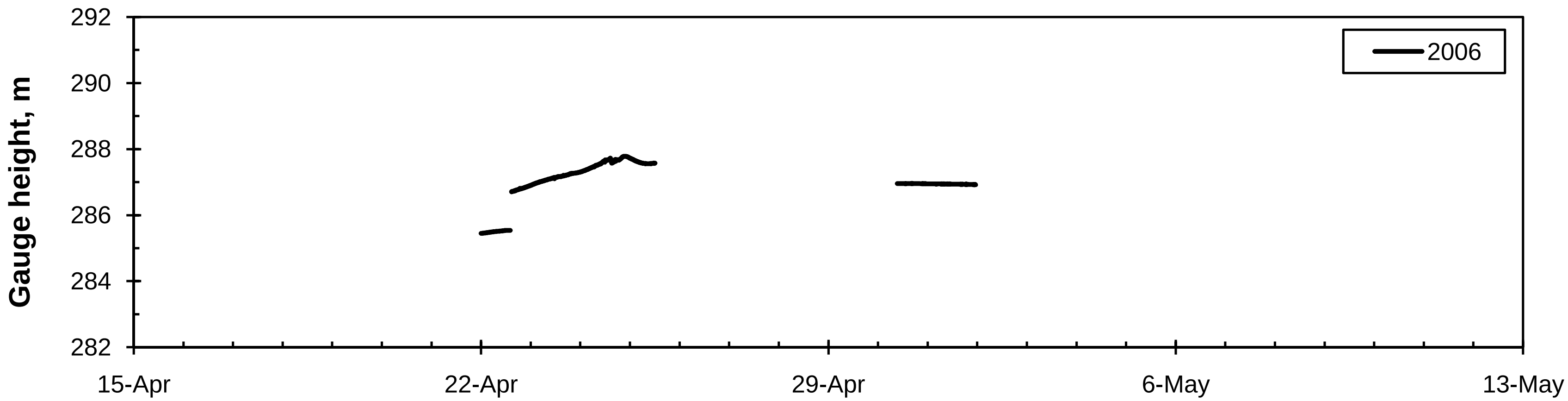


Figure G.4: Water levels and known breakup dates at the NWT/AB border station (WSC 070B008) during breakup in 2006.

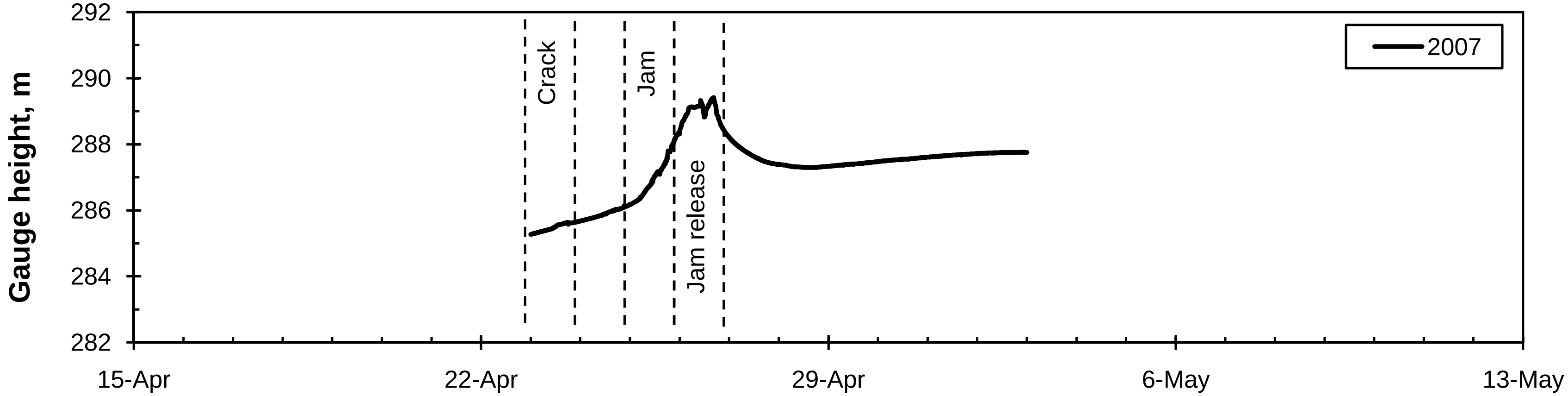


Figure G.5: Water levels and known breakup dates at the NWT/AB border station (WSC 070B008) during breakup in 2007.

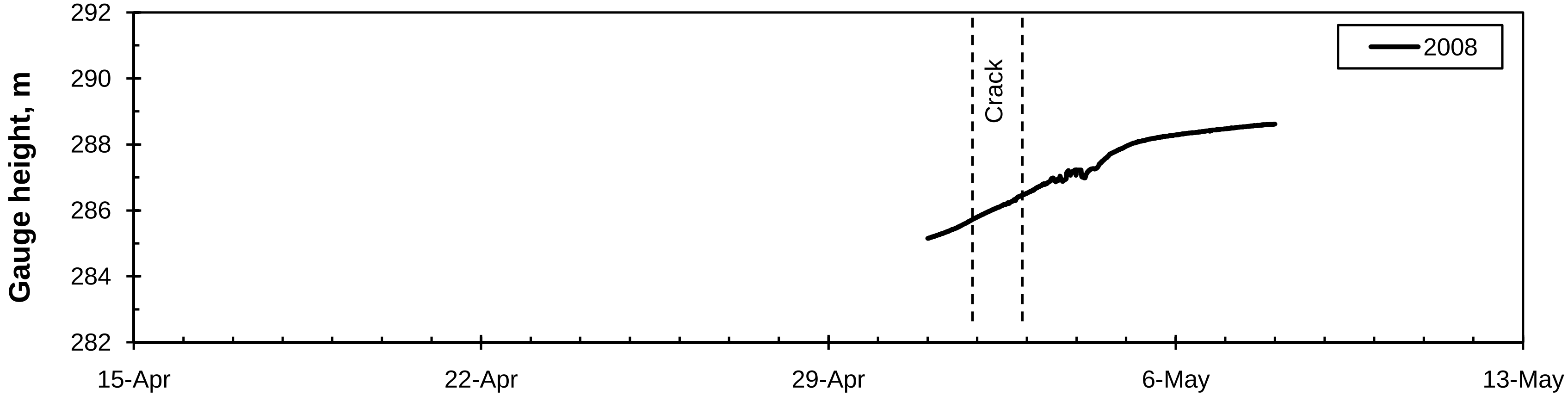


Figure G.6: Water levels and known breakup dates at the NWT/AB border station (WSC 070B008) during breakup in 2008.

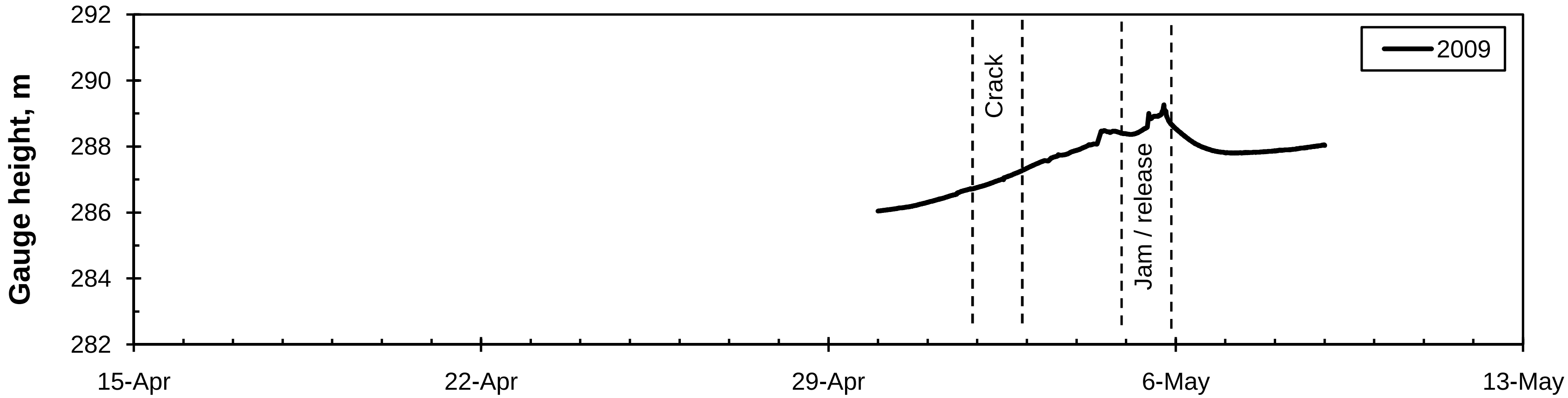


Figure G.7: Water levels and known breakup dates at the NWT/AB border station (WSC 070B008) during breakup in 2009.

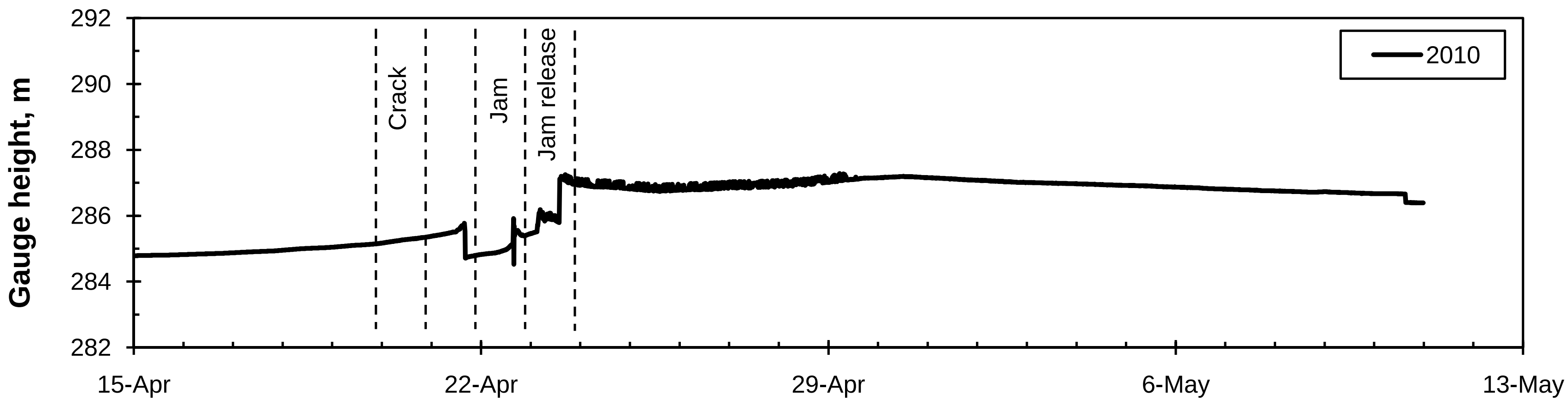


Figure G.8: Water levels and known breakup dates at the NWT/AB border station (WSC 070B008) during breakup in 2010.

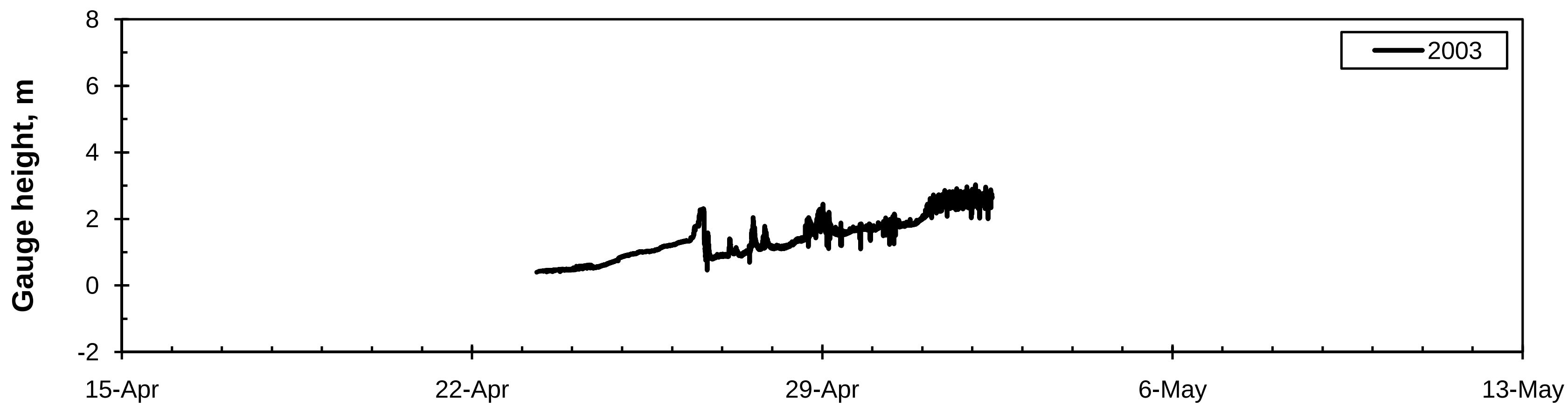


Figure G.9: Water levels and known breakup dates at the EMO Alexandra Falls station during breakup in 2003.

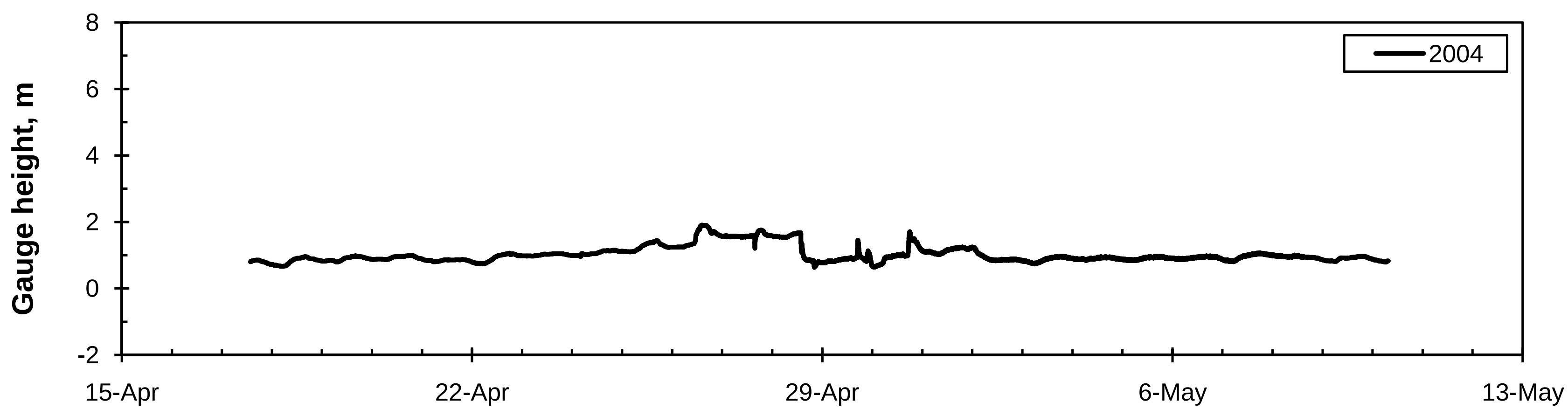


Figure G.10: Water levels and known breakup dates at the EMO Alexandra Falls station during breakup in 2004.

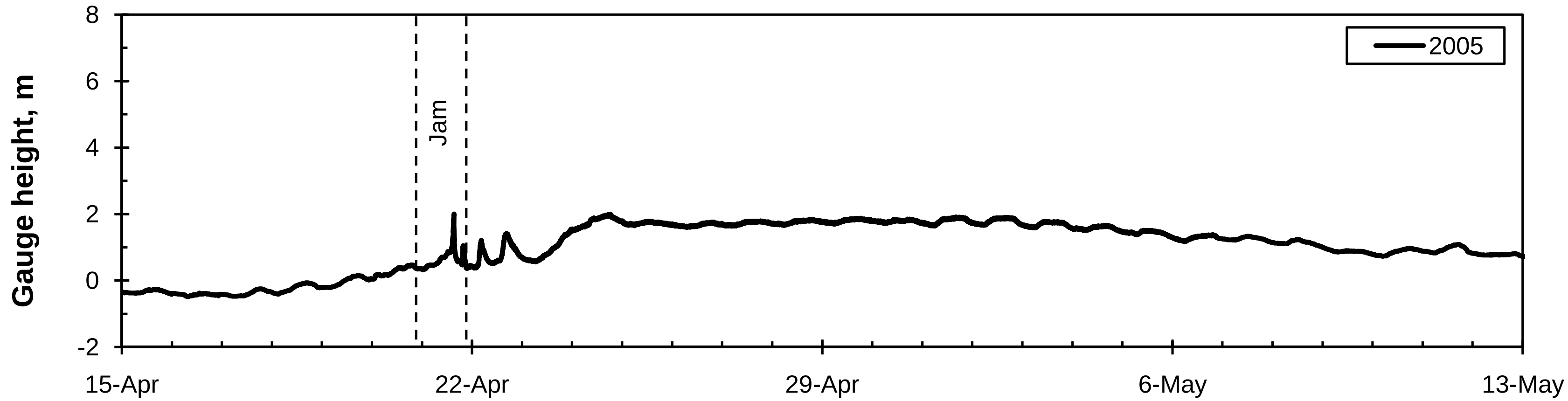


Figure G.11: Water levels and known breakup dates at the EMO Alexandra Falls station during breakup in 2005.

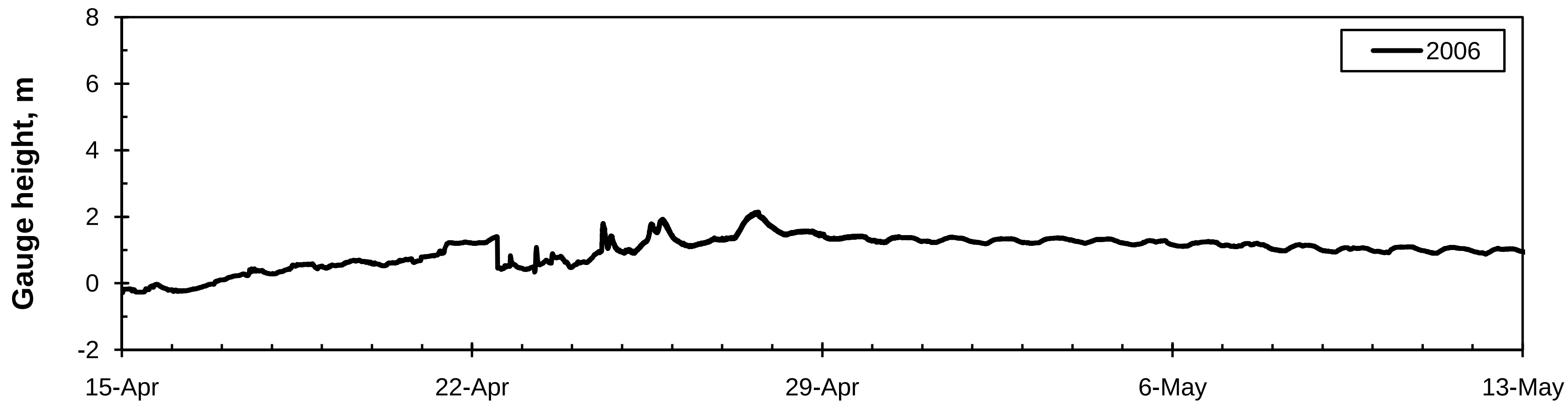


Figure G.12: Water levels and known breakup dates at the EMO Alexandra Falls station during breakup in 2006.

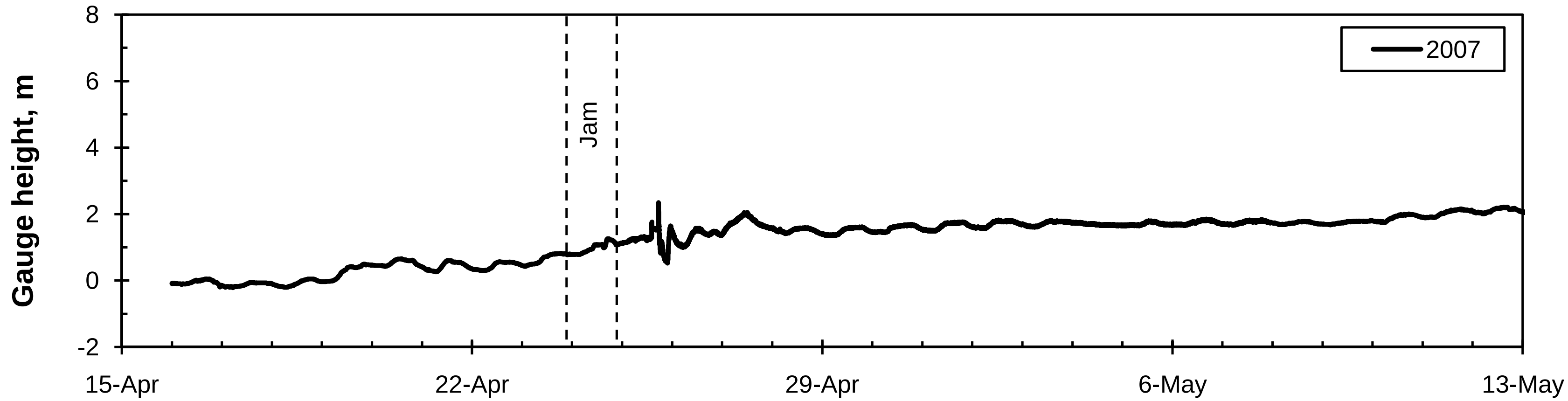


Figure G.13: Water levels and known breakup dates at the EMO Alexandra Falls station during breakup in 2007.

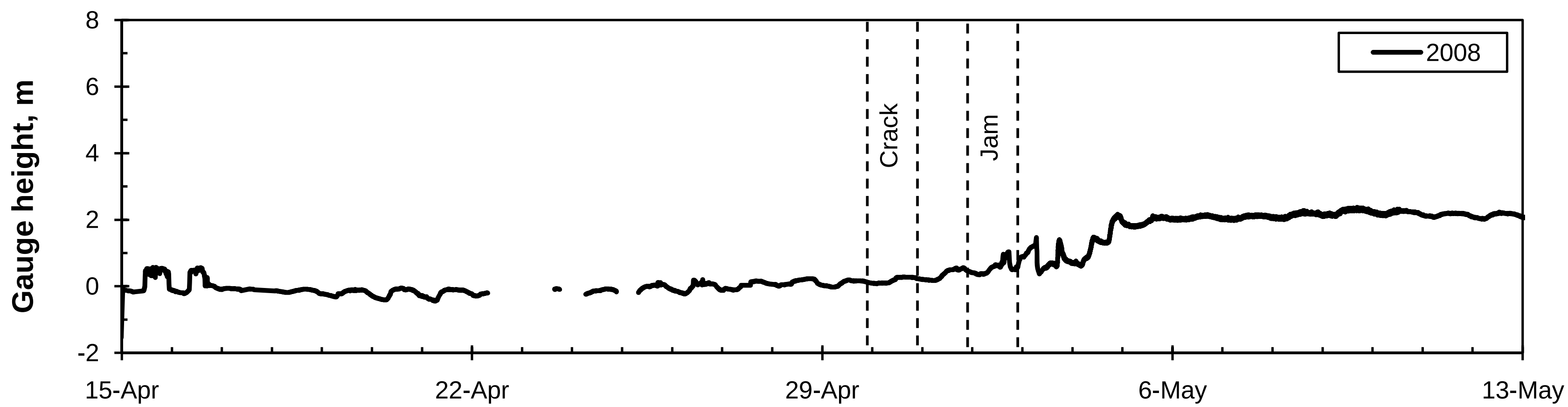


Figure G.14: Water levels and known breakup dates at the EMO Alexandra Falls station during breakup in 2008.

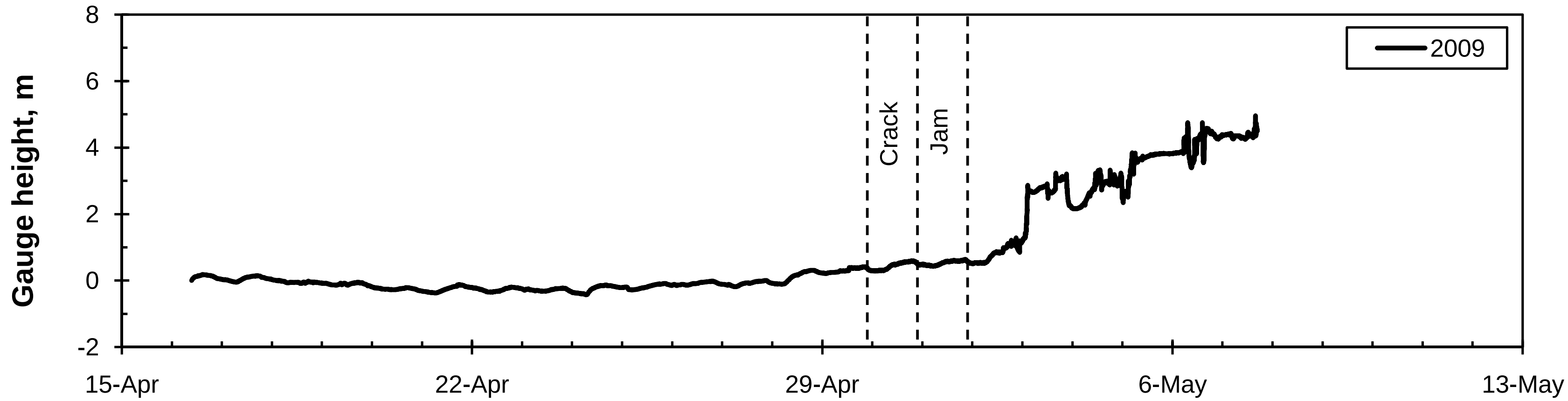


Figure G.15: Water levels and known breakup dates at the EMO Alexandra Falls station during breakup in 2009.

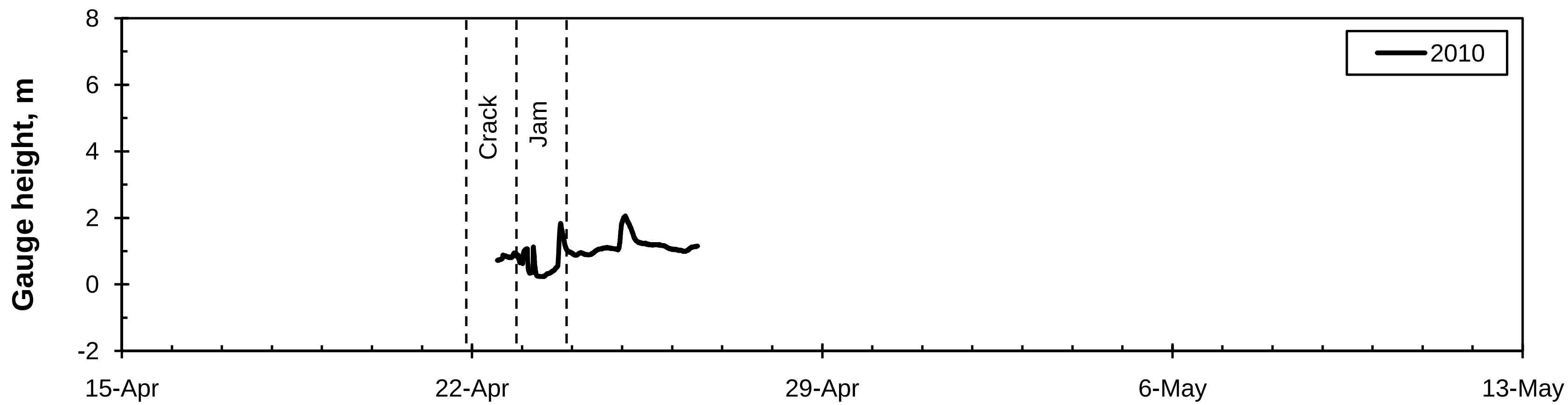


Figure G.16: Water levels and known breakup dates at the EMO Alexandra Falls station during breakup in 2010.

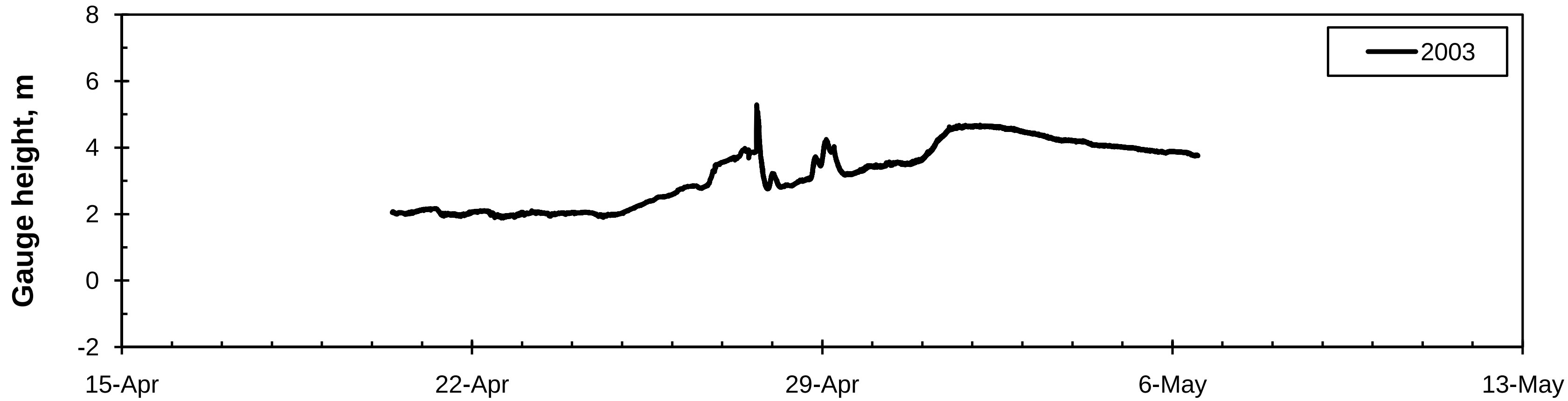


Figure G.17: Water levels and known breakup dates at the EMO Paradise Gardens station during breakup in 2003.

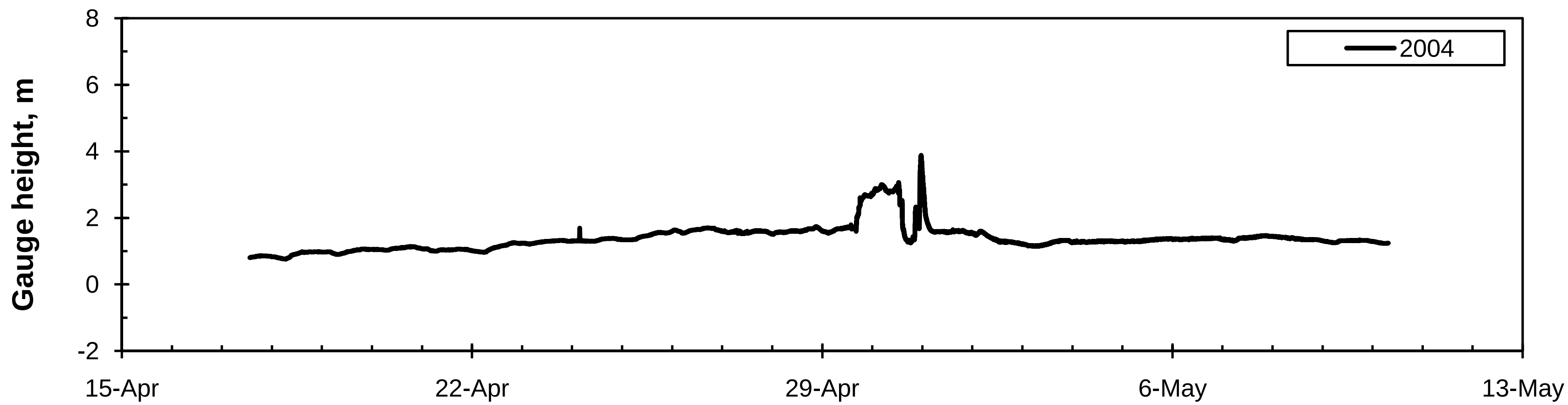


Figure G.18: Water levels and known breakup dates at the EMO Paradise Gardens station during breakup in 2004.

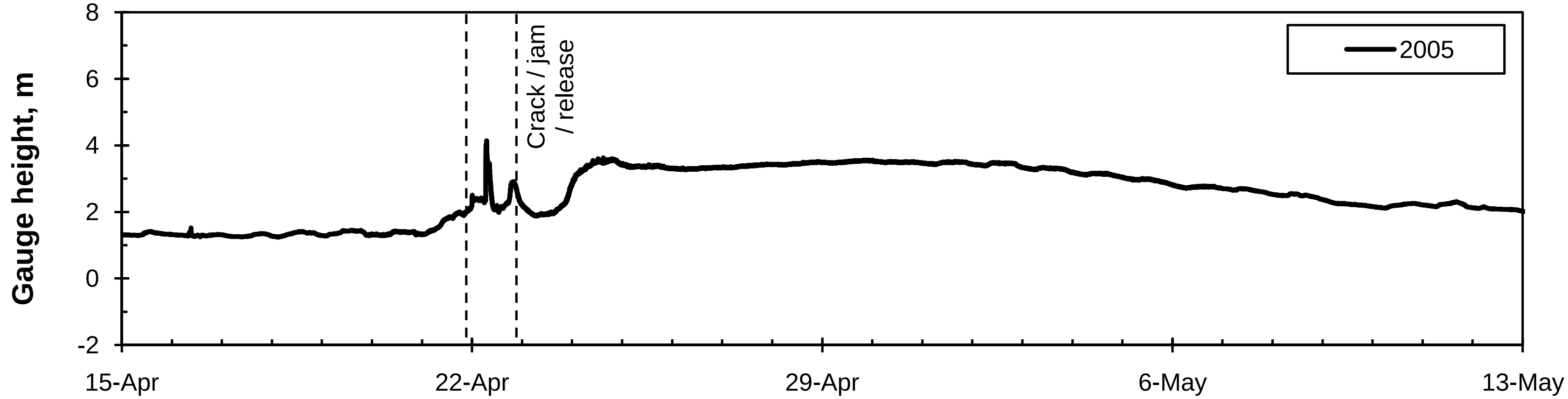


Figure G.19: Water levels and known breakup dates at the EMO Paradise Gardens station during breakup in 2005.

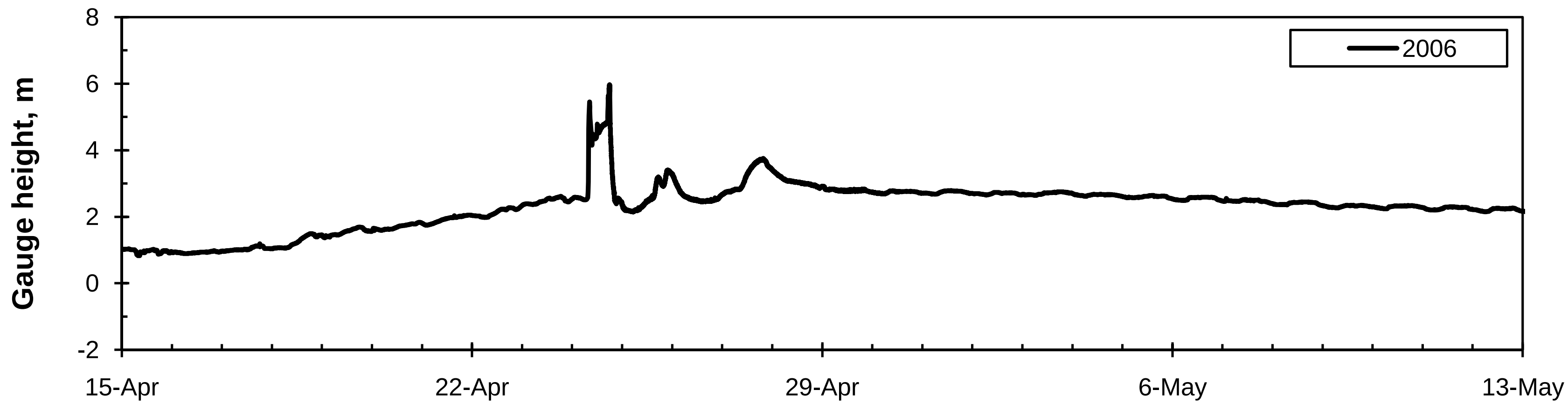


Figure G.20: Water levels and known breakup dates at the EMO Paradise Gardens station during breakup in 2006.

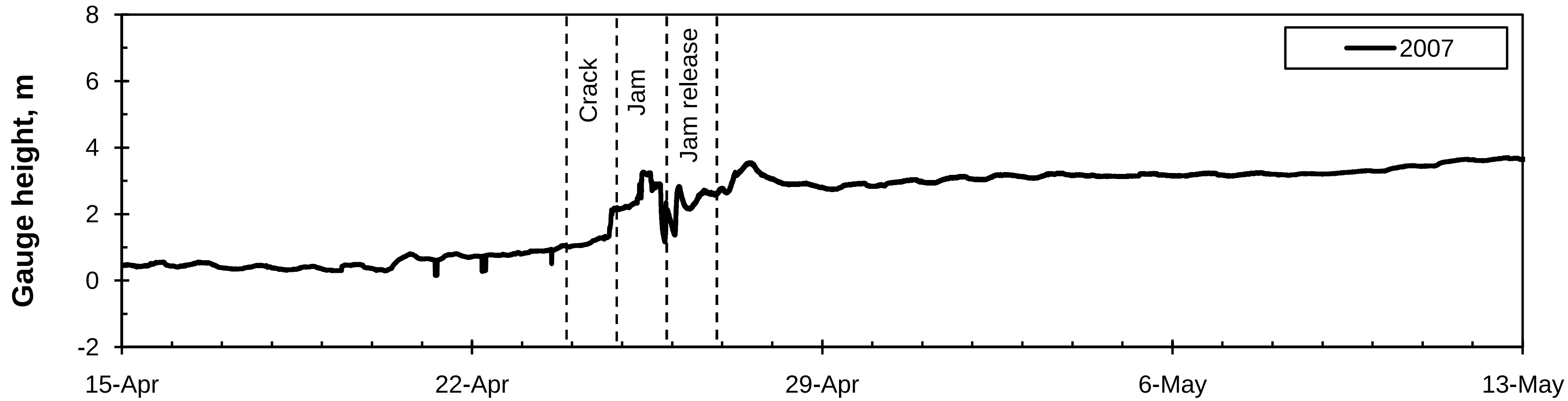


Figure G.21: Water levels and known breakup dates at the EMO Paradise Gardens station during breakup in 2007.

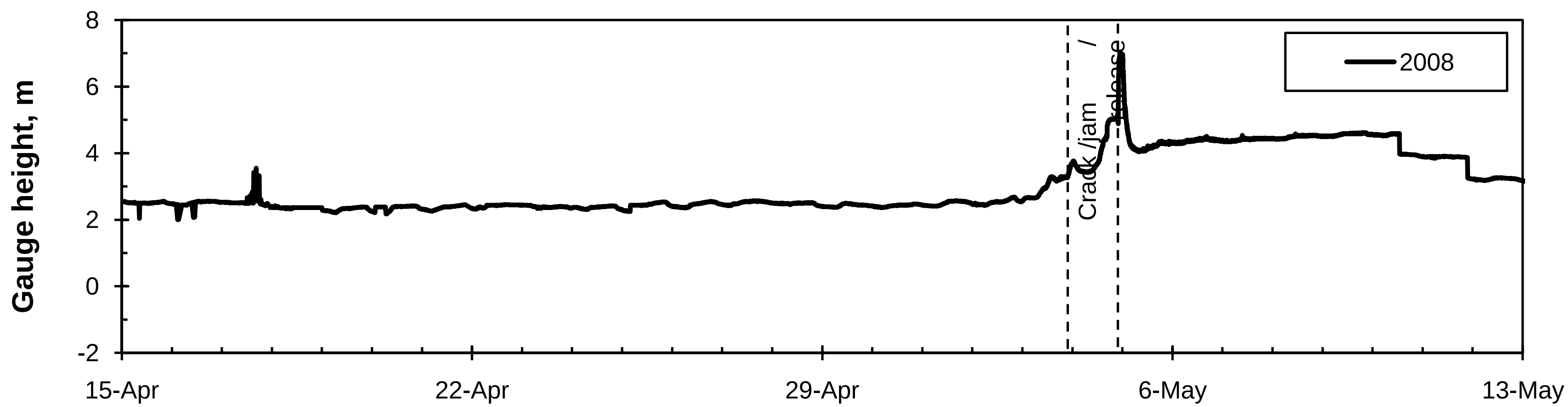


Figure G.22: Water levels and known breakup dates at the EMO Paradise Gardens station during breakup in 2008.

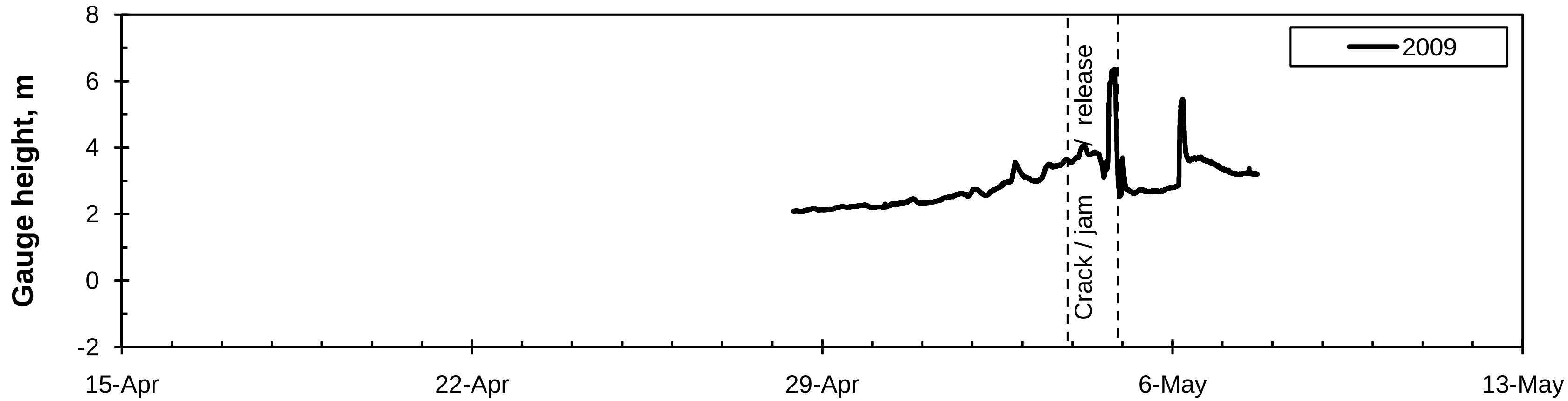


Figure G.23: Water levels and known breakup dates at the EMO Paradise Gardens station during breakup in 2009.

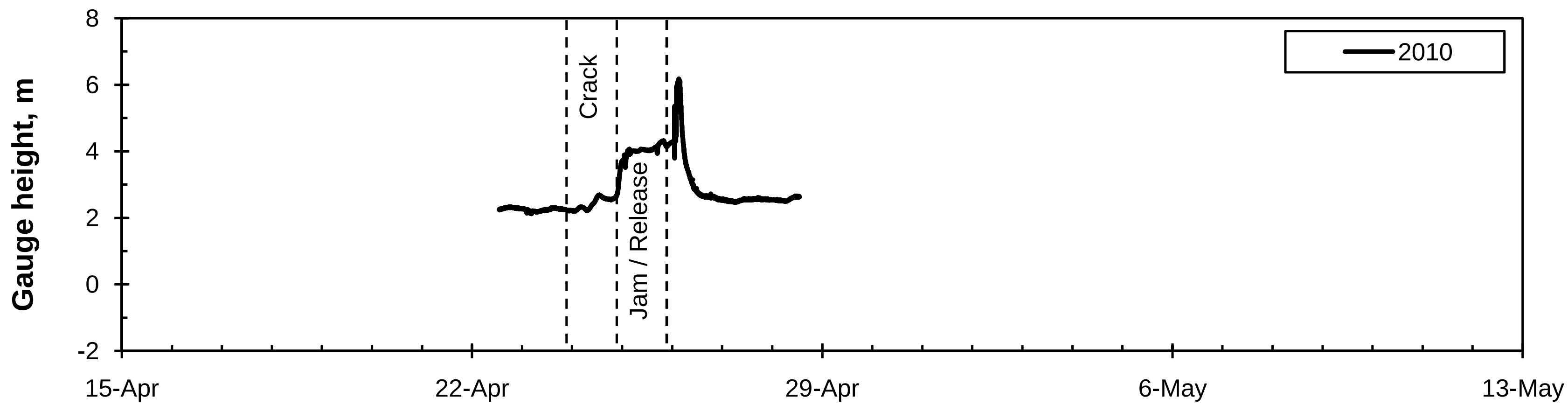


Figure G.24: Water levels and known breakup dates at the EMO Paradise Gardens station during breakup in 2010.

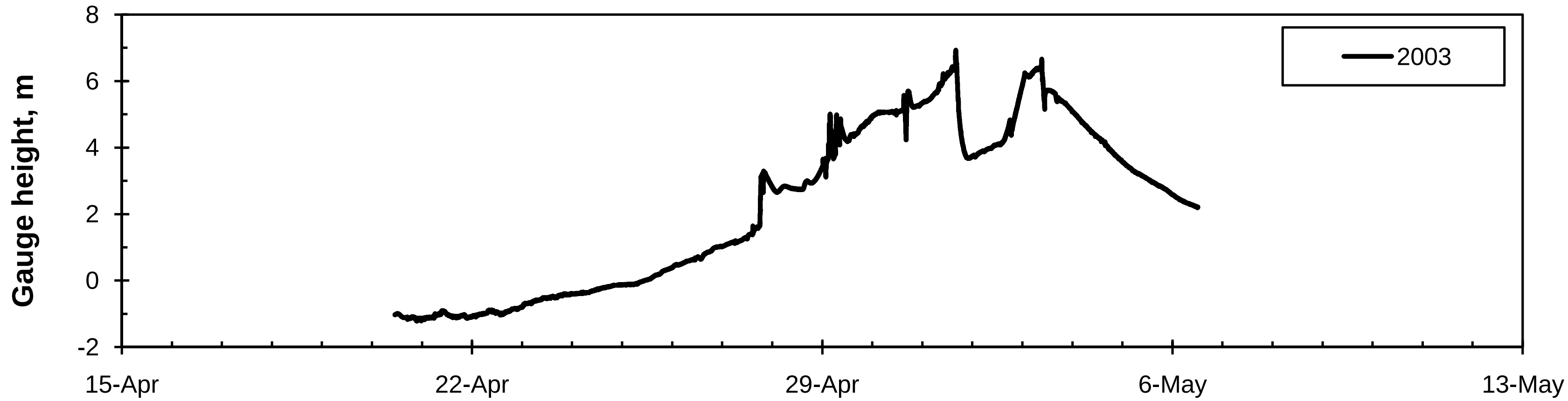


Figure G.33: Water levels and known breakup dates at the EMO Pine Point Bridge station during breakup in 2003.

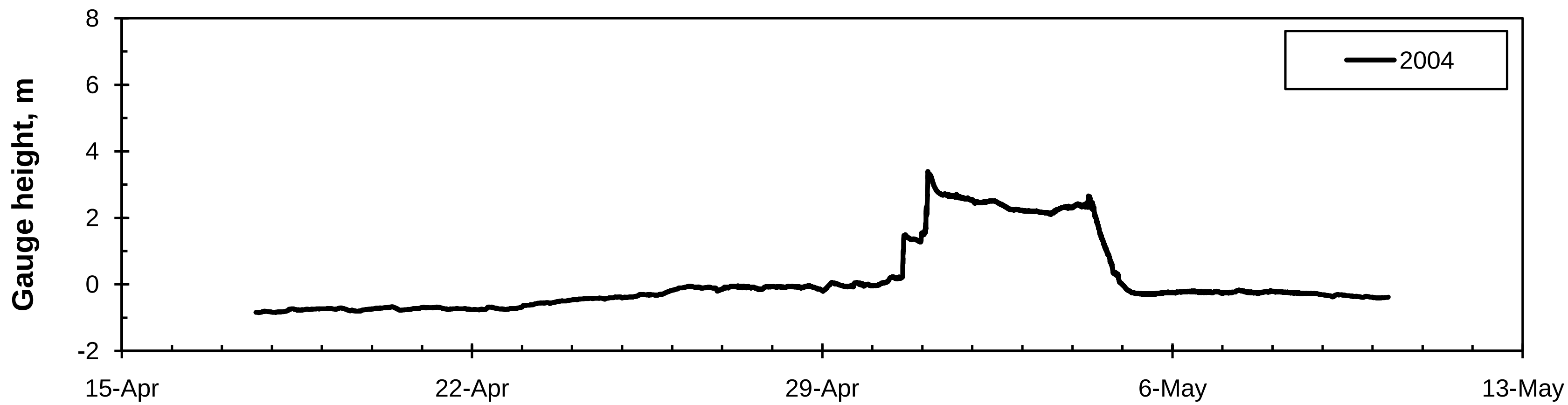


Figure G.34: Water levels and known breakup dates at the EMO Pine Point Bridge station during breakup in 2004.

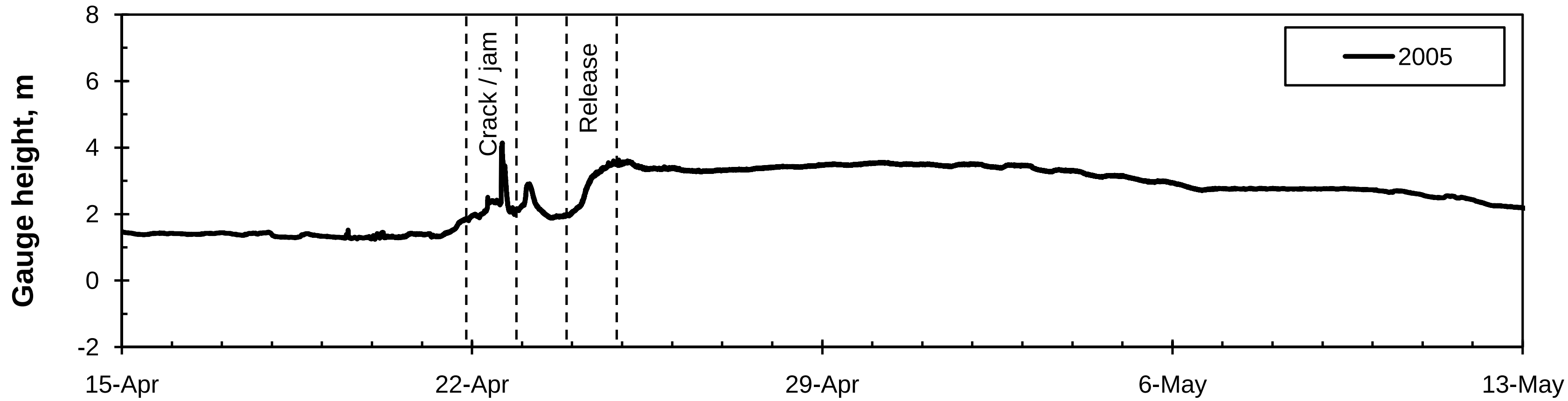


Figure G.35: Water levels and known breakup dates at the EMO Pine Point Bridge station during breakup in 2005.

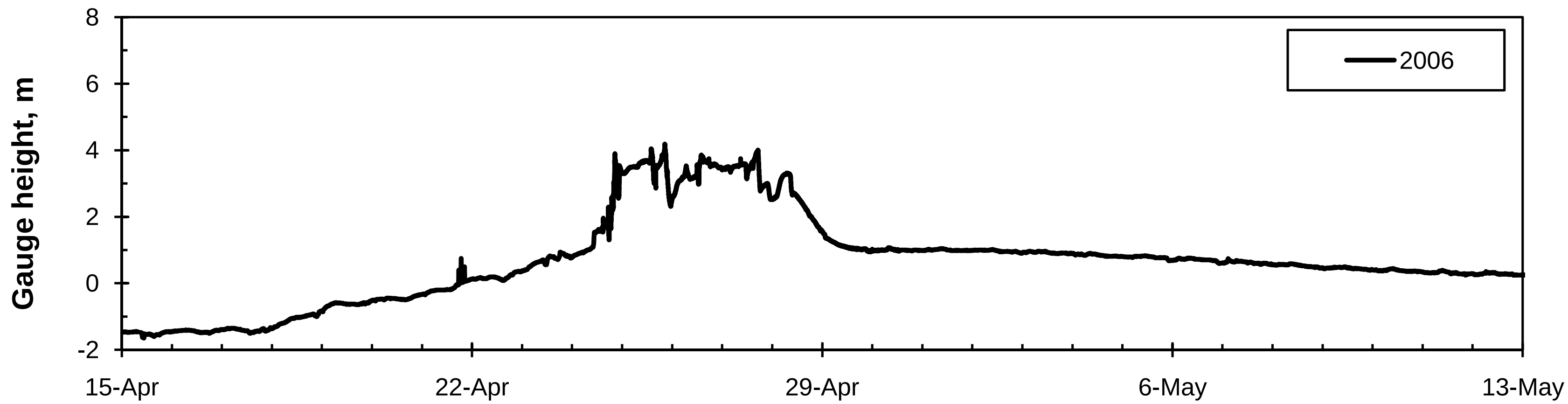


Figure G.36: Water levels and known breakup dates at the EMO Pine Point Bridge station during breakup in 2006.

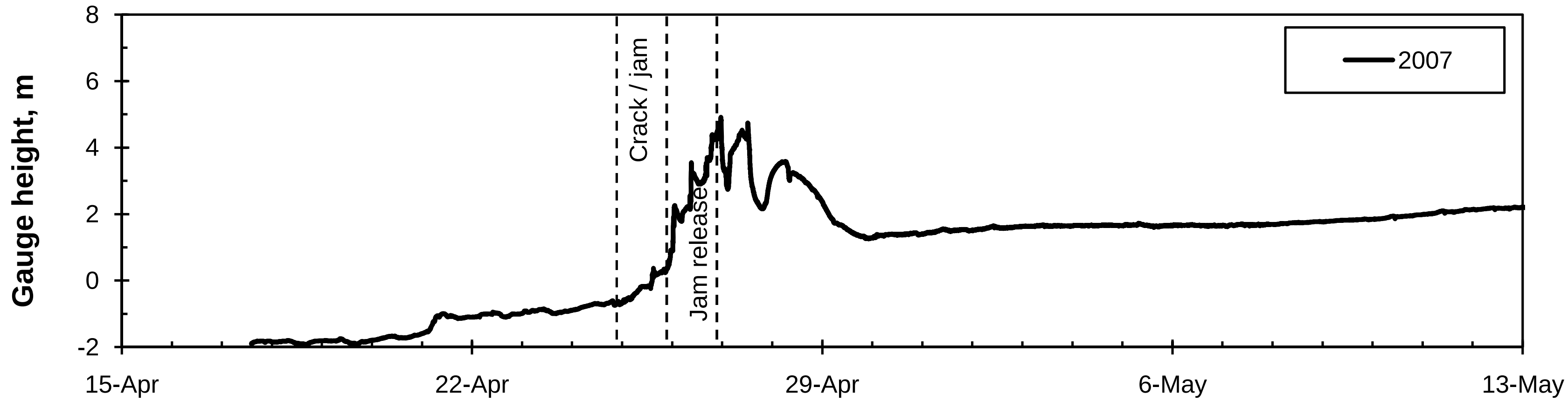


Figure G.37: Water levels at the EMO Pine Point Bridge station during breakup in 2007.

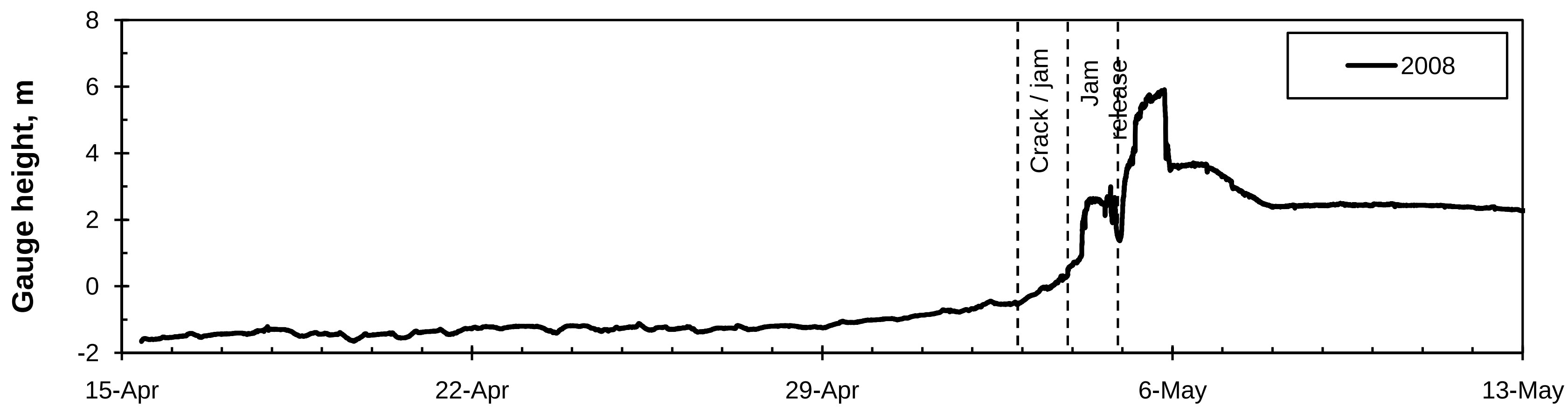


Figure G.38: Water levels at the EMO Pine Point Bridge station during breakup in 2008.

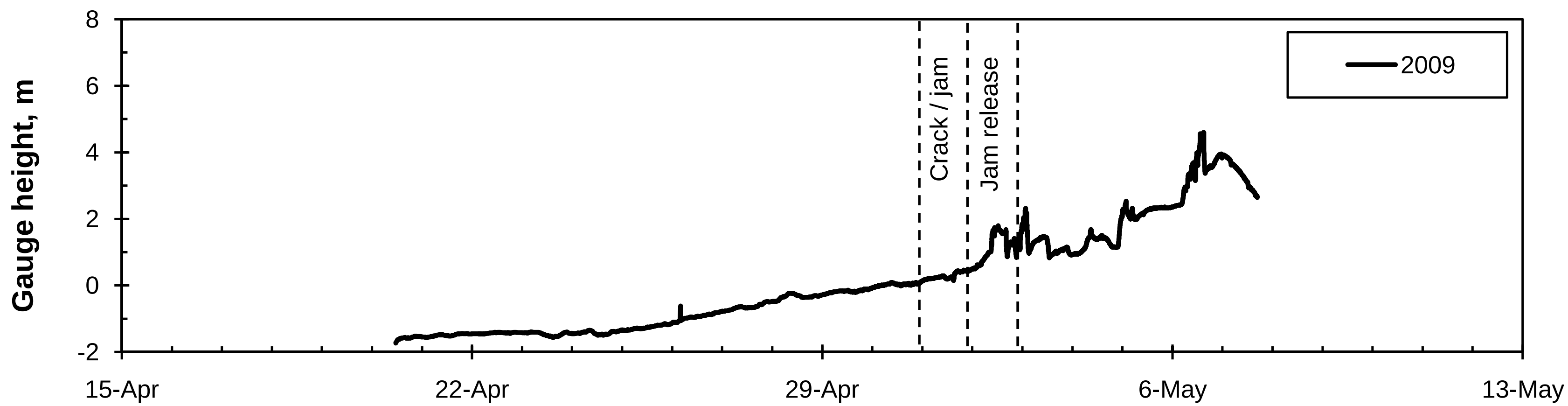


Figure G.39: Water levels at the EMO Pine Point Bridge station during breakup in 2009.

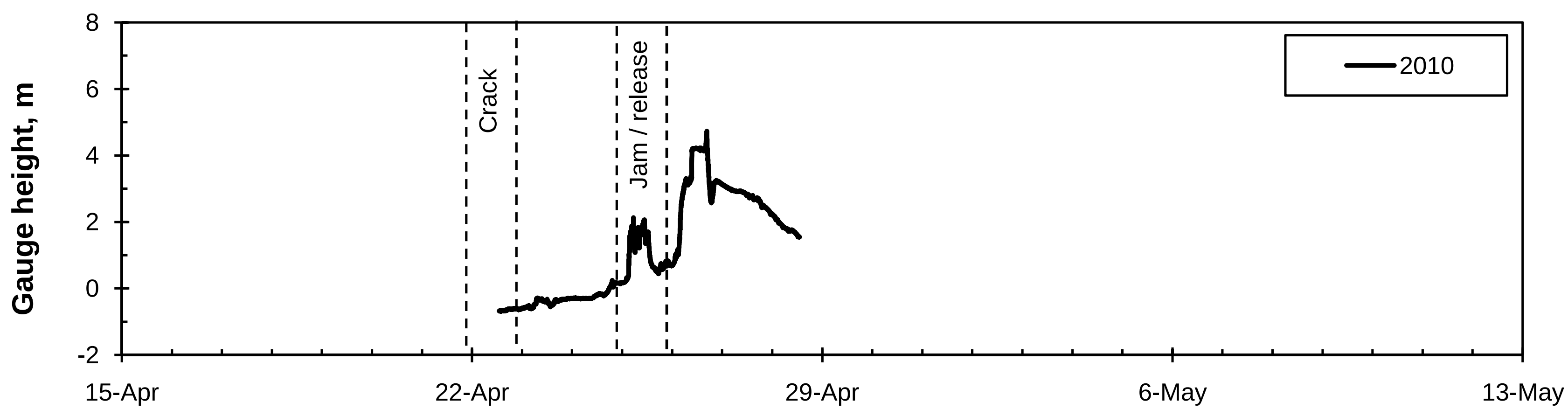


Figure G.40: Water levels at the EMO Pine Point Bridge station during breakup in 2010.

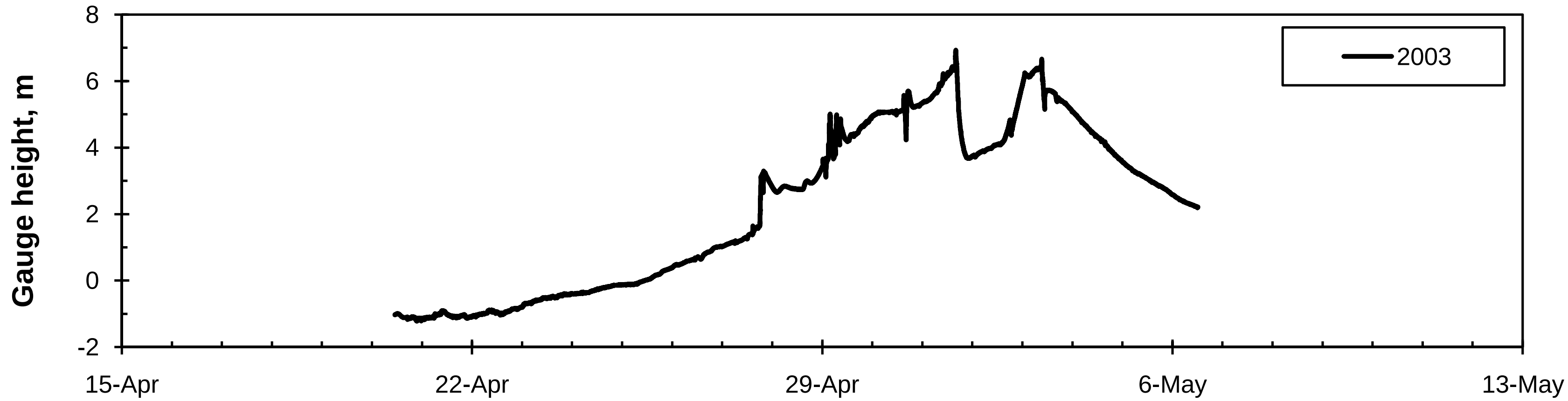


Figure G.33: Water levels and known breakup dates at the EMO Pine Point Bridge station during breakup in 2003.

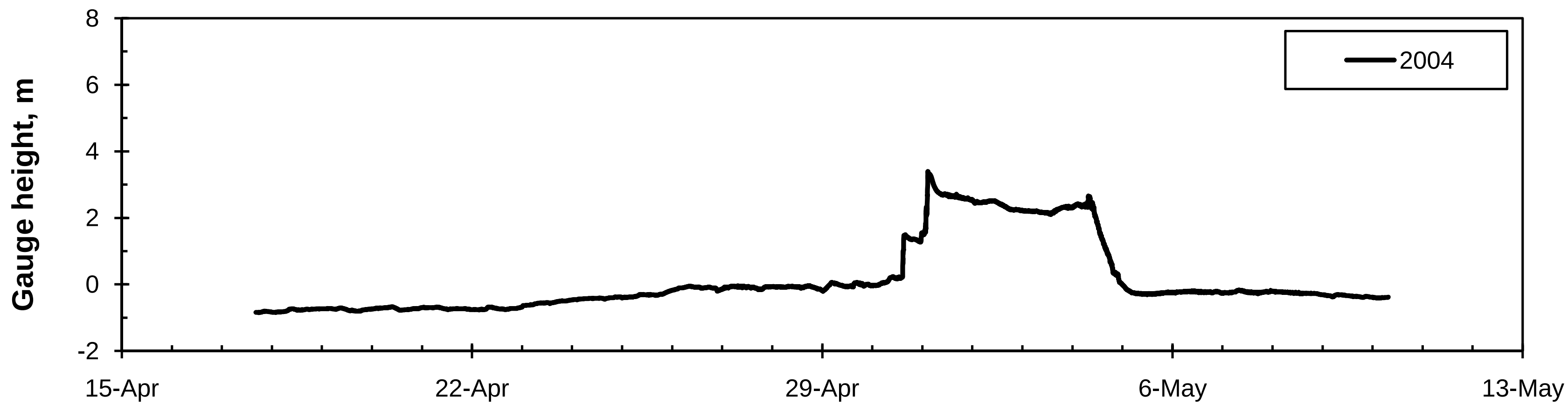


Figure G.34: Water levels and known breakup dates at the EMO Pine Point Bridge station during breakup in 2004.

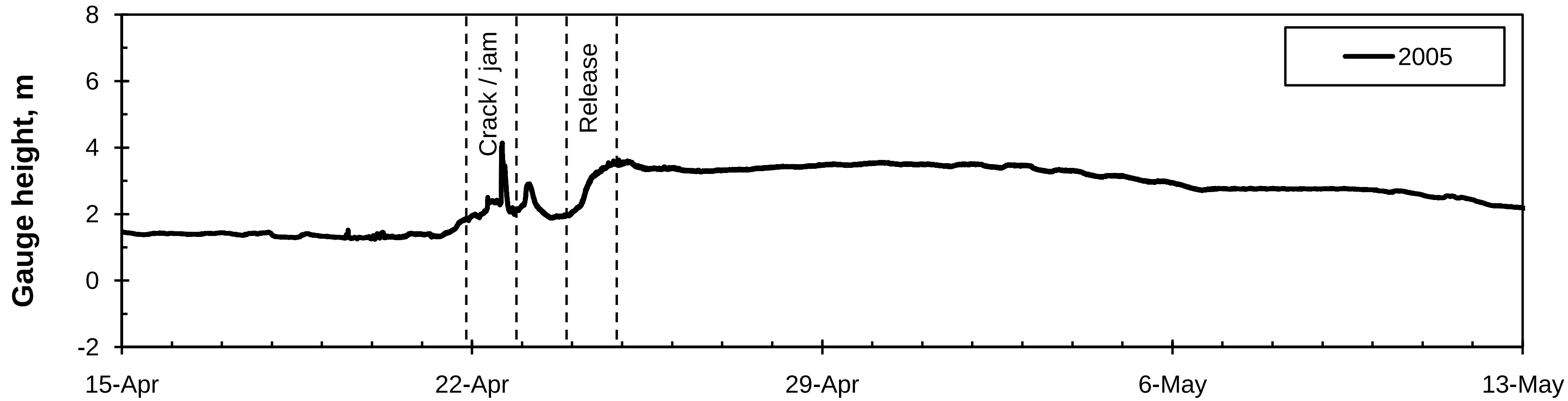


Figure G.35: Water levels and known breakup dates at the EMO Pine Point Bridge station during breakup in 2005.

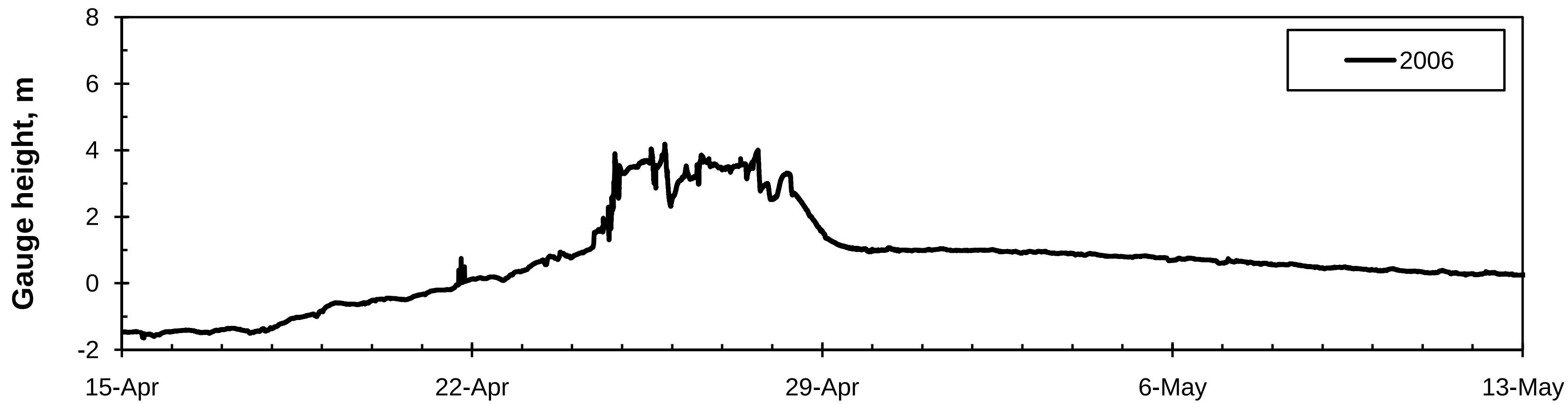


Figure G.36: Water levels and known breakup dates at the EMO Pine Point Bridge station during breakup in 2006.

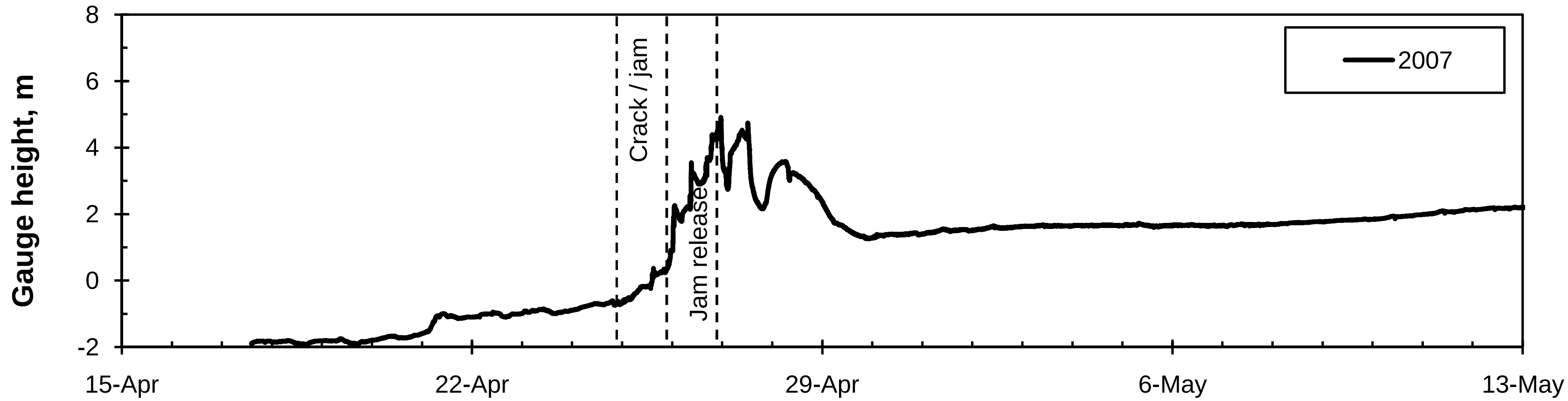


Figure G.37: Water levels at the EMO Pine Point Bridge station during breakup in 2007.

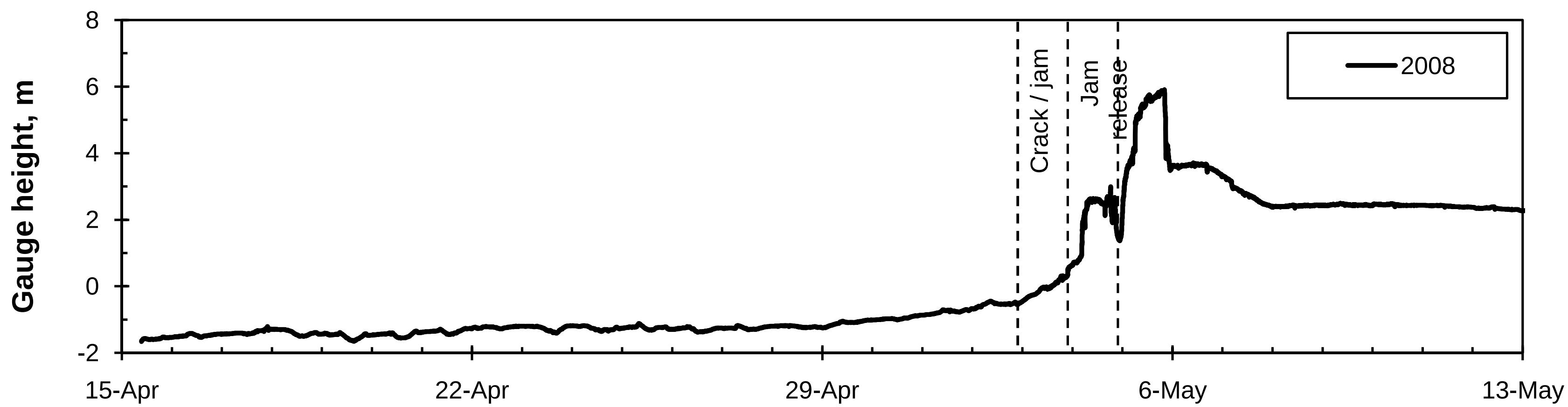


Figure G.38: Water levels at the EMO Pine Point Bridge station during breakup in 2008.

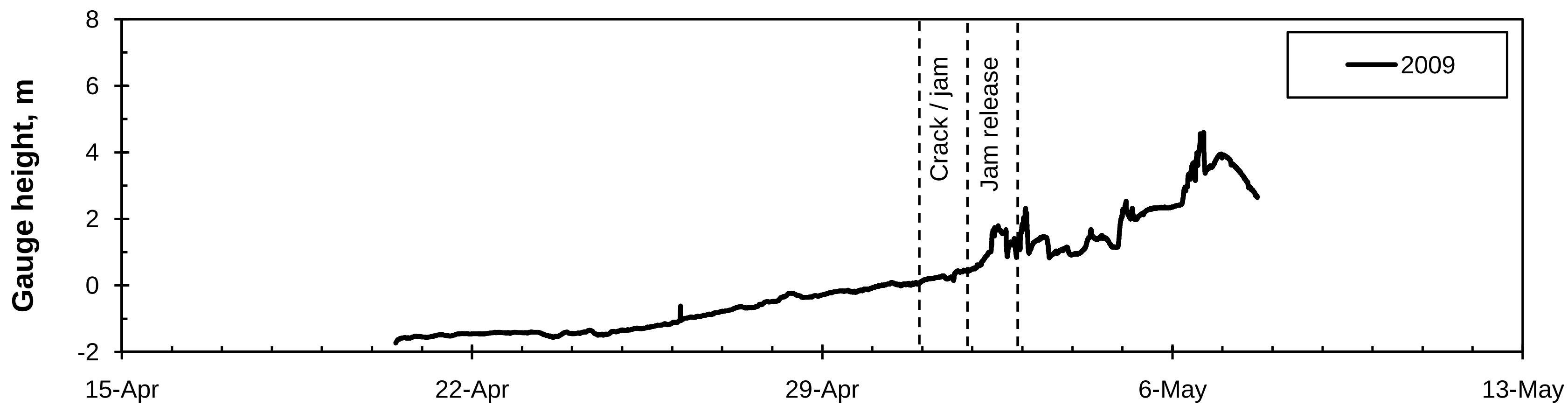


Figure G.39: Water levels at the EMO Pine Point Bridge station during breakup in 2009.

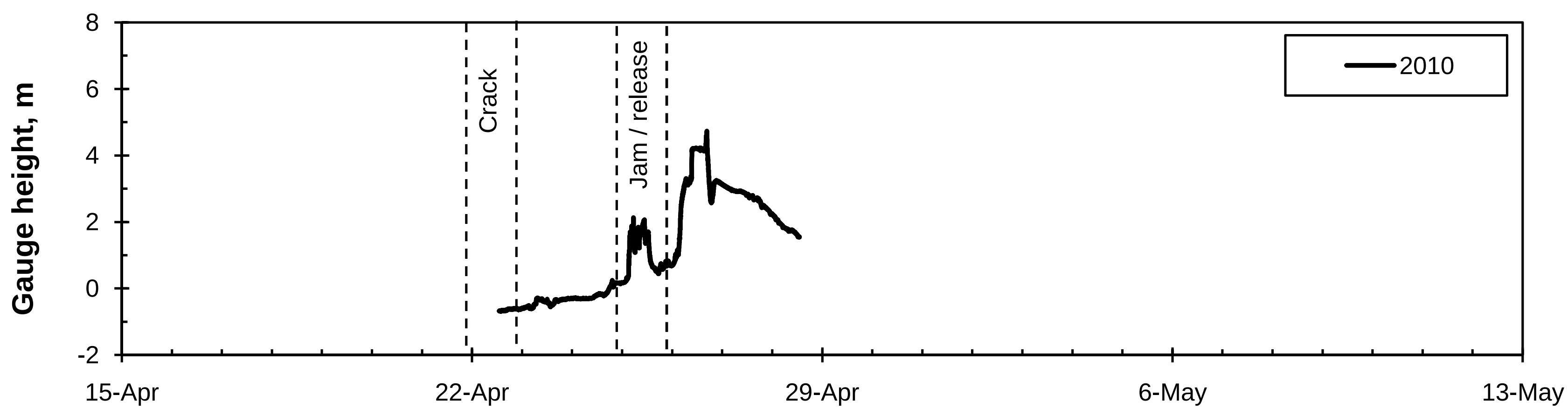


Figure G.40: Water levels at the EMO Pine Point Bridge station during breakup in 2010.

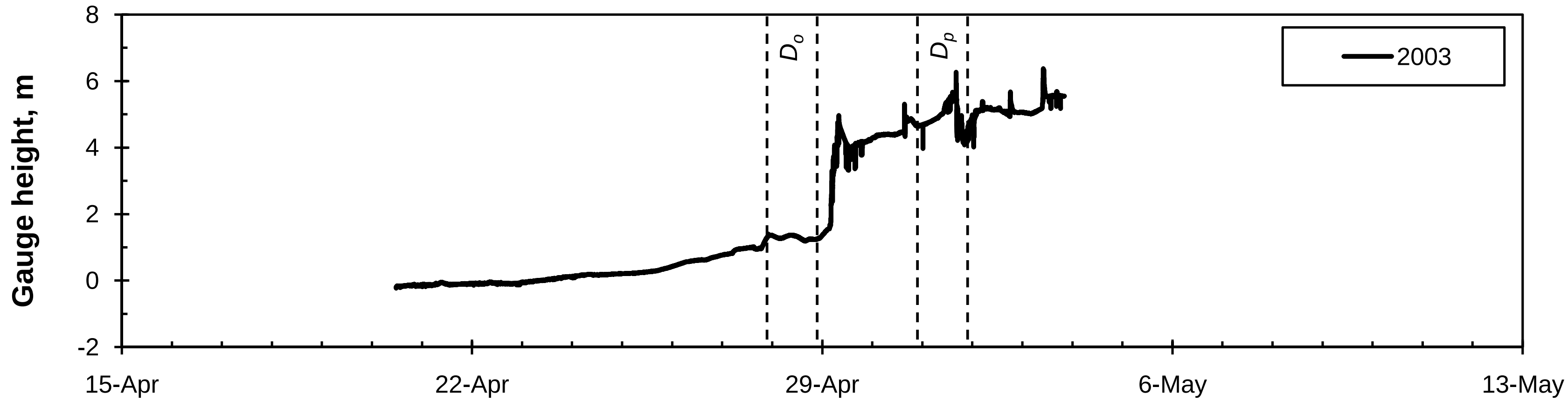


Figure G.41: Water levels and known breakup dates at the EMO West Channel Bridge station during breakup in 2003.

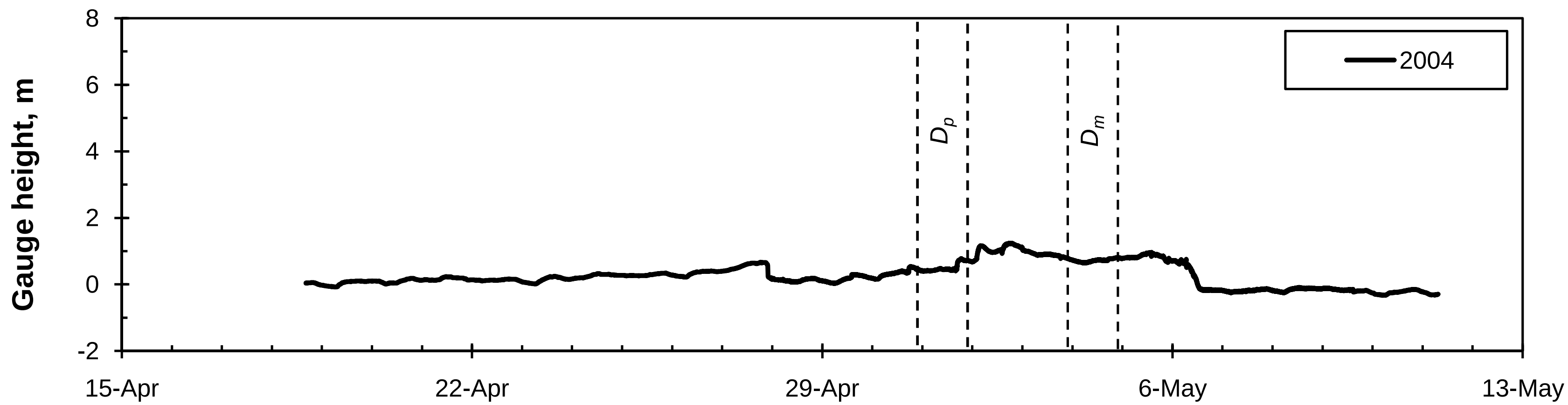


Figure G.42: Water levels and known breakup dates at the EMO West Channel Bridge station during breakup in 2004.

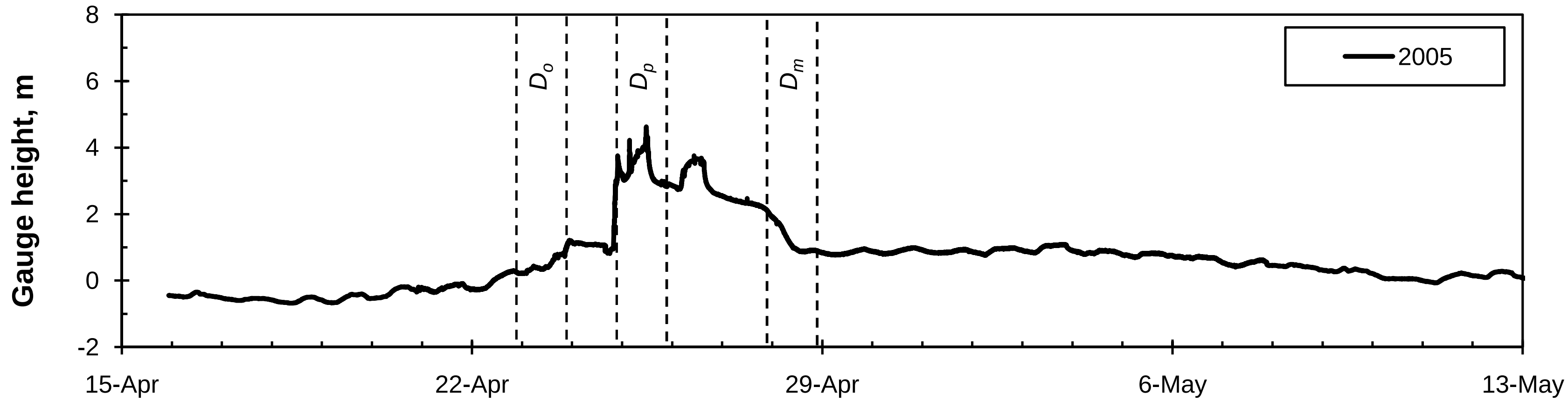


Figure G.43: Water levels and known breakup dates at the EMO West Channel Bridge station during breakup in 2005.

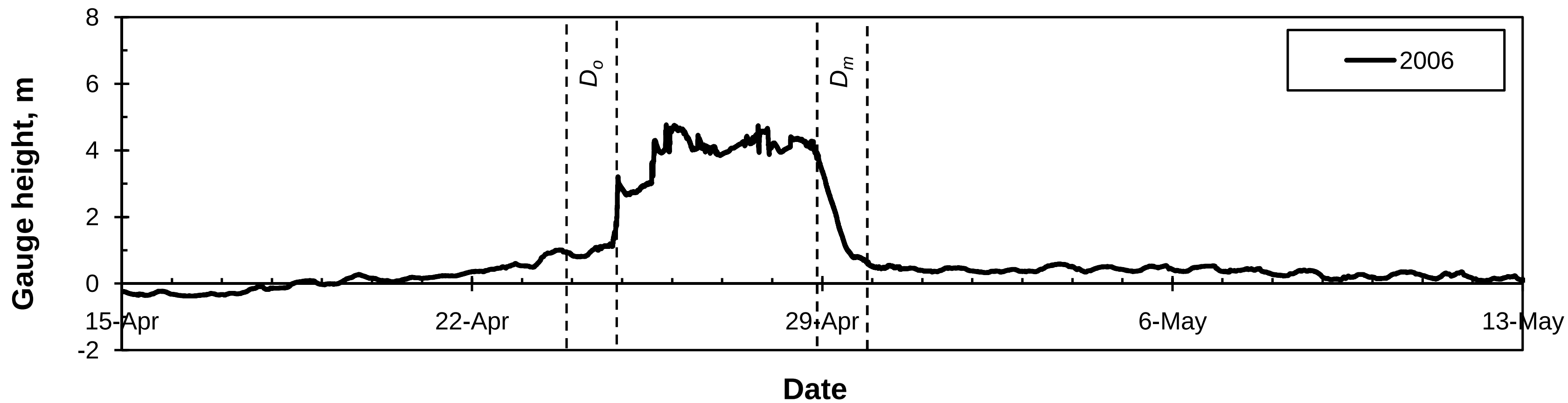


Figure G.44: Water levels and known breakup dates at the EMO West Channel Bridge station during breakup in 2006.

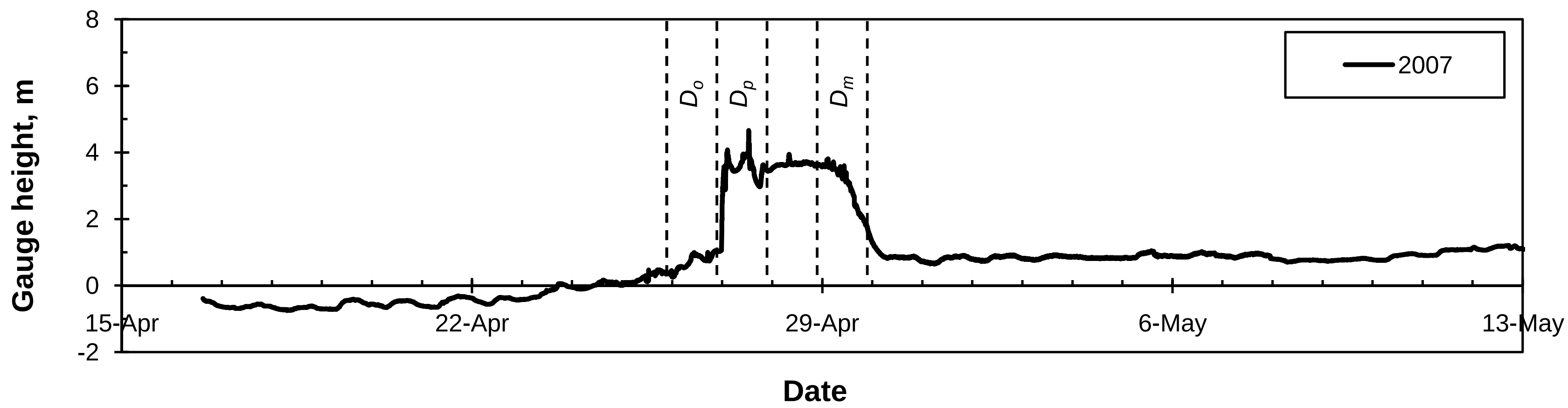


Figure G.45: Water levels and known breakup dates at the EMO West Channel Bridge station during breakup in 2007.

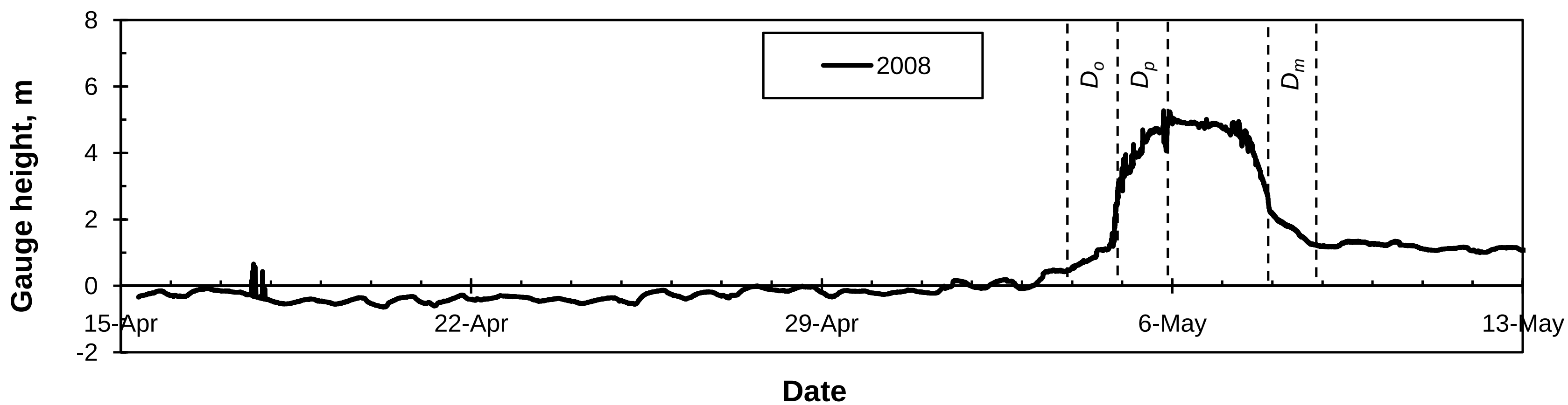


Figure G.46: Water levels and known breakup dates at the EMO West Channel Bridge station during breakup in 2008.

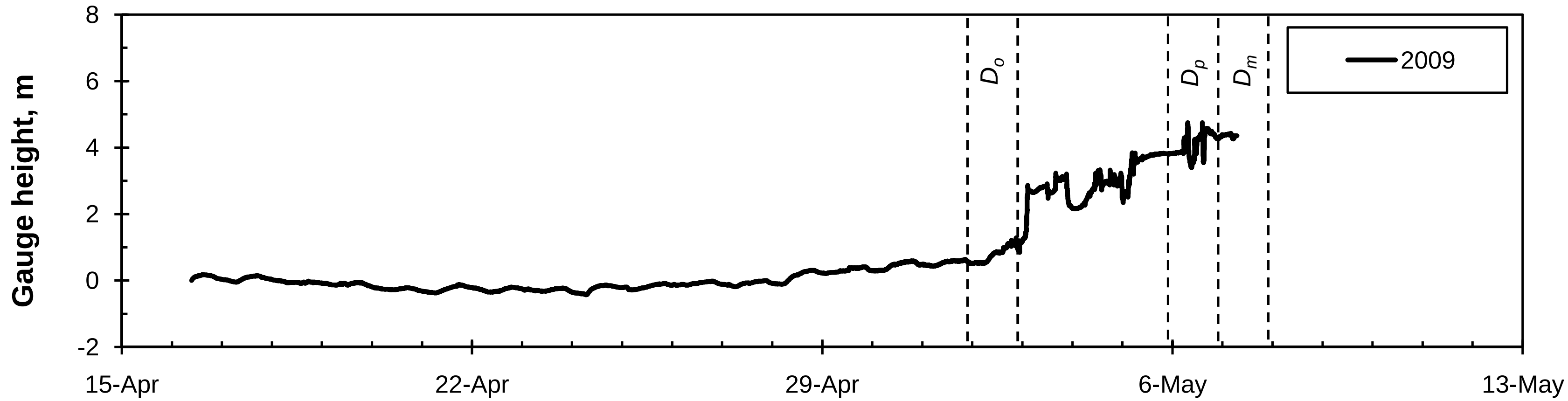


Figure G.47: Water levels and known breakup dates at the EMO West Channel Bridge station during breakup in 2009.

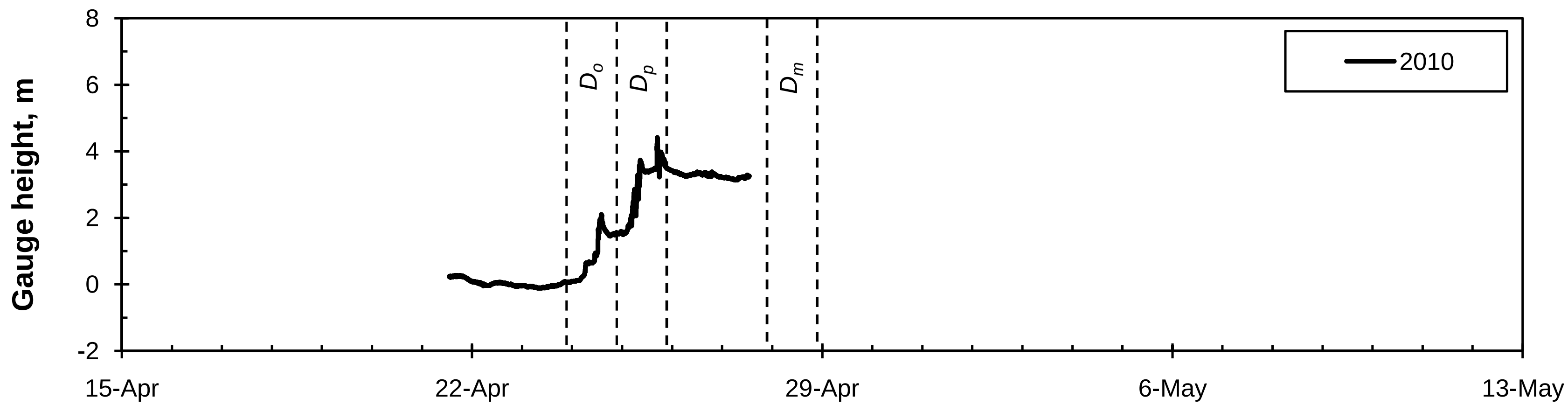


Figure G.48: Water levels and known breakup dates at the EMO West Channel Bridge station during breakup in 2010.

Appendix H: Hydrographs from the four WSC gauge stations located in the Hay River headwaters.

The hydrographs from the four WSC headwaters gauge stations were analyzed. The dates of first transverse cracking were extracted and annotated. The years of data available for each station are summarized in the following table.

Station Name	**Station Number**	**Years of data**						
Sousa Creek near High Level	SCHR 070A001	2004	2005	2006	2007	2008	2009	2010
Chinchaga River near High Level	CRHR 070B008	2004	2005	2006	2007	2008	2009	2010
Hay River near Meander River	HRMR 070B003				2007	2008	2009	2010
Steen River near Steen River	SRSR 070B004				2007	2008	2009	2010

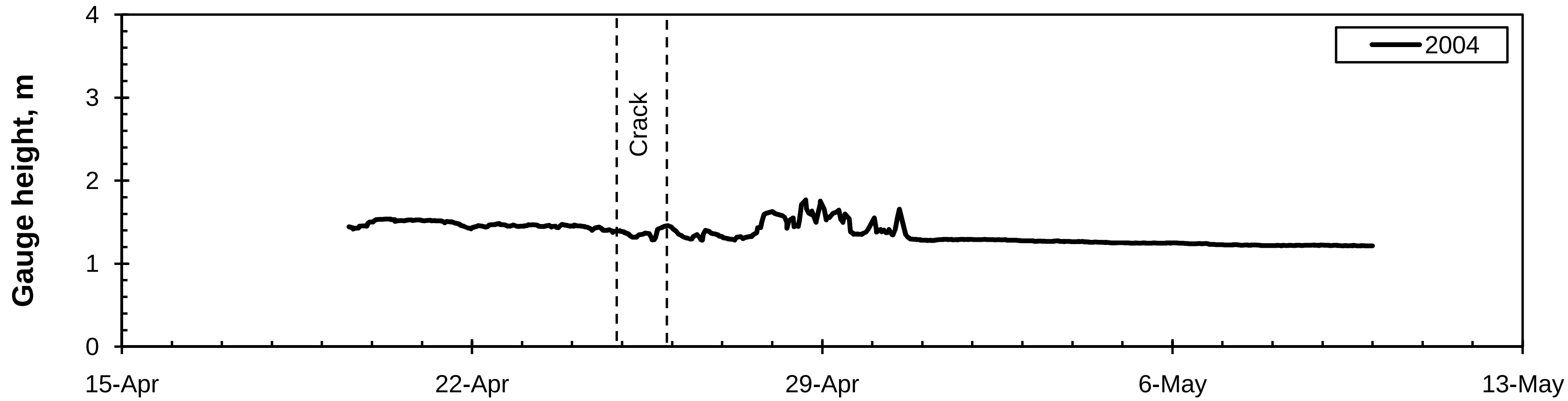


Figure H.1: Water levels at the WSC Sousa Creek near High Level station (SCHL 070A001) during breakup in 2004.

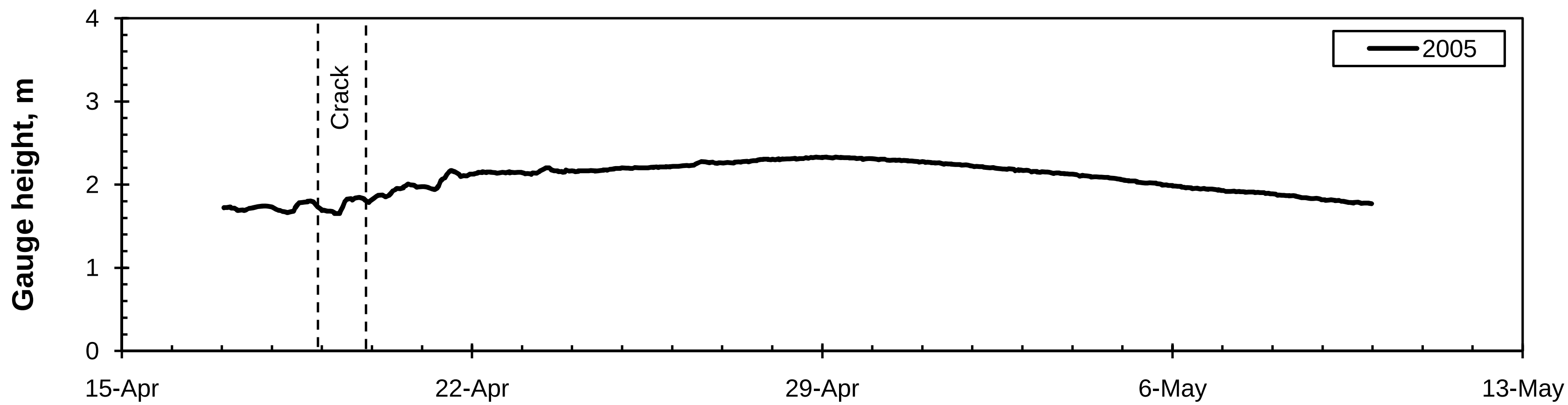


Figure H.2: Water levels at the WSC Sousa Creek near High Level station (SCHL 070A001) during breakup in 2005.

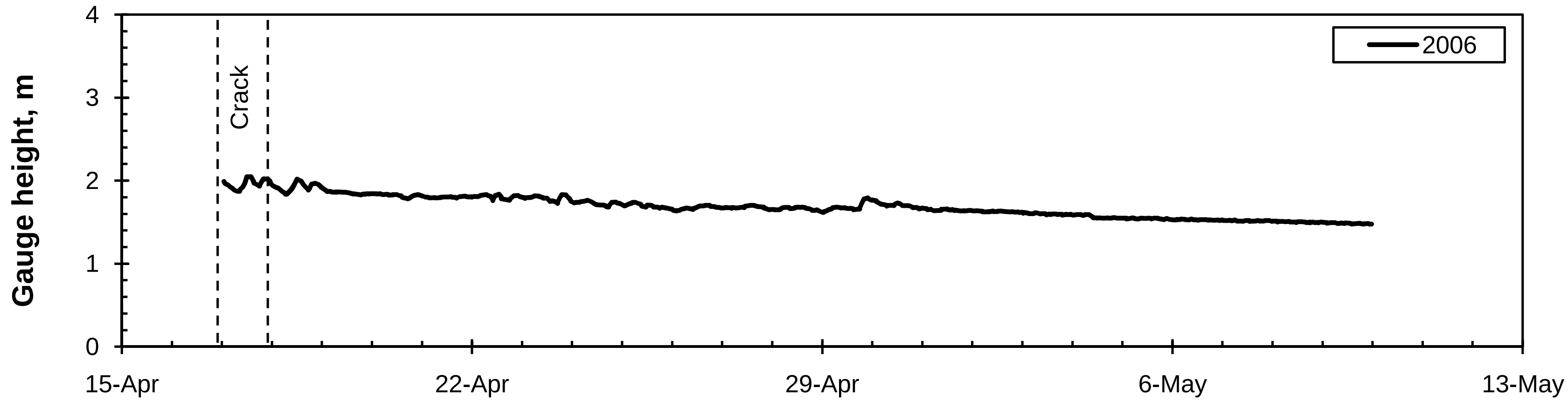


Figure H.3: Water levels at the WSC Sousa Creek near High Level station (SCHL 070A001) during breakup in 2006.

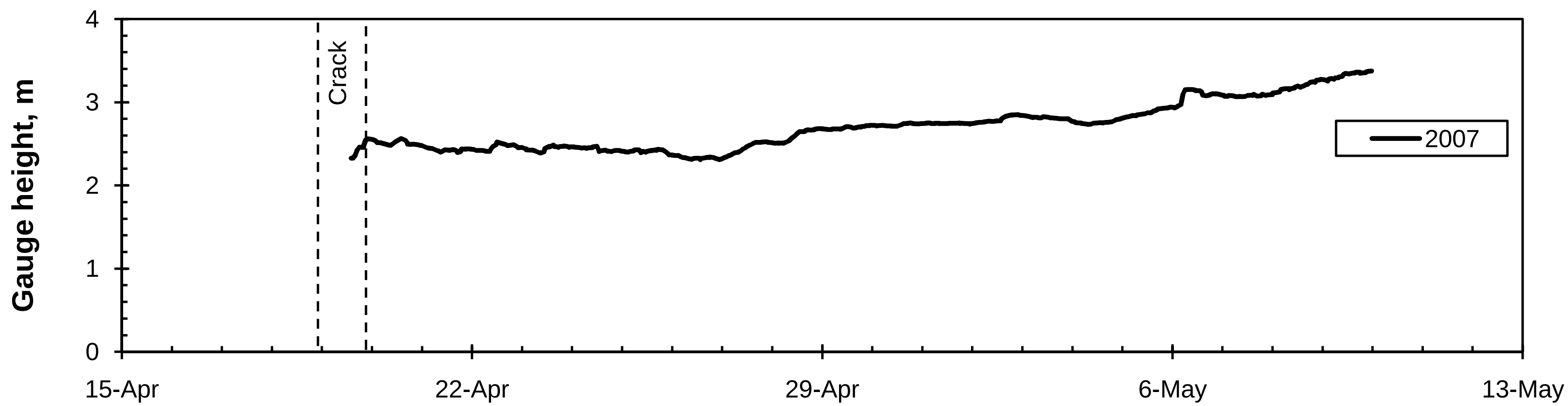


Figure H.4: Water levels at the WSC Sousa Creek near High Level station (SCHL 070A001) during breakup in 2007.

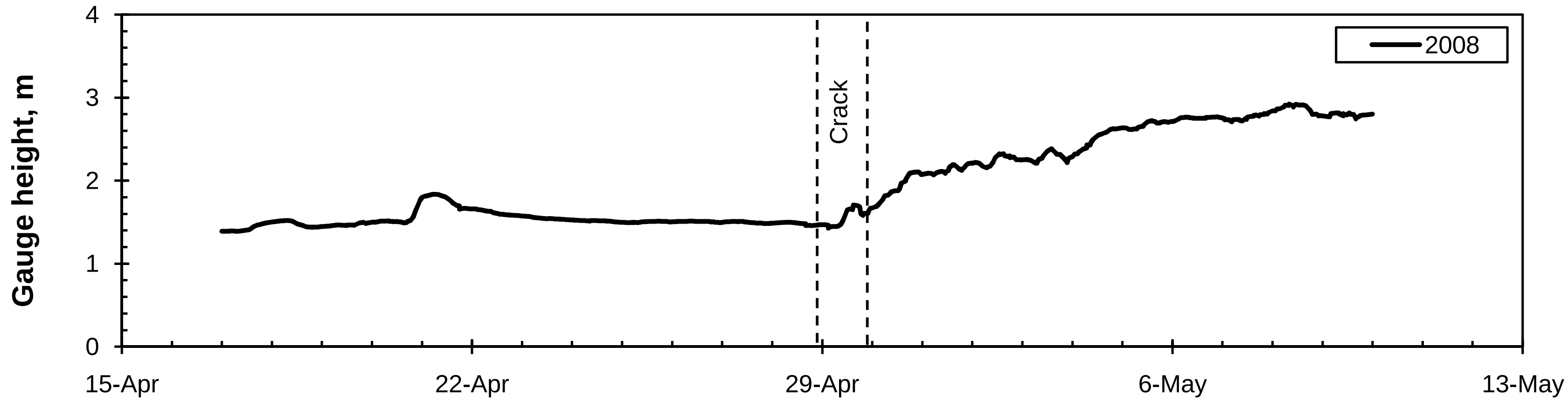


Figure H.5: Water levels at the WSC Sousa Creek near High Level station (SCHL 070A001) during breakup in 2008.

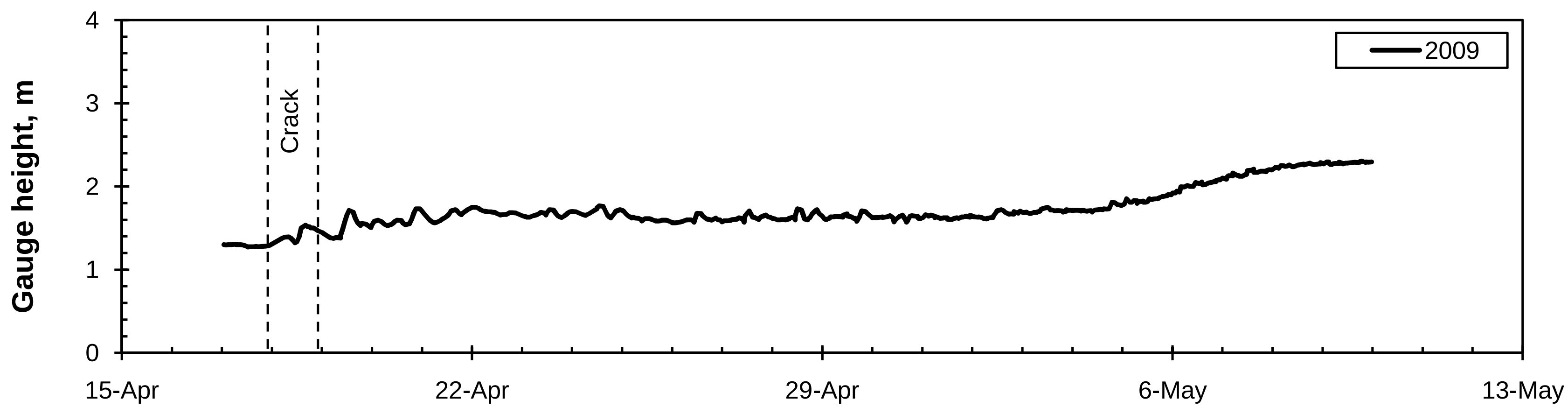


Figure H.6: Water levels at the WSC Sousa Creek near High Level station (SCHL 070A001) during breakup in 2009.

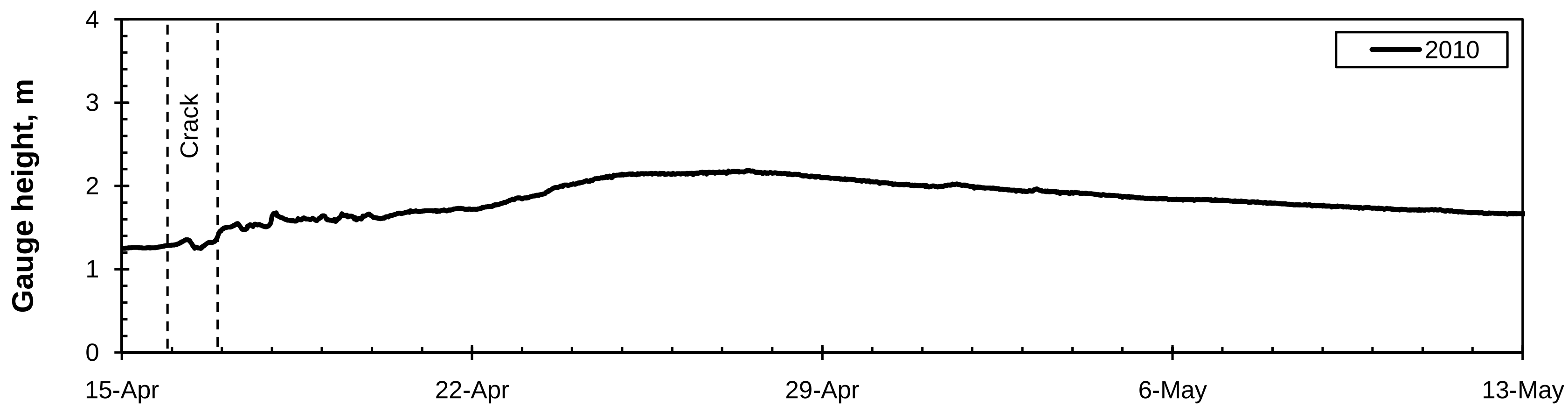


Figure H.7: Water levels at the WSC Sousa Creek near High Level station (SCHL 070A001) during breakup in 2010.

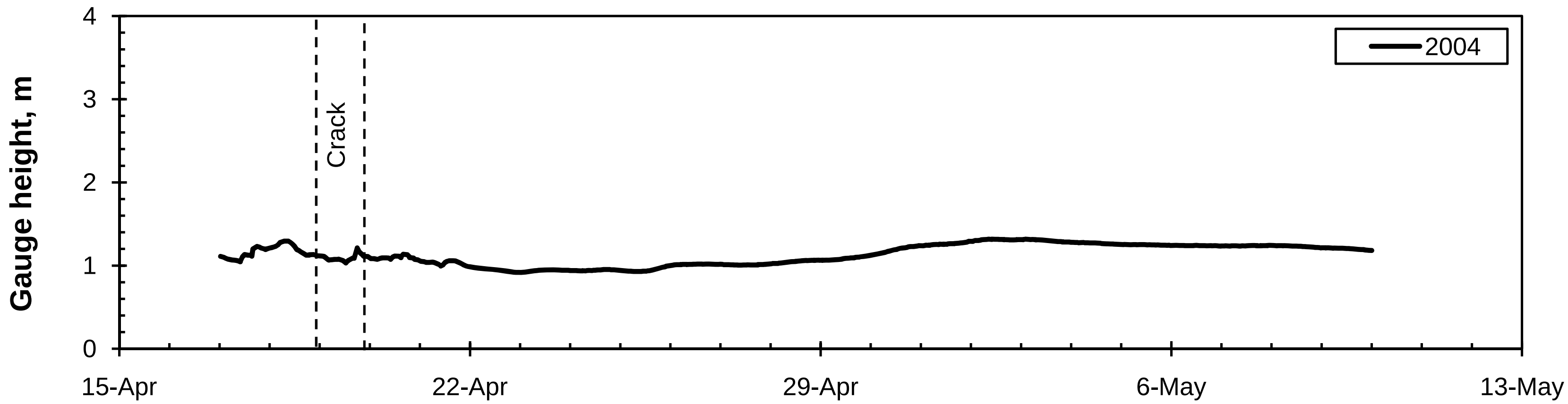


Figure H.8: Water levels at the WSC Chinchaga River near High Level station (CRHL 070B008) during breakup in 2004.

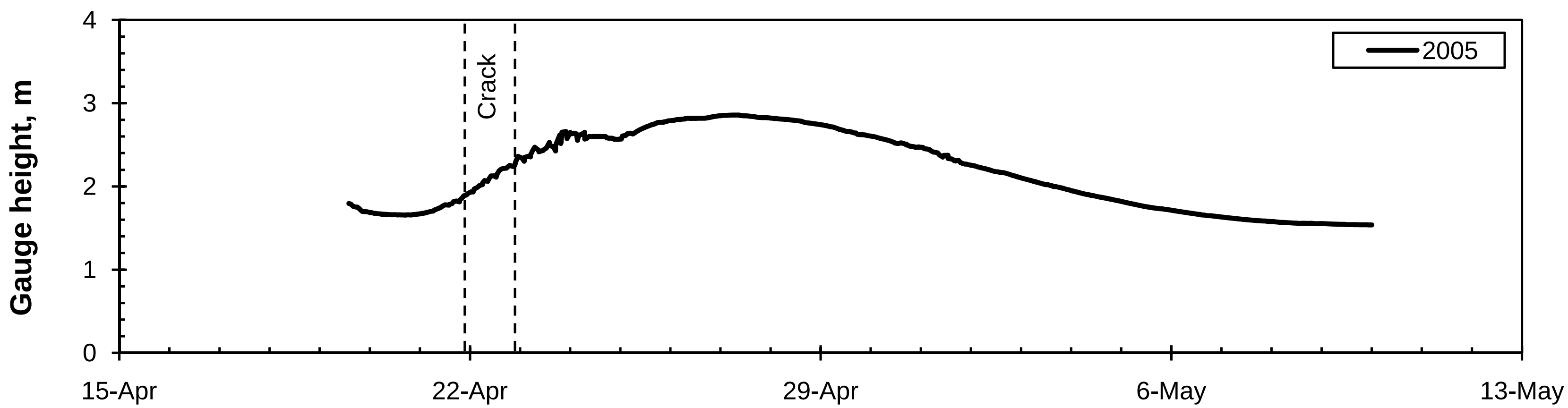


Figure H.9: Water levels at the WSC Chinchaga River near High Level station (CRHL 070B008) during breakup in 2005.

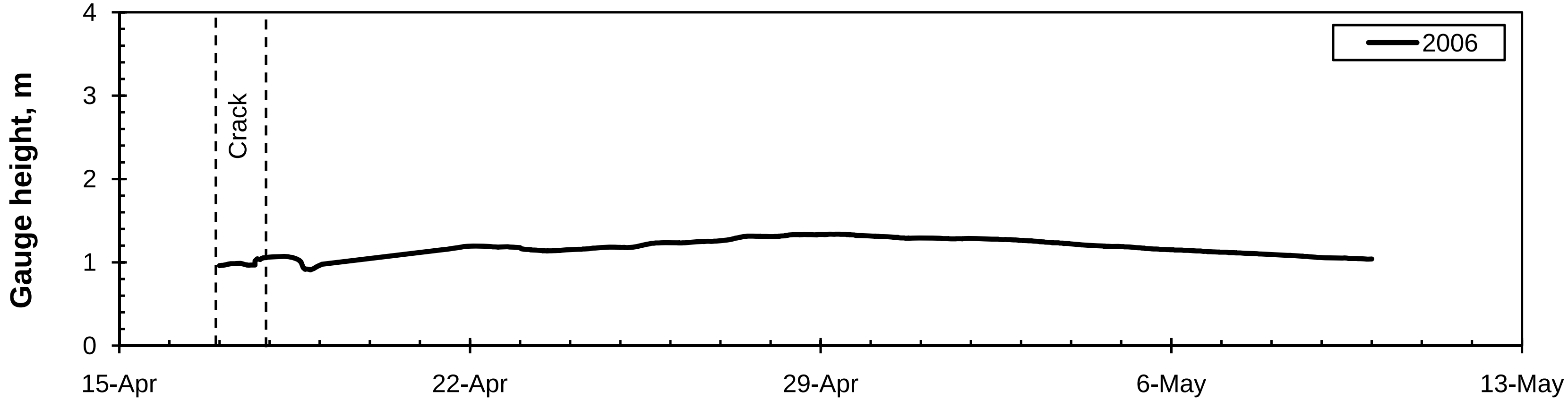


Figure H.10: Water levels at the WSC Chinchaga River near High Level station (CRHL 070B008) during breakup in 2006.

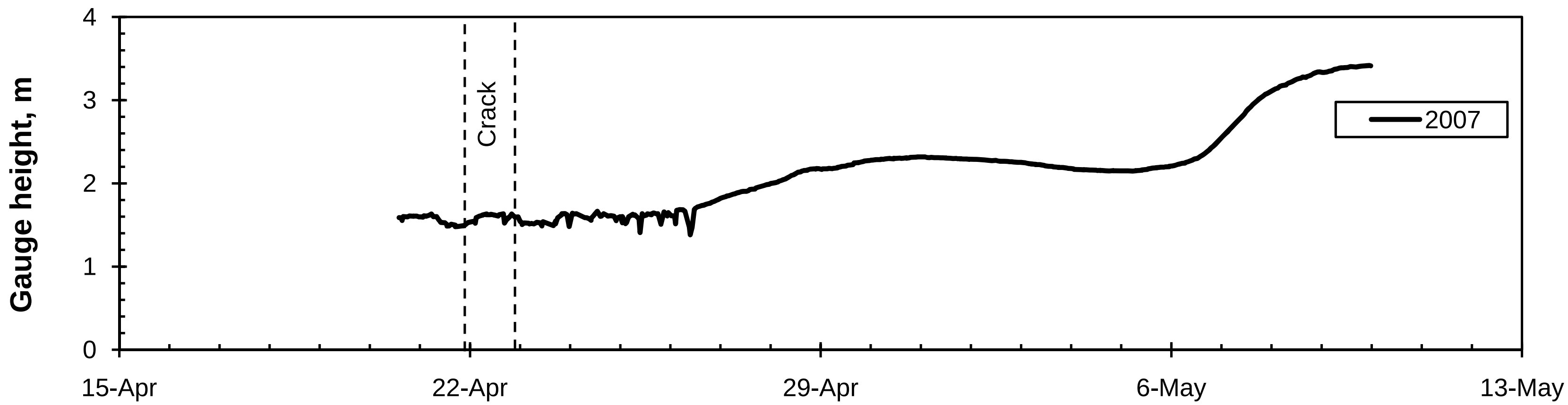


Figure H.11: Water levels at the WSC Chinchaga River near High Level station (CRHL 070B008) during breakup in 2007.

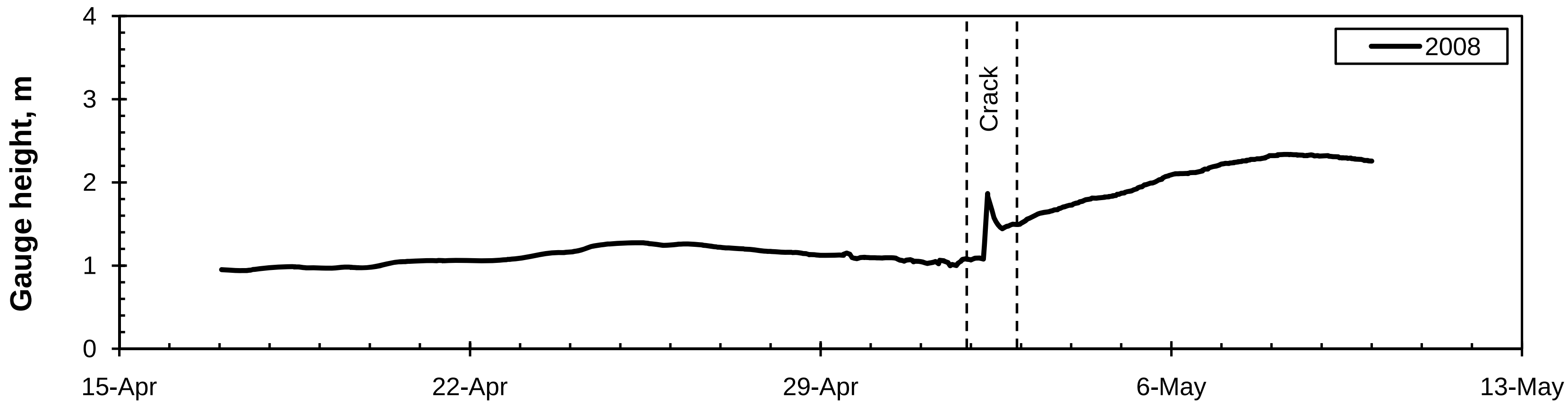


Figure H.12: Water levels at the WSC Chinchaga River near High Level station (CRHL 070B008) during breakup in 2008.

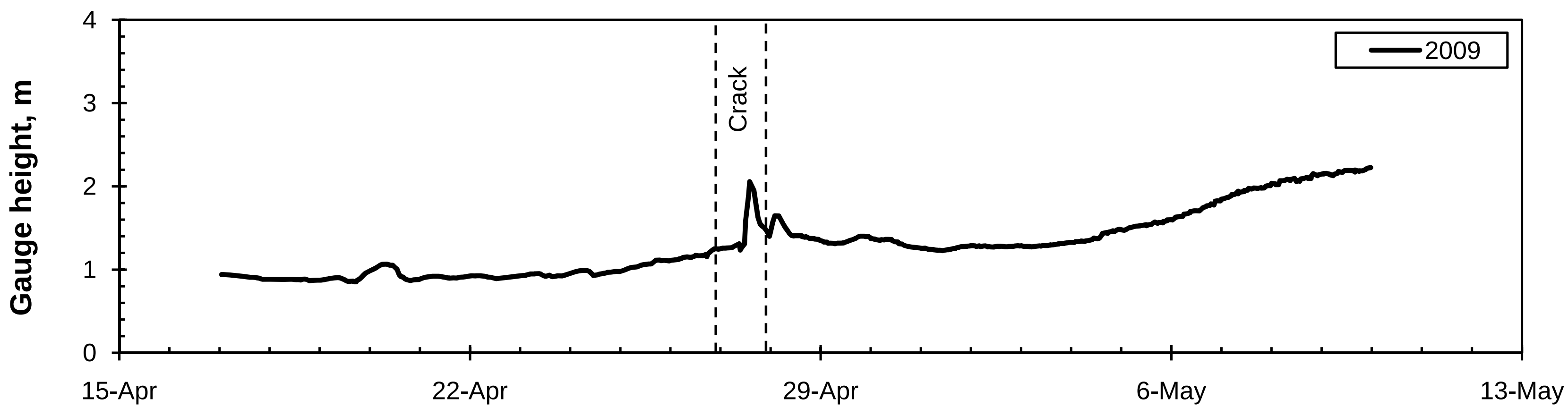


Figure H.13: Water levels at the WSC Chinchaga River near High Level station (CRHL 070B008) during breakup in 2009.

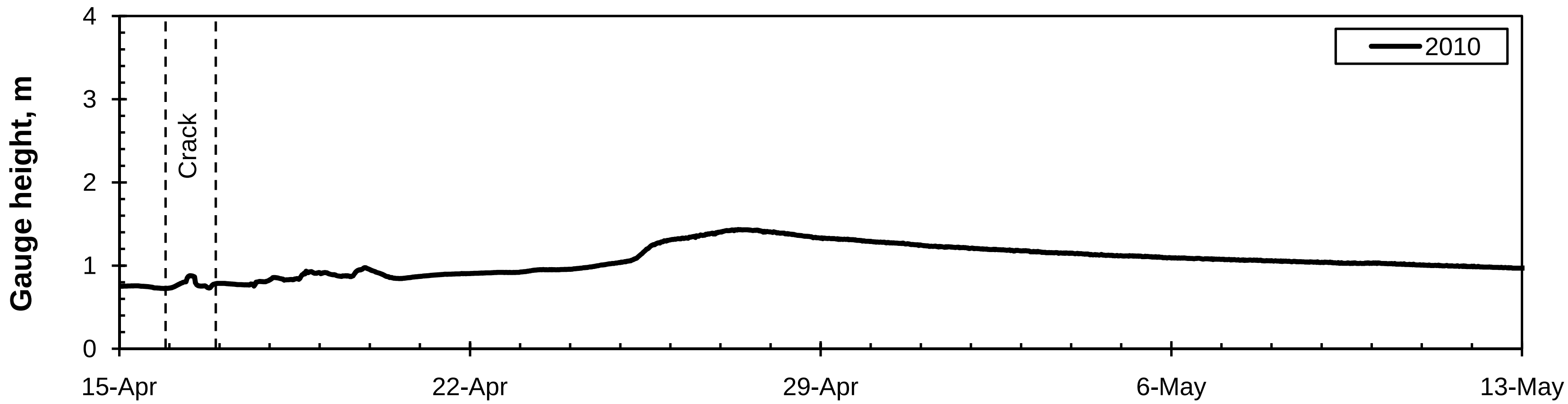


Figure H.14: Water levels at the WSC Chinchaga River near High Level station (CRHL 070B008) during breakup in 2010.

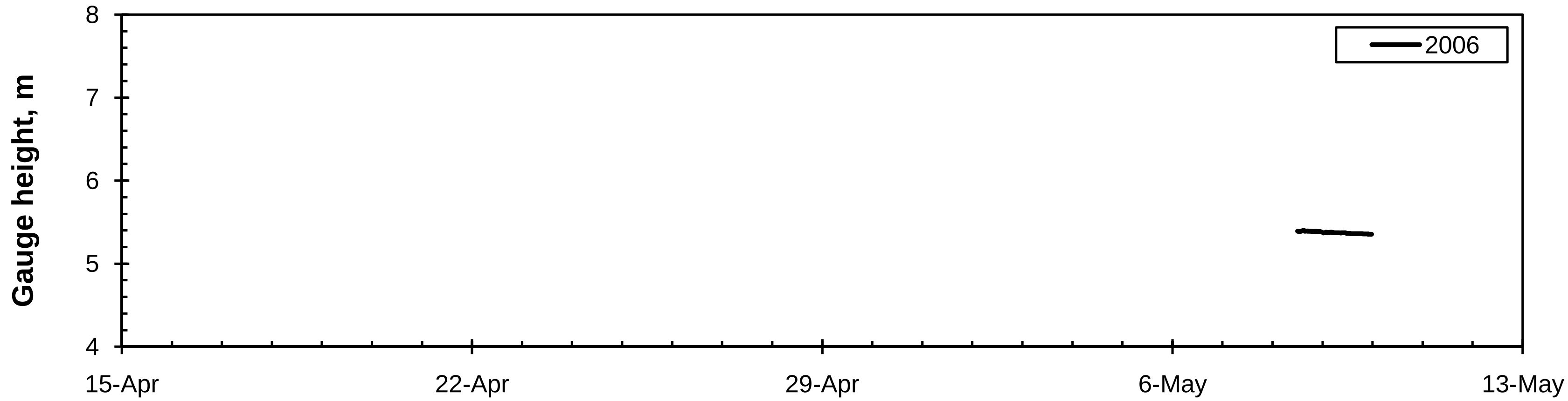


Figure H.15: Water levels at the WSC Hay River near Meander River station (HRMR 070B003) during breakup in 2006.

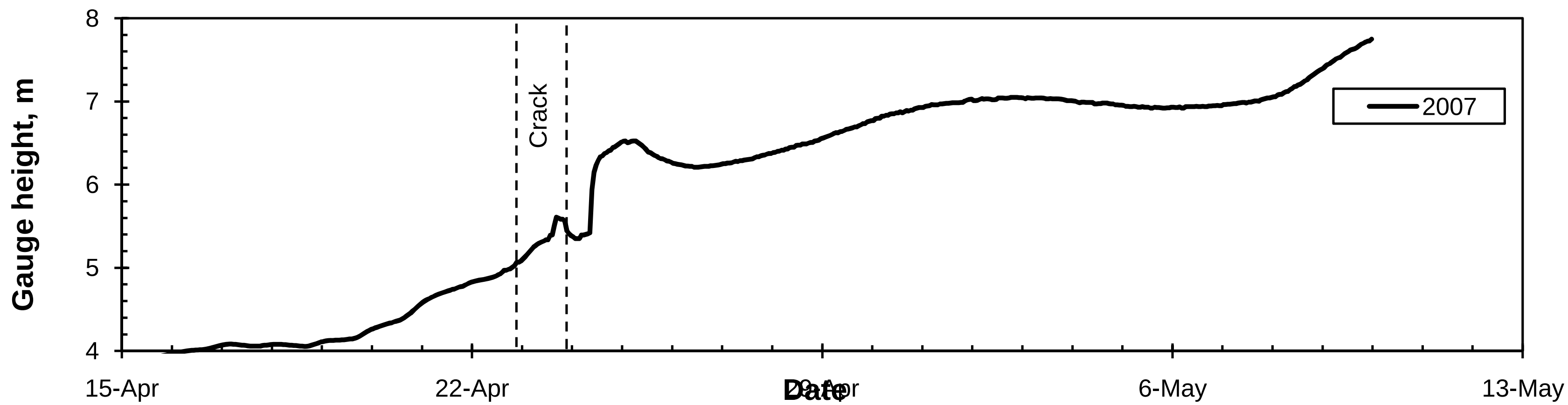


Figure H.16: Water levels at the WSC Hay River near Meander River station (HRMR 070B003) during breakup in 2007.

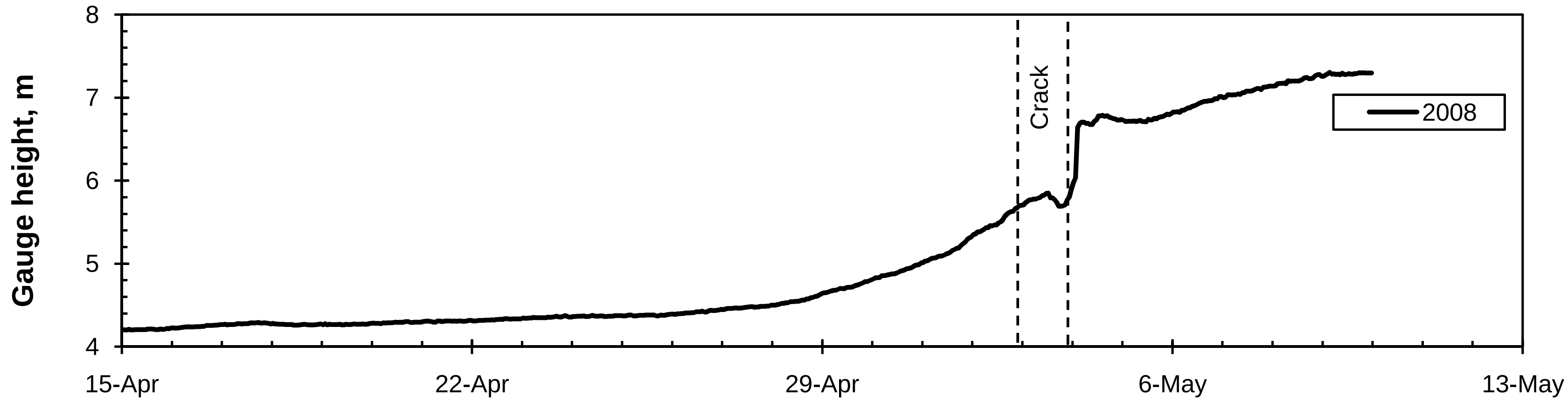


Figure H.17: Water levels at the WSC Hay River near Meander River station (HRMR 070B003) during breakup in 2008.

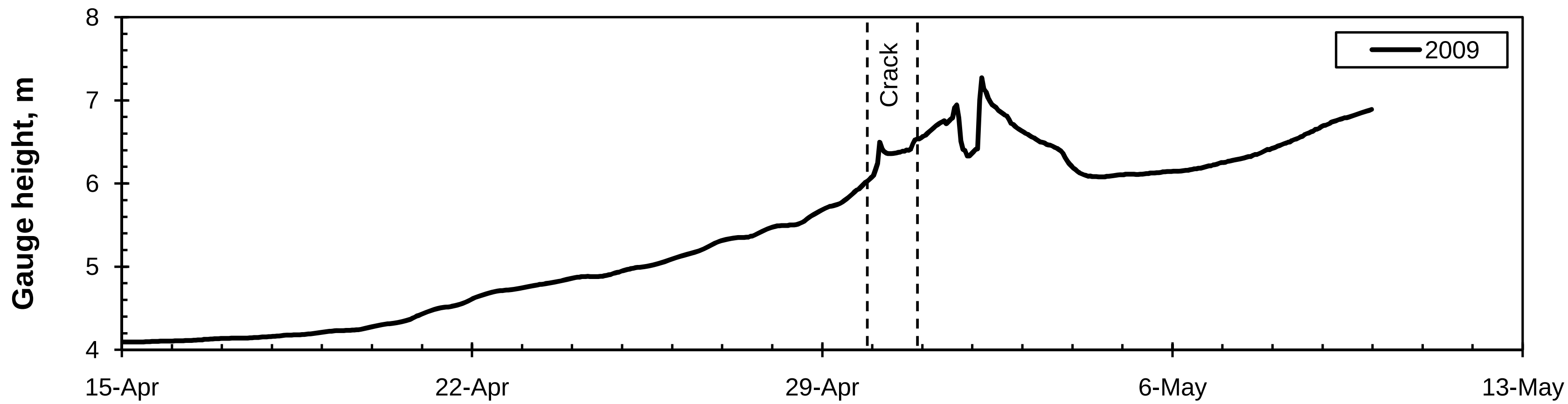


Figure H.18: Water levels at the WSC Hay River near Meander River station (HRMR 070B003) during breakup in 2009.

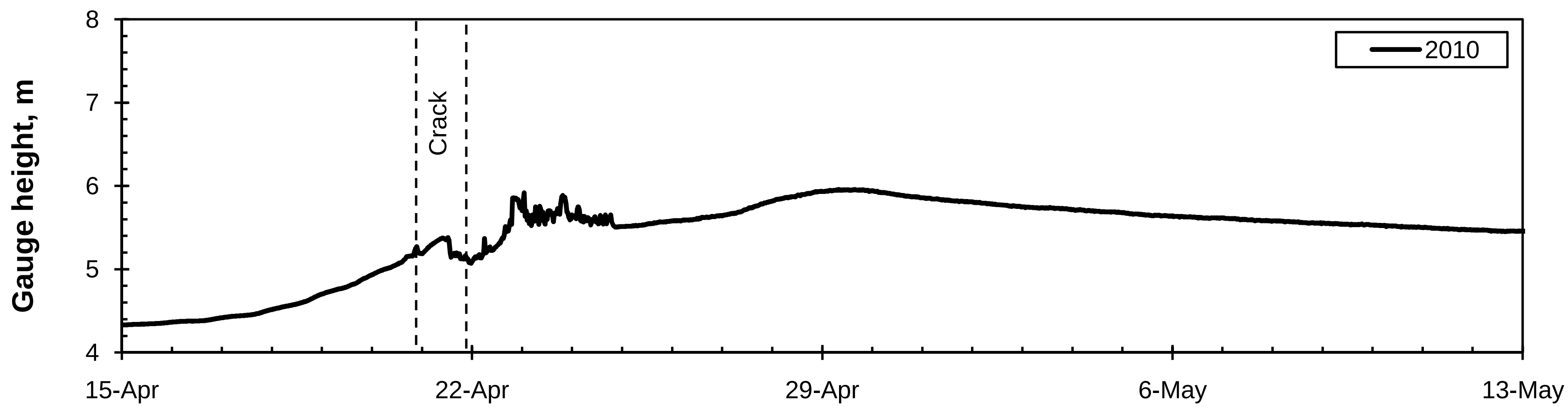


Figure H.19: Water levels at the WSC Hay River near Meander River station (HRMR 070B003) during breakup in 2010.

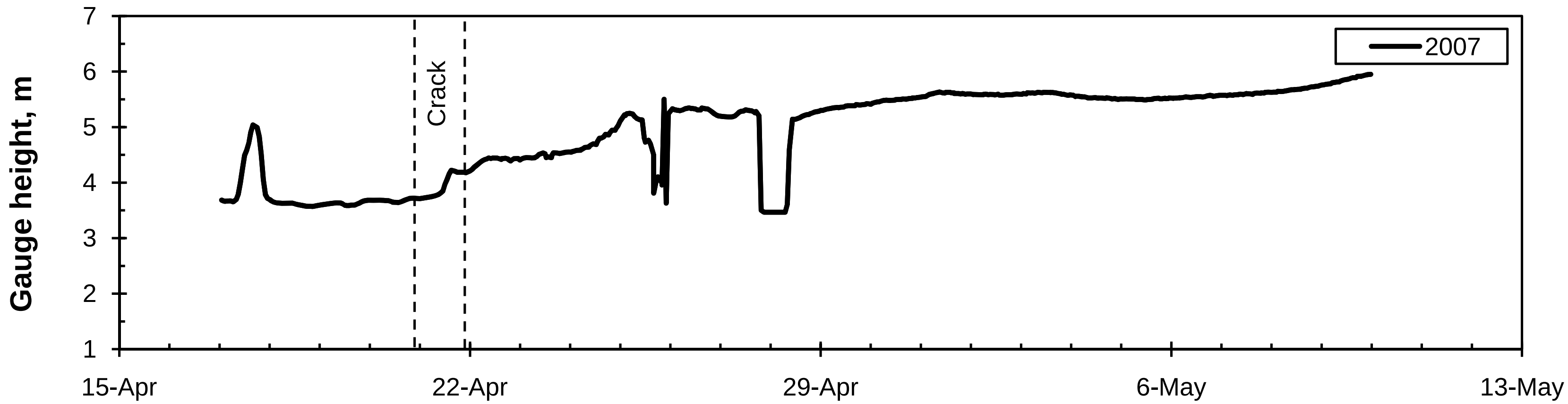


Figure H.20: Water levels at Steen River near Steen River (SRSR 070B004) during breakup in 2007.

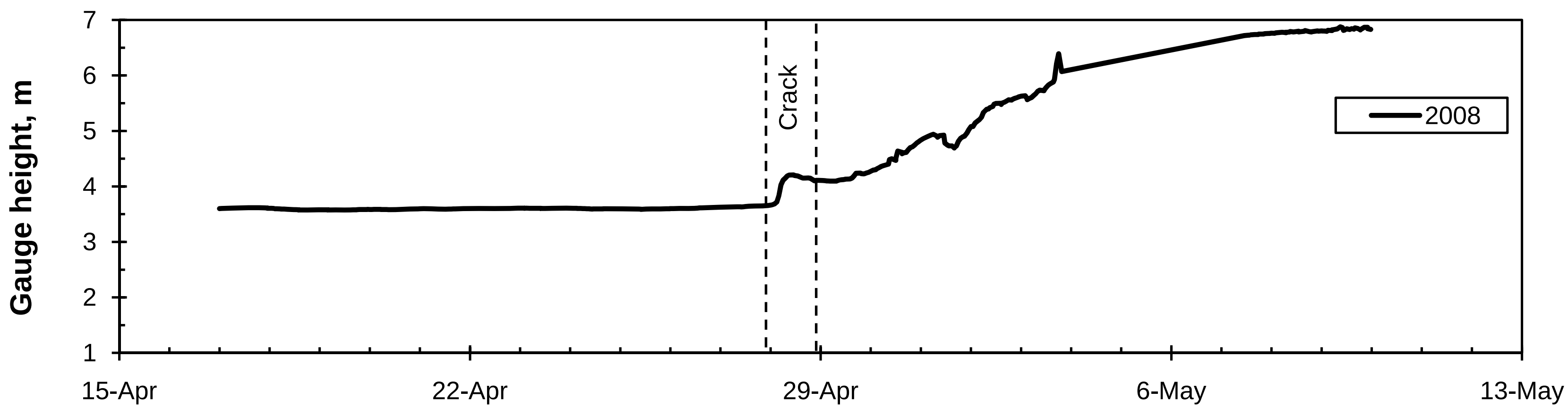


Figure H.21: Water levels at Steen River near Steen River (SRSR 070B004) during breakup in 2008.

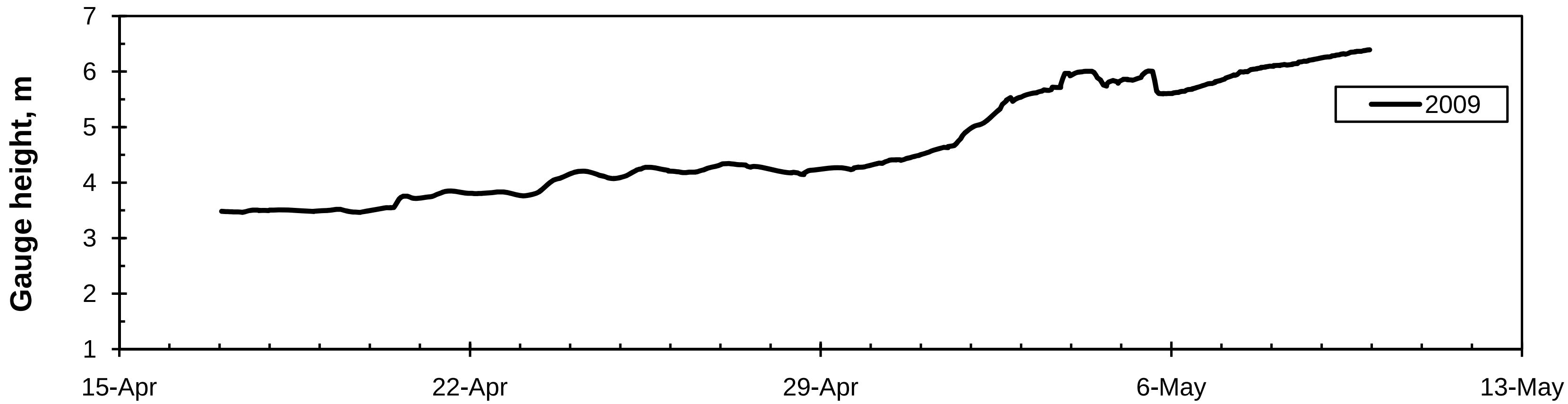


Figure H.22: Water levels at Steen River near Steen River (SRSR 070B004) during breakup in 2009.

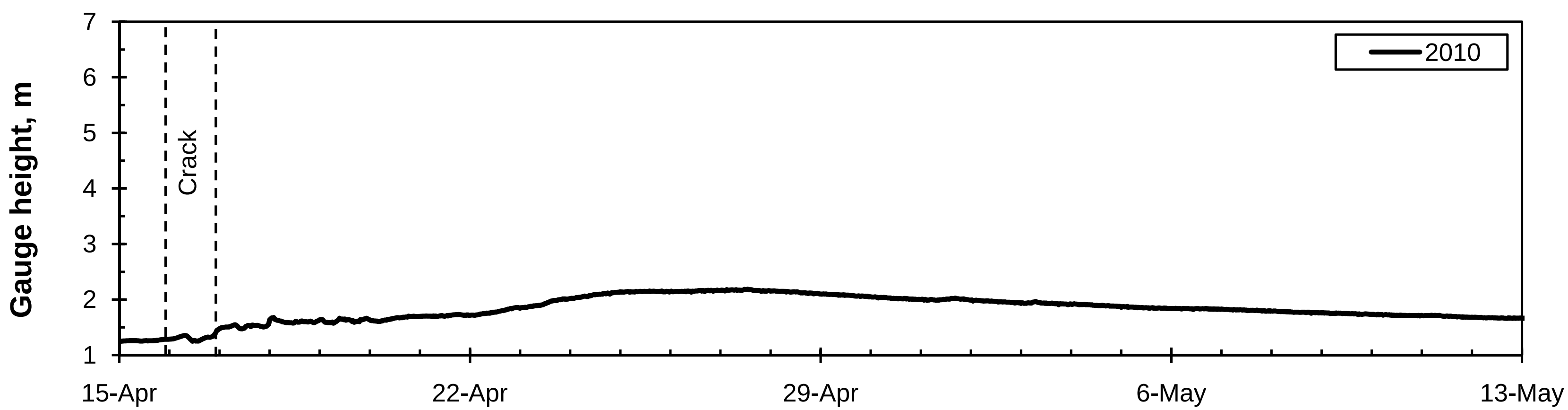


Figure H.23: Water levels at Steen River near Steen River (SRSR 070B004) during breakup in 2010.

Appendix I: Dates of stages of breakup at all ten study sites.

This Appendix contains the dates of stages of breakup at all ten study sites during 2005, 2007, 2008, 2009 and 2010, as determined though observation flight photographs and time-lapse ground photographs. The three tables in Appendix I are:

Table I.1: Dates of first transverse cracks (D_c) at all ten sites in the study reach.

Table I.2: Dates of local ice jams (D_j) at all ten sites in the study reach.

Table I.3: Dates of ice jam releases (D_r) at all ten sites in the study reach.

Table I.1: Dates of first transverse crack formation (D_c) at all sites.

	NWT/AB Border	Island at km 974	Grumbler Rapids	Mink Creek	Alexandra Falls	Escarpment Creek	Enterprise	Paradise Gardens	Golf Course	Pine Point Bridge
2005	21-Apr	21-Apr	-	21-Apr	-	-	22-Apr	22-Apr	22-Apr	22-Apr
2007	23-Apr	25-Apr	-	25-Apr	-	-	24-Apr	24-Apr	25-Apr	25-Apr
2008	2-May	2-May	3-May	2-May	30-Apr	30-Apr	4-May	4-May	4-May	3-May
2009	2-May	2-May	2-May	1-May	30-Apr	1-May	3-May	4-May	2-May	1-May
2010	20-Apr	21-Apr	21-Apr	22-Apr	22-Apr	22-Apr	24-Apr	24-Apr	24-Apr	22-Apr

Table I.2: Dates of local ice jam formation (D_j) at all sites.

	NWT/AB Border	Island at km 974	Grumbler Rapids	Mink Creek	Alexandra Falls	Escarpment Creek	Enterprise	Paradise Gardens	Golf Course	Pine Point Bridge
2005	-	-	-	22-Apr	21-Apr	-	22-Apr	22-Apr	23-Apr	22-Apr
2007	25-Apr	-	25-Apr	25-Apr	24-Apr	-	24-Apr	25-Apr	26-Apr	25-Apr
2008	-	-	3-May	3-May	2-May	3-May	4-May	4-May	4-May	3-May
2009	5-May	-	3-May	2-May	1-May	2-May	3-May	4-May	3-May	1-May
2010	22-Apr	22-Apr	22-Apr	23-Apr	23-Apr	23-Apr	24-Apr	25-Apr	25-Apr	24-Apr

Table I.3: Dates of ice jam releases (D_r) at all sites.

	NWT/AB Border	Island at km 974	Grumbler Rapids	Mink Creek	Alexandra Falls	Escarpment Creek	Enterprise	Paradise Gardens	Golf Course	Pine Point Bridge
2005	-	-	-	22-Apr	21-Apr	21-Apr	22-Apr	22-Apr	-	24-Apr
2007	26-Apr	-	25-Apr	25-Apr	24-Apr	-	25-Apr	26-Apr	26-Apr	26-Apr
2008	-	-	5-May	4-May	2-May	4-May	5-May	5-May	4-May	4-May
2009	5-May	-	-	2-May	1-May	6-May	6-May	4-May	3-May	2-May
2010	23-Apr	22-Apr	22-Apr	23-Apr	23-Apr	24-Apr	25-Apr	25-Apr	25-Apr	24-Apr

Appendix J: Ranges of dates of stages of breakup and days between stages of breakup at all ten study sites.

This Appendix contains the ranges of dates during which the stages of breakup occurred (D_c, D_j and D_r). As well, the number of days between stages of breakup at each of the ten study sites was determined (ΔD_{cj}, $\Delta D_{cr,}$ and ΔD_{jr}). Also included is the number of years of available data.

Appendix J: Summary of dates of breakup and days between breakup events at all ten study sites.

	Dates of occurrence											
	Day of First Crack (D_c)				Day of Ice Jam (D_j)				Day of Ice Jam Release (D_r)			
Site	Min	Max	Range	# Years	Min	Max	Range	# Years	Min	Max	Range	# Years
NWT/AB Border	20-Apr	2-May	12	5	22-Apr	5-May	13	3	23-Apr	5-May	12	3
Island at 974	21-Apr	2-May	11	5								
Grumbler Rapids	21-Apr	3-May	12	3	22-Apr	3-May	11	4	22-Apr	5-May	13	3
Mink Creek	21-Apr	2-May	11	5	22-Apr	3-May	11	5	22-Apr	4-May	12	5
Alexandra Falls	22-Apr	30-Apr	8	3	21-Apr	2-May	11	5	21-Apr	2-May	11	5
Escarpment Creek	22-Apr	1-May	9	3	23-Apr	3-May	10	3	21-Apr	6-May	15	4
Enterprise					22-Apr	4-May	12	5	22-Apr	6-May	14	5
Paradise Gardens	22-Apr	4-May	12	5	22-Apr	4-May	12	5	22-Apr	5-May	13	5
Golf Course	22-Apr	4-May	12	5	23-Apr	4-May	11	5	25-Apr	4-May	9	4
Pine Point Bridge	22-Apr	3-May	11	5	22-Apr	3-May	11	5	24-Apr	4-May	10	5
Onset of breakup HR					23-Apr	4-May	11	5				
Peak stage jam HR					25-Apr	6-May	11	5				

	Days in between events											
	From First Crack to Ice Jam (ΔD_{cj})				From First Crack to Ice Jam Release (ΔD_{cr})				From Ice Jam Formation to Release (ΔD_{jr})			
Site	Min	Max	Range	# Years	Min	Max	Range	# Years	Min	Max	Range	# Years
NWT/AB Border	2	3	1	3	3	3	0	3	0	1	1	3
Island at 974												
Grumbler Rapids	0	1	1	3	1	2	1	2	0	2	2	3
Mink Creek	0	1	1	5	0	2	2	5	0	1	1	5
Alexandra Falls	1	2	1	3	1	2	1	3				
Escarpment Creek	1	3	2	3	2	5	3	3	1	4	3	3
Enterprise									0	3	3	5
Paradise Gardens	0	1	1	5	0	2	2	5	0	1	1	5
Golf Course	0	1	1	5	0	1	1	4	0	0	0	4
Pine Point Bridge	0	2	2	5	1	2	1	5	0	2	2	5
Onset of breakup HR												
Peak stage jam HR												

Appendix K: Reach based lookup tables for days between sites and stages of breakup.

This Appendix contains the reach based lookup tables for days between sites and stages of breakup. The number of days between first cracking, local ice jamming and ice jam releasing between all sites were considered. Only combinations of sites and breakup events that occur within a two day range for all years of data are included. The nine tables in Appendix K are:

Table K.1: Days between first cracking at all locations.

Table K.2: Days between jamming at sites on the x-axis and cracking at sites on the y-axis.

Table K.3: Days between jam releasing at sites on the x-axis and cracking at sites on the y-axis.

Table K.4: Days between first cracking at sites on the x-axis and jamming at sites on the y-axis.

Table K.5: Days between ice jamming at all locations.

Table K.6: Days between jam releasing at sites on x-axis and jamming at sites on y-axis.

Table K.7: Days between first cracking at sites on x-axis and jam releasing at sites on y-axis.

Table K.8: Days between jamming at sites on x-axis and jam releasing at sites on y-axis.

Table K.9: Days between jam releasing at all locations.

These tables are color coded to illustrate the general pattern of breakup events. When the ranges are colored blue, the events happening at the sites on the x-axis occurred after the events at the sites on the y-axis. When ranges are color coded green, the two events occurred at approximately the same time. When the ranges are color coded red, the events happening at the sites on the x-axis occurred before events in the y-axis.

Table K1: Days between first cracking at all locations.

Reference Site	Border	Isl	Grumb.	MC	AF	Esc	Ent	PG	GC	PPB
First crack anywhere	0-2	0-2	1-3	0-2	0-2	0-2				1-3
First crack @ Border		0-2	0-1							
First crack @ Island	-2-0		0-1	-1-1						-1 -1
First crack @ Grumb	-1-0	-1-0		-1-1				1-3		-1 -1
First crack @ MC		-1-1	-1-1		-2-0	-2-0			0-2	0-1
First crack @ AF				0-2		0-1		2-4	2-4	
First crack @ Esc				0-2	-1 - 0			2-4		
First crack @ PG			-3 - -1		-4 - -2	-4 - -2				
First crack @ Golf C.				-2-0	-4 - -2					-2-0
First crack @ WSC HR		-1-1	-1-1	-1-0					0-2	0-2
First crack @ PPB		-1-1		-1-0	-3 - -1				0-2	

General pattern:
- before
- mostly before
- during
- mostly after
- after
- - N/A

Ie: when blue, event in x-axis happens AFTER event in y-axis.

Table K.2: Days between jamming at sites on x axis and cracking at sites on y axis.

Reference Site	Border	Isl	Grumb.	MC	AF	Esc	Ent	PG	GC	PPB	*Do*	*Dp*
First crack anywhere			2-3	1-3		2-3					2-4	4-6
First crack @ Border	2-3		1-2									3-5
First crack @ Island			0-1	0-2		0-2						2-4
First crack @ Grumb	1-3		0-1	0-2		0-2	1-3					2-4
First crack @ MC			0-2	0-1	-1 - 1	1			1 - 3	0-2	1-2	
First crack @ AF				1-3	1-2	1-3	2-4	3-4	3-4		2-4	
First crack @ Esc				1-3	0-2	1-3	2-4	3-4	2-4			3-5
First crack @ PG						-2 - -1	-1-0	0-1				1-3
First crack @ Golf C.			-2-0	-1-0	-2 --1	-1-0	-1 - 1	0-2	0-1	-1-0	0-1	
First crack @ WSC HR			0-2	0-1	-1 - 1	0-1			1-3	0-2	1-2	
First crack @ PPB				-1 - 1	-1-0	-1 - 1			1-2	0-1	0-1	

Table K.3: Days between jam releasing at sites on x axis and cracking at sites on y axis.

Reference Site	Border	Isl	Grumb.	MC	AF	Esc	Ent	PG	GC	PPB
First crack anywhere	3-5								3-5	2-4
First crack @ Border	3		2-3							
First crack @ Island	1-3			0-2						
First crack @ Grumb	2-3		1-2	0-2			2-4	2-4		
First crack @ MC				0-1	-1 - 1			0-2	1-2	1-3
First crack @ AF					1-2			3-5	3-4	2-4
First crack @ Esc					0-2		3-5	3-5	2-4	
First crack @ PG	-2-0					-1 - 1	0-1	-1 - 1	-2-0	
First crack @ Golf C.				-1 -0	-2 --1			0-2	0-1	0-2
First crack @ WSC HR			0-2	0-1	-1 - 1				1-3	1-2
First crack @ PPB				0-1	-1-0				1-2	1-2

General pattern:

before

mostly before

during

mostly after

after

- N/A

Ie: when blue,
event in x-axis
happens AFTER
event in y-axis.

Table K.4: Days between first cracking at sites on x axis and jamming at sites on y axis.

Reference Site	Border	Isl	Grumb	MC	AF	Esc	Ent	PG	GC	PPB
Jam @ Border	-3 - -2		-3- -1							
Jam @ Grumbler	-2 - -1	-1-0	-1-0	-2-0						
Jam @ Mink Creek		-2-0	-2-0	-1 - 0	-3 - -1	-3 - -1			0-1	-1 - 1
Jam @ Alex Falls				-1 - 1	-2 - -1	-2-0			1-2	0-1
Jam @ Escarpment		-2-0	-2-0	-1	-3 - -1	-3 - -1		1-2	0-1	-1 - 1
Jam @ Enterprise			-3 - -1		-4 - -2	-4 - -2		0-1	-1 - 1	
Jam @ PG					-4 - -3	-4 - -3		-1-0	-2-0	
Jam @ Golf Course				-3 - -1	-4 - -3	-4 - -2			-1-0	-2 - -1
Jam @ PPB				-2-0					0-1	0-1
Do @ Delta				-2 - -1	-4 - -2				-1-0	-2--1
Dp @ Delta	-5 - -3	-4 - -2	-4 - -2			-5 - -3		-3 - -1		

General pattern:
- before
- mostly before
- during
- mostly after
- after
- \- N/A

Ie: when blue, event in x-axis happens AFTER event in y-axis.

Table K.5: Days between jamming at all locations.

Reference Site	Border	Isl	Grumb	MC	AF	Esc	Ent	PG	GC	PPB	*Do*	*Dp*
Jam @ Border			-2-0									1-3
Jam @ Grumbler	0-2			-1 - 1		-1 - 1						2-3
Jam @ Mink Creek			-1 - 1		-1 - 0	0	-1 - 1	0-2	1-2	-1 - 1	0-1	2-4
Jam @ Alex Falls				0-1		0-1	0-2	1-3	2	0-1	1-2	
Jam @ Escarpment			-1 - 1	0	-1 - 0		1	1-2	1-2	-1 - 1	0-1	2-4
Jam @ Enterprise				-1 - 1	-2-0	-1		0-1	0-2			1-3
Jam @ PG				-2-0	-3 - -1	-2 - -1	-1 - 0		-1 - 1			
Jam @ Golf Course				-2 -1	-2	-2 --1	-2-0	-1 - 1		-2 - -1	-1 - 0	
Jam @ PPB				-1 - 1	-1-0	-1 - 1			1-2		0-1	
Do @ Delta				-1 - 0	-2 - -1	-1 - 0			0-1	-1 - 0		
Dp @ Delta	-3 - -1		-3- -2	-4 - -2		-4 - -2	-3 - -1					

Table K.6: Days between jam releasing at sites on x axis and jamming at sites on y axis.

Reference Site	Border	Isl	Grumb	MC	AF	Esc	Ent	PG	GC	PPB
Jam @ Border			0			1-2				
Jam @ Grumbler	1-2		0-2	-1 - 1		1-3		1-3		
Jam @ Mink Creek	1-2		0-2	-1 - 1	-1 - 0	1-3		1-3		0-2
Jam @ Alex Falls				0-2				1-3		1-3
Jam @ Escarpment				0-1	-1 - 0		2-3	2	1-2	0-1
Jam @ Enterprise				-1 - 1	-2-0			0-2	0-2	
Jam @ PG				-2-0	-3 - -1		0-1	0-1	-1 - 1	
Jam @ Golf Course				-2-0	-2				0	-1 - 1
Jam @ PPB				-1 - 1	-1-0				1-2	0-2
Do @ Delta				-1 -0	-2 - -1				0-1	0-1
Dp @ Delta	-2 - -1									

General pattern:
- before
- mostly before
- during
- mostly after
- after
- - N/A

Ie: when blue,
event in x-axis
happens AFTER
event in y-axis.

Table K.7: Days between first cracking at sites on x axis and jam releasing at sites on y axis.

Reference Site	Border	Isl	Grumb.	MC	AF	Esc	Ent	PG	GC	PPB
Jam Release @ Border	-3	-3- -1	-3- -2							
Jam Release @ Grumb	-3 - -2		-3 - -1							
Jam Release @ MC		-2-0	-2-0	-2-0					0-1	-1-0
Jam Release @ Esc										
Jam Release @ Ent			-4 - -2		-5 - -3	-5 - -3		-2-0		
Jam Release @ PG			-4 - -2	-3 - -1	-5 - -3	-5 - -3		-2-0	-2-0	
Jam Release @ GC				-3 - -1	-4 - -3	-4 - -2			-1-0	-3 - -1
Jam Release @ PPB				-3 - -1	-4 - -2				-2-0	-2--1

General pattern:

- before
- mostly before
- during
- mostly after
- after
- \- N/A

Ie: when blue, event in x-axis happens AFTER event in y-axis.

Table K.8: Days between jamming at sites on x axis and jam releasing at sites on y axis.

Reference Site	Border	Isl	Grumb	MC	AF	Esc	Ent	PG	GC	PPB	*Do*	*Dp*
Jam Release @ Border			-2 - -1									1-2
Jam Release @ Grumb	0		-2-0									
Jam Release @ MC			-1 - 1	-1 - 0	-2 - 0	-1 - 0	-1 - 1	0-2	0-2	-1 - 1	0-1	
Jam Release @ Esc	-2 - -1		-3- -1									
Jam Release @ Ent						-3 - -2		-2-0				
Jam Release @ PG			-3 - -1	-2 -0	-3 - -1	-2	-2 -0	-1-0	-1 - 1			
Jam Release @ GC	-3 - 1		-4- -2	-4- -2		-4- -2	-3 - 1					-2 -0
Jam Release @ PPB				-2-0	-3 - -1	-1-0			-1 - 1	-2-0	-1-0	

Table K.9: Days between jam releasing at all locations.

Reference Site	Border	Isl	Grumb	MC	AF	Esc	Ent	PG	GC	PPB
Jam Release @ Border			-1			1				
Jam Release @ Grumb	1			-1 - 1						
Jam Release @ MC			-1 - 1		-2 - 0			0-2	0-2	
Jam Release @ Esc	-1						0-1			
Jam Release @ Ent						-1 -0				
Jam Release @ PG				-2-0	-3 - -1				-1 - 0	
Jam Release @ GC				-2-0				0-1		-1 - 0
Jam Release @ PPB					-3 - -1				0-1	

General pattern:
- before
- mostly before
- during
- mostly after
- after
- - N/A

Ie: when blue,
event in x-axis
happens AFTER
event in y-axis.

Appendix L: Reach based lookup tables for years of available data for each site and breakup event combination.

This Appendix contains the reach based lookup tables for years of available data for each site and breakup event combination. Knowing how many years of data were used to determine the ranges adds validity when patterns appear. There are fewer years of data available when the dates of breakup events were not determined for some years. The nine tables in Appendix L are:

Table L.1: Days between first cracking at all locations.

Table L.2: Days between jamming at sites on the x-axis and cracking at sites on the y-axis.

Table L.3: Days between jam releasing at sites on the x-axis and cracking at sites on the y-axis.

Table L.4: Days between first cracking at sites on the x-axis and jamming at sites on the y-axis.

Table L.5: Days between ice jamming at all locations.

Table L.6: Days between jam releasing at sites on x-axis and jamming at sites on y-axis.

Table L.7: Days between first cracking at sites on x-axis and jam releasing at sites on y-axis.

Table L.8: Days between jamming at sites on x-axis and jam releasing at sites on y-axis.

Table L.9: Days between jam releasing at all locations.

These tables are color coded by years of available data.

Table L.1: Number of years of data between cracking at all locations.

Reference Site	Border	Isl	Grumb	MC	AF	Esc	PG	GC	PPB
First crack anywhere	5	5	3	5	3	3	5	5	5
First crack @ Border		5	3	5	3	3	5	5	5
First crack @ Island	5		3	5	3	3	5	5	5
First crack @ Grumb	3	3		3	3	3	3	3	3
First crack @ MC	5	5	3		3	3	5	5	5
First crack @ AF	3	3	3	3		3	3	3	3
First crack @ Esc	3	3	3	3	3		3	3	3
First crack @ PG	5	5	3	5	3	3		5	5
First crack @ Golf C.	5	5	3	5	3	3	5		5
First crack @ WSC HR	5	5	3	5	3	3	5	5	5
First crack @ PPB	5	5	3	5	3	3	5	5	

Years of Data:
- 5 years
- 4 years
- 3 years
- 2 years
- N/A

Table L.2: Number of years of data between jamming at sites on x axis and first cracking at sites on y axis.

Reference Site	Border	Isl	Grumb	MC	AF	Esc	Ent	PG	GC	PPB	*Do*	*Dp*
First crack anywhere	3		4	5	5	3	5	5	5	5	5	5
First crack @ Border	3		4	5	5	3	5	5	5	5	5	5
First crack @ Island	3		4	5	5	3	5	5	5	5	5	5
First crack @ Grumb	2		3	3	3	3	3	3	3	3	3	3
First crack @ MC	3		4	5	5	3	5	5	5	5	5	5
First crack @ AF	2		3	3	3	3	3	3	3	3	3	3
First crack @ Esc	2		3	3	3	3	3	3	3	3	3	3
First crack @ PG	3		4	5	5	3	5	5	5	5	5	5
First crack @ Golf C.	3		4	5	5	3	5	5	5	5	5	5
First crack @ WSC HR	3		4	5	5	3	5	5	5	5	5	5
First crack @ PPB	3		4	5	5	3	5	5	5	5	5	5

Table L.3: Number of years of data between jam releasing at sites on x axis and first cracking at sites on y axis.

Reference Site	Border	Isl	Grumb	MC	AF	Esc	Ent	PG	GC	PPB
First crack anywhere	3		3	5	5	4	5	5	4	5
First crack @ Border	3		3	5	5	4	5	5	4	5
First crack @ Island	3		3	5	5	4	5	5	4	5
First crack @ Grumb	3		2	3	3	3	3	3	3	3
First crack @ MC	3		3	5	5	4	5	5	4	5
First crack @ AF	2		2	3	3	3	3	3	3	3
First crack @ Esc	2		2	3	3	3	3	3	3	3
First crack @ PG	2		2	4	5	4	4	4	3	4
First crack @ Golf C.	3		3	5	5	4	5	5	4	5
First crack @ WSC HR	3		3	5	5	4	5	5	4	5
First crack @ PPB	3		3	5	5	4	5	5	4	5

Years of Data:

- 5 years
- 4 years
- 3 years
- 2 years
- N/A

Table L.4: Number of years of data between first cracking at sites on x axis and jamming at sites on y axis.

Reference Site	Border	Isl	Grumb	MC	AF	Esc	PG	GC	PPB
Jam @ Border	3	3	2	3	2	2	3	3	3
Jam @ Grumbler	4	4	3	4	3	3	4	4	4
Jam @ Mink Creek	5	5	3	5	3	3	5	5	5
Jam @ Alex Falls	5	5	3	5	3	3	5	5	5
Jam @ Escarpment	3	3	3	3	3	3	3	3	3
Jam @ Enterprise	5	5	3	5	3	3	5	5	5
Jam @ PG	5	5	3	5	3	3	5	5	5
Jam @ Golf Course	5	5	3	5	3	3	5	5	5
Jam @ PPB	5	5	3	5	3	3	5	5	5
Do @ Delta	5	5	3	5	3	3	5	5	5
Dp @ Delta	5	5	3	5	3	3	5	5	5

Years of Data:
- 5 years
- 4 years
- 3 years
- 2 years
- N/A

Table L.5: Number of years of data between jamming at all locations.

Reference Site	Border	Isl	Grumb	MC	AF	Esc	Ent	PG	GC	PPB	*Do*	*Dp*
Jam @ Border			3	3	3	2	3	3	3	3	3	3
Jam @ Grumbler	3			4	4	3	4	4	4	4	4	4
Jam @ Mink Creek	3		4		5	3	5	5	5	5	5	5
Jam @ Alex Falls	3		4	5		3	5	5	5	5	5	5
Jam @ Escarpment	2		3	3	3		3	3	3	3	3	3
Jam @ Enterprise	3		4	5	5	3		5	5	5	5	5
Jam @ PG	3		4	5	5	3	5		5	5	5	5
Jam @ Golf Course	3		4	5	5	3	5	5		5	5	5
Jam @ PPB	3		4	5	5	3	5	5	5		5	5
Do @ Delta	3		4	5	5	3	5	5	5	5		5
Dp @ Delta	3		4	5	5	3	5	5	5	5	5	

Table L.6: Number of years of data between jam releasing at sites on x axis and jamming sites on y axis.

Reference Site	Border	Isl	Grumb	MC	AF	Esc	Ent	PG	GC	PPB
Jam @ Border	3		2	3	3	2	3	3	3	3
Jam @ Grumbler	3		3	4	4	3	4	4	4	4
Jam @ Mink Creek	3		3	5	5	4	5	5	4	5
Jam @ Alex Falls	3		3	5		4	5	5	4	5
Jam @ Escarpment	2		2	3	3	3	3	3	3	3
Jam @ Enterprise	3		3	5	5	4	5	5	4	5
Jam @ PG	3		3	5	5	4	5	5	4	5
Jam @ Golf Course	3		3	5	5	4	5	5	4	5
Jam @ PPB	3		3	5	5	4	5	5	4	5
Do @ Delta	3		3	5	5	4	5	5	4	5
Dp @ Delta	3		3	5	5	4	5	5	4	5

Years of Data:

- 5 years
- 4 years
- 3 years
- 2 years
- N/A

Table L.7: Number of years of data between first cracking at sites on x axis and jam releasing at sites on y axis.

Reference Site	Border	Isl	Grumb	MC	AF	Esc	Ent	PG	GC	PPB
Jam Release @ Border	3	3	2	3	2	2		3	3	3
Jam Release @ Grumb	3	3	2	3	2	2		3	3	3
Jam Release @ Mink	5	5	3	5	3	3		5	5	5
Jam Release @ Esc	4	4	3	4	3	3		4	4	4
Jam Release @ Ent	5	5	3	5	3	3		5	5	5
Jam Release @ PG	5	5	3	5	3	3		5	5	5
Jam Release @ GC	4	4	3	4	3	3		4	4	4
Jam Release @ PPB	5	5	3	5	3	3		5	5	5

Years of Data:
- 5 years
- 4 years
- 3 years
- 2 years
- N/A

Table L.8: Number of years of data between day of jamming at sites on x axis and jam releasing at sites on y axis.

Reference Site	Border	Isl	Grumb	MC	AF	Esc	Ent	PG	GC	PPB	*Do*	*Dp*
Jam Release @ Border	3		3	3	3	2	3	3	3	3	3	3
Jam Release @ Grumb	2		3	3	3	2	3	3	3	3	3	3
Jam Release @ Mink	3		4	5	5	3	5	5	5	5	5	5
Jam Release @ Esc	2		3	4	4	3	4	4	4	4	4	4
Jam Release @ Ent	3		4	5	5	3	5	5	5	5	5	5
Jam Release @ PG	3		4	5	5	3	5	5	5	5	5	5
Jam Release @ GC	3		4	5	5	3	5	5	5	5	5	5
Jam Release @ PPB	3		4	5	5	3	5	5	5	5	5	5

Table L.9: Number of years of data between jam releasing at all locations.

Reference Site	Border	Isl	Grumb	MC	AF	Esc	Ent	PG	GC	PPB
Jam Release @ Border			2	3	3	2	3	3	3	3
Jam Release @ Grumb	2			3	3	2	3	3	3	3
Jam Release @ Mink	3		3		5	4	5	5	4	5
Jam Release @ Esc	2		2	4	4		4	4	3	4
Jam Release @ Ent	3		3	5	5	4		5	4	5
Jam Release @ PG	3		3	5	5	4	5		4	5
Jam Release @ GC	3		3	4	5	3	4	4		4
Jam Release @ PPB	3		3	5	5	4	5	5	4	

Years of Data:

- 5 years
- 4 years
- 3 years
- 2 years
- N/A

Appendix M: Reach based lookup tables for days between sites and stages of breakup, color coded by years of available data.

This Appendix contains the reach based lookup tables for days between sites and stages of breakup, color coded by years of available data. Only combinations of sites and breakup events that occur within 2 days range for all years of data are included. Only combinations of sites and breakup events with more than two years of data are included. The nine tables in Appendix M are:

Table M.1: Days between first cracking at all locations.

Table M.2: Days between jamming at sites on the x-axis and cracking at sites on the y-axis.

Table M.3: Days between jam releasing at sites on the x-axis and cracking at sites on the y-axis.

Table M.4: Days between first cracking at sites on the x-axis and jamming at sites on the y-axis.

Table M.5: Days between ice jamming at all locations.

Table M.6: Days between jam releasing at sites on x-axis and jamming at sites on y-axis.

Table M.7: Days between first cracking at sites on x-axis and jam releasing at sites on y-axis.

Table M.8: Days between jamming at sites on x-axis and jam releasing at sites on y-axis.

Table M.9: Days between jam releasing at all locations.

Table M.1: Days between first cracking at all locations, color coded by years of data.

Reference Site	Border	Isl	Grumb	MC	AF	Esc	Ent	PG	GC	PPB
First crack anywhere	0-2	0-2	1-3	0-2	0-2	0-2				1-3
First crack @ Border		0-2	0-1							
First crack @ Island	-2-0		0-1	-1-1						-1 -1
First crack @ Grumb	-1-0	-1-0		-1-1				1-3		-1 -1
First crack @ MC		-1-1	-1-1		-2-0	-2-0			0-2	0-1
First crack @ AF				0-2		0-1		2-4	2-4	
First crack @ Esc				0-2	-1 - 0			2-4		
First crack @ PG			-3 - -1		-4 - -2	-4 - -2				
First crack @ GC				-2-0	-4 - -2					-2-0
First crack @ WSC HR		-1-1	-1-1	-1-0					0-2	0-2
First crack @ PPB		-1-1		-1-0	-3 - -1				0-2	

Years of Data:
- 5 years
- 4 years
- 3 years
- 2 years
- N/A

Table M.2: Days between jamming at sites on x axis and cracking at sites on y axis, color coded by years of data.

Reference Site	Border	Isl	Grumb	MC	AF	Esc	Ent	PG	GC	PPB	*Do*	*Dp*
First crack anywhere			2-3	1-3		2-3					2-4	4-6
First crack @ Border	2-3		1-2									3-5
First crack @ Island			0-1	0-2		0-2						2-4
First crack @ Grumb	1-3		0-1	0-2		0-2	1-3					2-4
First crack @ MC			0-2	0-1	-1 - 1	1			1 - 3	0-2	1-2	
First crack @ AF				1-3	1-2	1-3	2-4	3-4	3-4		2-4	
First crack @ Esc				1-3	0-2	1-3	2-4	3-4	2-4			3-5
First crack @ PG						-2 - -1	-1-0	0-1				1-3
First crack @ GC			-2-0	-1-0	-2 --1	-1-0	-1 - 1	0-2	0-1	-1-0	0-1	
First crack @ WSC HR			0-2	0-1	-1 - 1	0-1			1-3	0-2	1-2	
First crack @ PPB				-1 - 1	-1-0	-1 - 1			1-2	0-1	0-1	

Table M.3: Days between jam releasing at the sites on x axis and cracking at sites on y axis, color coded by years of data

Reference Site	Border	Isl	Grumb	MC	AF	Esc	Ent	PG	GC	PPB
First crack anywhere	3-5								3-5	2-4
First crack @ Border	3		2-3							
First crack @ Island	1-3			0-2						
First crack @ Grumb	2-3		1-2	0-2			2-4	2-4		
First crack @ MC				0-1	-1 - 1			0-2	1-2	1-3
First crack @ AF					1-2			3-5	3-4	2-4
First crack @ Esc					0-2		3-5	3-5	2-4	
First crack @ PG	-2-0					-1 - 1	0-1	-1 - 1	-2-0	
First crack @ GC				-1 -0	-2 --1			0-2	0-1	0-2
First crack @ WSC HR			0-2	0-1	-1 - 1				1-3	1-2
First crack @ PPB				0-1	-1-0				1-2	1-2

Years of Data:
- 5 years
- 4 years
- 3 years
- 2 years
- N/A

Table M.4: Days between first cracking at sites on x axis and jamming at sites on y axis, color coded by years of data.

Reference Site	Border	Isl	Grumb	MC	AF	Esc	Ent	PG	GC	PPB
Jam @ Border	-3 - -2		-3- -1							
Jam @ Grumbler	-2 - -1	-1-0	-1-0	-2-0						
Jam @ Mink Creek		-2-0	-2-0	-1 - 0	-3 - -1	-3 - -1			0-1	-1 - 1
Jam @ Alex Falls				-1 - 1	-2 - -1	-2-0			1-2	0-1
Jam @ Escarpment		-2-0	-2-0	-1	-3 - -1	-3 - -1		1-2	0-1	-1 - 1
Jam @ Enterprise			-3 - -1		-4 - -2	-4 - -2		0-1	-1 - 1	
Jam @ PG					-4 - -3	-4 - -3		-1-0	-2-0	
Jam @ Golf Course				-3 - -1	-4 - -3	-4 - -2			-1-0	-2 - -1
Jam @ PPB				-2-0					0-1	0-1
Do @ Delta				-2 - -1	-4 - -2				-1-0	-2--1
Dp @ Delta	-5 - -3	-4 - -2	-4 - -2			-5 - -3		-3 - -1		

Years of Data:
- 5 years
- 4 years
- 3 years
- 2 years
- N/A

Table M.5: Days between jamming at all locations, color coded by years of data.

Reference Site	Border	Isl	Grumb	MC	AF	Esc	Ent	PG	GC	PPB	*Do*	*Dp*
Jam @ Border			-2-0									1-3
Jam @ Grumbler	0-2			-1 - 1		-1 - 1						2-3
Jam @ Mink Creek			-1 - 1		-1 - 0	0	-1 - 1	0-2	1-2	-1 - 1	0-1	2-4
Jam @ Alex Falls				0-1		0-1	0-2	1-3	2	0-1	1-2	
Jam @ Escarpment			-1 - 1	0	-1 - 0		1	1-2	1-2	-1 - 1	0-1	2-4
Jam @ Enterprise				-1 - 1	-2-0	-1		0-1	0-2			1-3
Jam @ PG				-2-0	-3 - -1	-2 - -1	-1 - 0		-1 - 1			
Jam @ Golf Course				-2 -1	-2	-2 --1	-2-0	-1 - 1		-2--1	-1 - 0	
Jam @ PPB				-1 - 1	-1-0	-1 - 1			1-2		0-1	
Do @ Delta				-1 - 0	-2 - -1	-1 - 0			0-1	-1 - 0		
Dp @ Delta	-3 - -1		-3- -2	-4 - -2		-4 - -2	-3 - -1					

Table M.6: Days between jam releasing at sites on x axis and jamming at sites on y axis, color coded by years of data

Reference Site	Border	Isl	Grumb	MC	AF	Esc	Ent	PG	GC	PPB
Jam @ Border			0			1-2				
Jam @ Grumbler	1-2		0-2	-1 - 1		1-3		1-3		
Jam @ Mink Creek	1-2		0-2	-1 - 1	-1 - 0	1-3		1-3		0-2
Jam @ Alex Falls				0-2				1-3		1-3
Jam @ Escarpment				0-1	-1 - 0		2-3	2	1-2	0-1
Jam @ Enterprise				-1 - 1	-2-0			0-2	0-2	
Jam @ PG				-2-0	-3 - -1		0-1	0-1	-1 - 1	
Jam @ Golf Course				-2-0	-2				0	-1 - 1
Jam @ PPB				-1 - 1	-1-0				1-2	0-2
Do @ Delta				-1 -0	-2 - -1				0-1	0-1
Dp @ Delta	-2 - -1									

Years of Data:
- 5 years
- 4 years
- 3 years
- 2 years
- N/A

Table M.7: Days between first cracking at sites on x axis and jam releasing at sites on y axis, color coded by years of data

Reference Site	Border	Isl	Grumb	MC	AF	Esc	Ent	PG	GC	PPB
Jam Release @ Border	-3	-3- -1	-3- -2							
Jam Release @ Grumb	-3 - -2		-3 - -1							
Jam Release @ MC		-2-0	-2-0	-2-0					0-1	-1-0
Jam Release @ Esc										
Jam Release @ Ent			-4 - -2		-5 - -3	-5 - -3		-2-0		
Jam Release @ PG			-4 - -2	-3 - -1	-5 - -3	-5 - -3		-2-0	-2-0	
Jam Release @ GC				-3 - -1	-4 - -3	-4 - -2			-1-0	-3 - -1
Jam Release @ PPB				-3 - -1	-4 - -2				-2-0	-2--1

Years of Data:
- 5 years
- 4 years
- 3 years
- 2 years
- N/A

Table M.8: Days between jamming at sites on x axis and jam releasing at sites on y axis, color coded by years of data

Reference Site	Border	Isl	Grumb	MC	AF	Esc	Ent	PG	GC	PPB	*Do*	*Dp*
Jam Release @ Border	-1 - 0		-2 - -1									1-2
Jam Release @ Grumb	0		-2-0									
Jam Release @ MC			-1 - 1	-1 - 0	-2 - 0	-1 - 0	-1 - 1	0-2	0-2	-1 - 1	0-1	
Jam Release @ Esc	-2 - -1		-3- -1									
Jam Release @ Ent						-3 - -2		-2-0				
Jam Release @ PG			-3 - -1	-2 -0	-3 - -1	-2	-2 -0	-1-0	-1 - 1			
Jam Release @ GC	-3 - 1		-4- -2	-4- -2		-4- -2	-3 - 1					-2 -0
Jam Release @ PPB				-2-0	-3 - -1	-1-0			-1 - 1	-2-0	-1-0	

Table M.9: Days between jam releasing at all locations, color coded by years of data.

Reference Site	Border	Isl	Grumb	MC	AF	Esc	Ent	PG	GC	PPB
Jam Release @ Border			-1			1				
Jam Release @ Grumb	1			-1 - 1						
Jam Release @ MC			-1 - 1		-2 - 0			0-2	0-2	0-2
Jam Release @ Esc	-1						0-1			
Jam Release @ Ent						-1 -0				
Jam Release @ PG				-2-0	-3 - -1				-1 - 0	
Jam Release @ GC				-2-0				0-1		-1 - 0
Jam Release @ PPB				-2-0	-3 - -1				0-1	

Years of Data:

- 5 years
- 4 years
- 3 years
- 2 years
- N/A

Appendix N: Known dates of historic progression of breakup events.

This Appendix contains the known dates of upstream breakup events documented in consultant and research reports. The sources of the historic data are as follows:

Year	**Reference**
1977	UMA (1978)
1985	Gerard and Stanley (1988a)
1987	Gerard and Stanley (1988a)
1988	Gerard and Stanley (1988a)
1989	Gerard and Jasek (1990)

The dates of first cracking (D_c), local ice jamming (D_j) and ice jam releasing (D_r) are tabulated and compared to the thresholds of dates on which the breakup events occurred, from 2005 to 2010. The three tables in Appendix N are:

Table N.1: Historic dates of first cracking (D_c) compared to the range of dates established using site specific analysis from 2005 to 2010.

Table N.2: Historic dates of local ice jamming (D_j) compared to the range of dates established using site specific analysis from 2005 to 2010.

Table N.3: Historic dates of ice jam releasing (D_r) compared to the range of dates established using site specific analysis from 2005 to 2010.

Table N.1: Historic dates of first cracking (D_c) compared to the range of dates established by analysis from '05 to '10.

	PG	PPB
1977	2-May	27-Apr
1985		1-May
1987		
1988		
1989	2-May	
Min	22-Apr	22-Apr
Max	4-May	3-May
River km	1071	1098

Table N.2: Historic dates of local ice jamming (D_j) compared to the range of dates established by analysis from '05 to '10.

	Border	Grumb	AF	Esc	Ent	PG	GC	PPB	Do	Dp
1977			27-Apr	28-Apr	1-May	2-May		27-Apr	27-Apr	3-May
1985								1-May	6-May	7-May
1987						25-Apr	25-Apr		25-Apr	27-Apr
1988			24-Apr	24-Apr	25-Apr			27-Apr	27-Apr	27-Apr
1989	1-May	2-May			2-May	2-May	2-May		2-May	6-May
Min	22-Apr	22-Apr	21-Apr	23-Apr	22-Apr	22-Apr	23-Apr	22-Apr	23-Apr	25-Apr
Max	5-May	3-May	2-May	3-May	4-May	4-May	4-May	3-May	4-May	6-May
River km	945.5	987	1034	1041	1048	1071	1089	1098	1108	1108

Table N.3: Historic dates of ice jam releasing (D_r) compared to the range of dates established by analysis from '05 to '10.

	Border	Grumb	MC	PG
1977				2-May
1985	5-May			
1987				
1988			24-Apr	
1989	2-May	2-May		2-May
Min	23-Apr	22-Apr	22-Apr	22-Apr
Max	5-May	5-May	4-May	5-May
River km	945.5	987	1027	1071

Appendix O: Order of breakup events at all sites.

This Appendix contains the order of breakup events at all sites. There are two methods that these orders were determined for each year:

Table O.1: For each year, the orders of each breakup event (cracking, jamming and jam releasing) are ranked separately by order of occurrence.

Table O.2: For each year, the orders of all breakup events are ranked together by order of occurrence.

These two sets of rankings were presented to determine any general patterns in the sequencing of events, independent of the consistency of the number of days between events.

Table O.1: Each breakup event ranked seperately by order of occurrence.
These breakup events did not occur at the sites shaded in grey.

2005

Crack (D_c)	**Jam (D_j)**	**Release (D_r)**
1 Border	1 AF	1 AF
1 Island	2 MC	1 Esc
1 MC	2 Ent	2 MC
2 PG	2 PG	2 Ent
2 GC	2 PPB	2 PG
2 PPB	3 GC	4 PPB
- Grumb	3 D_o	- Border
- AF	5 D_p	- Island
- Esc	- Border	- Grumb
N/A Ent	- Island	- GC
	- Grumb	
	- Esc	

2007

Crack (D_c)	**Jam (D_j)**	**Release (D_r)**
1 Border	2 AF	2 AF
2 PG	2 Ent	3 Grumb
3 Island	3 Border	3 MC
3 MC	3 Grumb	3 Ent
3 GC	3 MC	4 Border
3 PPB	3 PG	4 PG
- Grumb	3 PPB	4 GC
- AF	4 GC	4 PPB
- Esc	4 D_o	- Island
N/A Ent	5 D_p	- Esc
	- Island	
	- Esc	

2008

Crack (D_c)	**Jam (D_j)**	**Release (D_r)**
1 AF	3 AF	3 AF
1 Esc	4 Grumb	5 MC
3 Border	4 MC	5 Esc
3 Island	4 Esc	5 GC
3 MC	4 PPB	5 PPB
4 Grumb	5 Ent	6 Grumb
4 PPB	5 PG	6 Ent
5 PG	5 GC	6 PG
5 GC	5 D_o	- Border
N/A Ent	6 D_p	- Island
	- Border	
	- Island	

2009

Crack (D_c)	**Jam (D_j)**	**Release (D_r)**
1 AF	2 AF	2 AF
2 MC	2 PPB	3 MC
2 Esc	3 MC	3 PPB
2 PPB	3 Esc	4 GC
3 Border	3 D_o	5 PG
3 Island	4 Grumb	6 Border
3 Grumb	4 Ent	7 Esc
3 GC	4 GC	7 Ent
5 PG	5 PG	- Island
N/A Ent	6 Border	- Grumb
	7 D_p	
	- Island	

2010

Crack (D_c)	**Jam (D_j)**	**Release (D_r)**
1 Border	3 Border	3 Island
2 Island	3 Island	3 Grumb
2 Grumb	3 Grumb	4 Border
3 MC	4 MC	4 MC
3 AF	4 AF	4 AF
3 Esc	4 Esc	5 Esc
3 PPB	5 Ent	5 PPB
5 PG	5 PPB	6 Ent
5 GC	5 D_o	6 PG
N/A Ent	6 PG	6 GC
	6 GC	
	6 D_p	

Reach 2
Reach 3
Reach 4
Reach 5
Order of event not known.
N/A Event does not occur at this site.

Table O.2: All breakup events ranked from first crack anywhere.
These breakup events did not occur at the sites shaded in grey.

2005

Crack (D_c)	Jam (D_j)	Release (D_r)
1 Border	1 AF	1 AF
1 Island	2 MC	1 Esc
1 MC	2 Ent	2 MC
2 PG	2 PG	2 Ent
2 GC	2 PPB	2 PG
2 PPB	3 GC	4 PPB
- Grumb	3 D_o	- Border
- AF	5 D_p	- Island
- Esc	- Border	- Grumb
N/A Ent	- Island	- GC
	- Grumb	
	- Esc	

2007

Crack (D_c)	Jam (D_j)	Release (D_r)
1 Border	2 AF	2 AF
2 PG	2 Ent	3 Grumb
3 Island	3 Border	3 MC
3 MC	3 Grumb	3 Ent
3 GC	3 MC	4 Border
3 PPB	3 PG	4 PG
- Grumb	3 PPB	4 GC
- AF	4 GC	4 PPB
- Esc	4 D_o	- Island
N/A Ent	5 D_p	- Esc
	- Island	
	- Esc	

2008

Crack (D_c)	Jam (D_j)	Release (D_r)
1 AF	3 AF	3 AF
1 Esc	4 Grumb	5 MC
2 Border	4 MC	5 Esc
2 Island	4 Esc	5 GC
2 MC	4 PPB	5 PPB
4 Grumb	5 Ent	6 Grumb
4 PPB	5 PG	6 Ent
5 PG	5 GC	6 PG
5 GC	5 D_o	- Border
N/A Ent	6 D_p	- Island
	- Border	
	- Island	

2009

Crack (D_c)	Jam (D_j)	Release (D_r)
1 AF	2 AF	2 AF
2 MC	2 PPB	3 MC
2 Esc	3 MC	3 PPB
2 PPB	3 Esc	4 GC
3 Border	3 D_o	5 PG
3 Island	4 Grumb	6 Border
3 Grumb	4 Ent	7 Esc
3 GC	4 GC	7 Ent
5 PG	5 PG	- Island
N/A Ent	6 Border	- Grumb
	7 D_p	
	- Island	

2010

Crack (D_c)	Jam (D_j)	Release (D_r)
1 Border	3 Border	3 Island
2 Island	3 Island	3 Grumb
2 Grumb	3 Grumb	4 Border
3 MC	4 MC	4 MC
3 AF	4 AF	4 AF
3 Esc	4 Esc	5 Esc
3 PPB	5 Ent	5 PPB
5 PG	5 PPB	6 Ent
5 GC	5 D_o	6 PG
N/A Ent	6 PG	6 GC
	6 GC	
	6 D_p	

Appendix P: Ranges of accumulated degree days of thaw (*ADDT*) during stages of breakup and the increase in accumulated degree days of thaw (*ADDT*) between stages of breakup at all ten study sites.

This Appendix contains the results of the site specific analysis of the six conventions of accumulated degree days of thaw (*ADDT*). Each table shows the ranges of accumulated degree days of thaw (*ADDT*) during which the stages of breakup occurred. As well, the increase in accumulated degree days of thaw (*ADDT*) between stages of breakup at each of the ten study sites was determined. Also included is the number of years of available data. The six sets of tables in Appendix P are:

Table P.1: Hay River total degree of thaw on dates of occurrence and between breakup events at all sites.

Table P.2: Hay River accumulated degree days of thaw, base 0˚C on dates of occurrence and between breakup events at all sites.

Table P.3: Hay River accumulated degree days of thaw, base -5˚C on dates of occurrence and between breakup events at all sites.

Table P.4: High Level total degree days of thaw on dates of occurrence and between breakup events at all sites.

Table P.5: High Level accumulated degree days of thaw, base 0˚C on dates of occurrence and between breakup events at all sites.

Table P.6: High Level accumulated degree days of thaw, base -5˚C on dates of occurrence and between breakup events at all sites.

Not one of the six conventions of degree days of thaw analysis produced exceptionally consistent results. There was little difference between them overall. As a result of this, the simplest convention to calculate was chosen: the total days of thaw in Hay River.

Table P.1: Hay River total degree days of thaw ($TDDT_{HR}$) on dates of occurrence and between breakup events at all sites.

	Hay River *TDDT* ($TDDT_{HR}$), ˚C-days on dates of occurrence											
	Day of First Crack (TDD_{HRc})				Day of Ice Jam (TDD_{HRj})				Day of Ice Jam Release (TDD_{HRr})			
Site	Min	Max	Range	# Years	Min	Max	Range	# Years	Min	Max	Range	# Years
NWT/AB Border	36	102	66	5	44	128	84	3	44	131	87	3
Island at 974	37	116	80	5								
Grumbler Rapids	37	116	80	3	44	128	84	4	55	128	72	3
Mink Creek	29	128	98	5	37	131	94	5	37	131	94	5
Alexandra Falls	36	128	91	3	41	131	91	5	41	131	91	5
Escarpment Creek	29	128	98	3	37	131	94	3	42	131	90	4
Enterprise					44	131	88	5	45	131	86	5
Paradise Gardens	47	131	85	5	51	131	81	5	51	131	81	5
Golf Course	37	131	95	5	44	131	88	5	44	131	88	4
Pine Point Bridge	29	127	98	5	29	131	102	5	37	131	95	5
Onset of breakup HR					37	131	95	5				
Peak stage jam HR					45	131	86	5				

	Increase in Hay River *TDD* (ΔTDD_{HR}) between events, ˚C-days between events											
	Crack to Ice Jam ($\Delta TDDT_{HRcj}$)				Crack to Ice Jam Release ($\Delta TDDT_{HRcr}$)				Ice Jam to Release ($\Delta TDDT_{HRjr}$)			
Site	Min	Max	Range	# Years	Min	Max	Range	# Years	Min	Max	Range	# Years
NWT/AB Border	7	26	19	3	7	29	22	3	0	5	5	3
Island at 974												
Grumbler Rapids	0	11	11	3	7	11	4	2	0	7	7	3
Mink Creek	0	9	9	5	0	14	14	5	0	4	4	5
Alexandra Falls	4	19	15	3	4	19	15	3				
Escarpment Creek	4	28	25	3	4	33	29	3	0	9	8	3
Enterprise									0	8	8	5
Paradise Gardens	0	8	8	5	0	13	13	5	0	5	5	5
Golf Course	0	7	7	5	0	7	7	4	0	0	0	4
Pine Point Bridge	0	4	4	5	4	8	4	5	0	8	8	5
Onset of breakup HR												
Peak stage jam HR												

Table P.2: Hay River accumulated degree days of thaw ($ADDT_{HR0}$), base 0˚C on dates of occurrence and between breakup events at all sites.

	Hay River *ADDT* Base 0˚C ($ADDT_{HR0}$), ˚C-days on dates of occurrence											
	Day of First Crack ($ADDT_{HR0c}$)				Day of Ice Jam ($ADDT_{HR0j}$)				Day of Ice Jam Release ($ADDT_{HR0r}$)			
Site	Min	Max	Range	# Years	Min	Max	Range	# Years	Min	Max	Range	# Years
NWT/AB Border	7	36	29	5	25	53	28	3	25	57	32	3
Island at 974	18	42	24	5								
Grumbler Rapids	18	45	27	3	25	53	28	4	26	53	27	3
Mink Creek	10	53	43	5	18	57	39	5	18	57	39	5
Alexandra Falls	6	53	47	3	10	57	46	5	10	57	46	5
Escarpment Creek	10	53	43	3	18	57	39	3	22	57	35	4
Enterprise					18	57	39	5	26	57	31	5
Paradise Gardens	18	57	39	5	25	57	32	5	25	57	32	5
Golf Course	18	57	39	5	25	57	32	5	25	57	32	4
Pine Point Bridge	10	53	43	5	10	57	47	5	18	57	39	5
Onset of breakup HR					18	57	39	5				
Peak stage jam HR					26	57	31	5				

	Increase in Hay River *ADDT* base 0˚C ($\Delta ADDT_{HR0}$) between events, ˚C-days between events											
	Crack to Ice Jam ($\Delta ADDT_{HR0cj}$)				Crack to Ice Jam Release ($\Delta ADDT_{HR0cr}$)				Ice Jam to Release ($\Delta ADDT_{HR0jr}$)			
Site	Min	Max	Range	# Years	Min	Max	Range	# Years	Min	Max	Range	# Years
NWT/AB Border	7	26	19	3	7	29	22	3	0	5	5	3
Island at 974												
Grumbler Rapids	0	11	11	3	7	11	4	2	0	7	7	3
Mink Creek	0	9	9	5	0	14	14	5	0	4	4	5
Alexandra Falls	4	19	15	3	4	19	15	3				
Escarpment Creek	4	28	25	3	4	33	29	3	0	9	8	3
Enterprise									0	8	8	5
Paradise Gardens	0	8	8	5	0	13	13	5	0	5	5	5
Golf Course	0	7	7	5	0	7	7	4	0	0	0	4
Pine Point Bridge	0	4	4	5	4	8	4	5	0	8	8	5
Onset of breakup HR												
Peak stage jam HR												

Table P.3: Hay River accumulated degree days of thaw ($ADDT_{HR\text{-}5}$), base -5˚C on dates of occurrence and between breakup events at all sites.

	Hay River *ADDT* Base -5˚C ($ADDT_{HR\text{-}5}$), ˚C-days on dates of occurrence											
	Day of First Crack ($ADDT_{HR\text{-}5c}$)				Day of Ice Jam ($ADDT_{HR\text{-}5j}$)				Day of Ice Jam Release ($ADDT_{HR\text{-}5r}$)			
Site	Min	Max	Range	# Years	Min	Max	Range	# Years	Min	Max	Range	# Years
NWT/AB Border	104	148	44	5	133	183	50	3	133	192	59	3
Island at 974	123	167	44	5								
Grumbler Rapids	123	167	44	3	133	183	50	4	133	183	50	3
Mink Creek	111	183	73	5	123	192	69	5	123	192	69	5
Alexandra Falls	102	183	82	3	111	192	81	5	111	192	81	5
Escarpment Creek	111	183	73	3	123	192	69	3	133	197	64	4
Enterprise					120	197	77	5	133	201	68	5
Paradise Gardens	120	197	77	5	133	201	68	5	140	201	61	5
Golf Course	123	197	74	5	135	201	66	5	135	201	66	4
Pine Point Bridge	111	183	73	5	111	197	86	5	123	197	74	5
Onset of breakup HR					123	197	74	5				
Peak stage jam HR					148	201	53	5				

	Increase in Hay River *ADDT* base -5˚C ($\Delta ADDT_{HR\text{-}5}$) between events, ˚C-days between events											
	Crack to Ice Jam ($\Delta ADDT_{HR\text{-}5cj}$)				Crack to Ice Jam Release ($\Delta ADDT_{HR\text{-}5cr}$)				Ice Jam to Release ($\Delta ADDT_{HR\text{-}5jr}$)			
Site	Min	Max	Range	# Years	Min	Max	Range	# Years	Min	Max	Range	# Years
NWT/AB Border	17	36	19	3	20	44	25	3	0	9	9	3
Island at 974												
Grumbler Rapids	0	16	16	3	16	17	1	2	0	17	17	3
Mink Creek	0	14	14	5	0	24	24	5	0	9	9	5
Alexandra Falls	9	29	20	3	9	29	20	3				
Escarpment Creek	9	43	35	3	14	53	39	3	5	25	19	3
Enterprise									0	13	13	5
Paradise Gardens	0	13	13	5	0	23	23	5	0	10	10	5
Golf Course	0	12	12	5	0	12	12	4	0	0	0	4
Pine Point Bridge	0	14	14	5	9	18	8	5	0	18	18	5
Onset of breakup HR	0	39	39	5								
Peak stage jam HR	4	46	42	5								

Table P.4: High Level total degree days of thaw ($TDDT_{HL}$) on dates of occurrence and between breakup events at all sites.

	High Level *TDDT* ($TDDT_{HL}$), ˚C-days on dates of occurrence											
	Day of First Crack ($TDDT_{HLc}$)				Day of Ice Jam ($TDDT_{HLj}$)				Day of Ice Jam Release ($TDDT_{HLr}$)			
Site	Min	Max	Range	# Years	Min	Max	Range	# Years	Min	Max	Range	# Years
NWT/AB Border	86	118	32	5	110	143	34	3	110	147	37	3
Island at 974	86	133	47	4								
Grumbler Rapids	87	133	46	3	96	143	48	4	112	143	32	3
Mink Creek	79	143	65	4	87	147	59	5	87	147	59	4
Alexandra Falls	67	143	76	3	79	147	68	5	79	147	68	5
Escarpment Creek	67	143	76	3	87	147	59	3	105	147	41	3
Enterprise					98	147	48	5	110	149	40	4
Paradise Gardens	102	147	44	5	105	149	44	5	106	149	43	5
Golf Course	87	147	59	4	98	149	51	5	98	149	51	4
Pine Point Bridge	79	143	65	5	79	147	68	5	87	147	59	5
Onset of breakup HR					87	147	59	5				
Peak stage jam HR					113	149	37	5				

	Increase in High Level *TDD* (ΔTDD_{HL}) between events, ˚C-days between events											
	Crack to Ice Jam (ΔTDD_{HLcj})				Crack to Ice Jam Release (ΔTDD_{HLcr})				Ice Jam to Release (ΔTDD_{HLjr})			
Site	Min	Max	Range	# Years	Min	Max	Range	# Years	Min	Max	Range	# Years
NWT/AB Border	22	25	4	3	23	30	7	3	0	8	8	3
Island at 974												
Grumbler Rapids	0	11	11	3	10	17	6	2	0	17	17	3
Mink Creek	0	10	10	4	0	19	19	4	0	10	10	4
Alexandra Falls	3	19	16	3	3	19	16	3				
Escarpment Creek	3	28	25	3	3	38	35	3	0	23	23	3
Enterprise									3	11	9	4
Paradise Gardens	0	9	9	5	0	17	17	5	0	8	8	5
Golf Course	0	11	11	4	0	11	11	4	0	0	0	4
Pine Point Bridge	0	3	3	5	3	19	16	5	0	19	19	5
Onset of breakup HR												
Peak stage jam HR												

Table P.5: High Level accumulated degree days of thaw ($ADDT_{HL0}$), base 0˚C on dates of occurrence and between breakup events at all sites.

	High Level *ADDT* Base 0˚C ($ADDT_{HL0}$), ˚C-days on dates of occurrence											
	Day of First Crack ($ADDT_{HL0c}$)				Day of Ice Jam ($ADDT_{HL0j}$)				Day of Ice Jam Release ($ADDT_{HL0r}$)			
Site	Min	Max	Range	# Years	Min	Max	Range	# Years	Min	Max	Range	# Years
NWT/AB Border	58	104	46	5	98	129	31	3	98	132	35	3
Island at 974	58	119	61	4								
Grumbler Rapids	68	119	51	3	68	129	61	4	85	129	45	3
Mink Creek	58	129	71	4	68	132	64	5	75	132	57	4
Alexandra Falls	40	129	90	3	58	132	74	5	58	132	74	5
Escarpment Creek	40	129	90	3	68	132	64	3	78	132	55	3
Enterprise					78	132	55	5	85	135	50	4
Paradise Gardens	78	132	55	5	78	135	58	5	85	135	50	5
Golf Course	75	132	57	4	78	135	58	5	78	135	58	4
Pine Point Bridge	67	129	63	5	67	132	66	5	75	132	57	5
Onset of breakup HR					75	132	57	5				
Peak stage jam HR					85	135	50	5				

	Increase in High Level *ADDT* Base 0˚C ($\Delta ADDT_{HL0}$) between events, ˚C-days between events											
	Crack to Ice Jam ($\Delta ADDT_{HL0cj}$)				Crack to Ice Jam Release ($\Delta ADDT_{HL0cr}$)				Ice Jam to Release ($\Delta ADDT_{HL0jr}$)			
Site	Min	Max	Range	# Years	Min	Max	Range	# Years	Min	Max	Range	# Years
NWT/AB Border	22	25	4	3	23	30	7	3	0	8	8	3
Island at 974												
Grumbler Rapids	0	11	11	3	10	17	7	2	0	17	17	3
Mink Creek	0	10	10	4	0	19	19	4	0	10	10	4
Alexandra Falls	3	19	16	3	3	19	16	3				
Escarpment Creek	3	28	25	3	3	38	35	3	0	29	29	3
Enterprise									3	18	15	4
Paradise Gardens	0	9	9	5	0	17	17	5	0	8	8	5
Golf Course	0	11	11	4	0	11	11	4	0	0	0	4
Pine Point Bridge	0	3	3	5	3	19	16	5	0	19	19	5
Onset of breakup HR	0	30	30	5								
Peak stage jam HR	3	37	34	5								

Table P.6: High Level accumulated degree days ($ADDT_{HL-5}$), base -5˚C on dates of occurrence and between breakup events at all sites.

	High Level *ADDT* Base -5˚C ($ADDT_{HL-5}$), ˚C-days on dates of occurrence											
	Day of First Crack ($ADDT_{HL-5c}$)				Day of Ice Jam ($ADDT_{HL-5j}$)				Day of Ice Jam Release ($ADDT_{HL-5r}$)			
Site	Min	Max	Range	# Years	Min	Max	Range	# Years	Min	Max	Range	# Years
NWT/AB Border	58	237	179	4	203	274	72	3	215	274	59	3
Island at 974	175	237	62	5								
Grumbler Rapids	190	237	47	3	190	253	63	4	203	245	43	3
Mink Creek	175	245	70	5	190	253	64	5	203	253	51	5
Alexandra Falls	40	245	206	3	175	253	78	5	175	253	78	5
Escarpment Creek	146	245	99	3	190	253	64	3	204	286	81	4
Enterprise					188	258	70	5	203	286	83	5
Paradise Gardens	78	266	188	4	203	266	63	5	215	266	50	4
Golf Course	75	258	183	5	204	266	62	5	204	266	62	4
Pine Point Bridge	190	258	68	4	190	245	55	5	204	258	54	4
Onset of breakup HR					204	258	54	5				
Peak stage jam HR					216	286	69	5				

	Increase in High Level *ADDT* Base -5˚C between events (ΔADD_{tHR-5}), ˚C-days between events											
	Crack to Ice Jam ($\Delta ADDT_{HL-5cj}$)				Crack to Ice Jam Release ($\Delta ADDT_{HL-5cr}$)				Ice Jam to Release ($\Delta ADDT_{HL-5jr}$)			
Site	Min	Max	Range	# Years	Min	Max	Range	# Years	Min	Max	Range	# Years
NWT/AB Border	32	38	6	3	38	45	7	3	0	13	13	3
Island at 974												
Grumbler Rapids	0	16	16	3	15	27	12	2	15	27	12	2
Mink Creek	0	15	15	5	0	29	29	5	0	29	29	5
Alexandra Falls	8	29	21	3	8	29	21	3				
Escarpment Creek	8	43	35	3	40	62	22	3	40	62	22	3
Enterprise									0	33	33	5
Paradise Gardens	0	14	14	4	0	27	27	4	0	13	13	4
Golf Course	0	16	16	5	0	16	16	4	0	16	16	4
Pine Point Bridge	0	13	13	4	0	15	15	4	13	15	2	4
Onset of breakup HR	0	45	45	4								
Peak stage jam HR	8	57	49	4								

Appendix Q: Reach based lookup tables for total degree days (*TDD*) between sites and stages of breakup.

This Appendix contains the reach based lookup tables for total degree days of thaw (*TDDT*) between sites and stages of breakup. The number of total degree of thaw days (*TDDT*) between first cracking, local ice jamming and ice jam releasing between all sites were considered. Only combinations of sites and breakup events that occur within a 10˚C-day range for all years of data are included. The nine tables in Appendix Q are:

Table Q.1: Total degree days of thaw (*TDD*) between first cracking at all locations.

Table Q.2: Total degree days of thaw (*TDD*) between jamming at sites on the x-axis and cracking at sites on the y-axis.

Table Q.3: Total degree days of thaw (*TDD*) between jam releasing at sites on the x-axis and cracking at sites on the y-axis.

Table Q.4: Total degree days of thaw (*TDD*) between first cracking at sites on the x-axis and jamming at sites on the y-axis.

Table Q.5: Total degree days of thaw (*TDD*) between ice jamming at all locations.

Table Q.6: Total degree days of thaw (*TDD*) between jam releasing at sites on x-axis and jamming at sites on y-axis.

Table Q.7: Total degree days of thaw (*TDD*) between first cracking at sites on x-axis and jam releasing at sites on y-axis.

Table Q.8: Total degree days of thaw (*TDD*) between jamming at sites on x-axis and jam releasing at sites on y-axis.

Table Q.9: Total degree days of thaw (*TDD*) between jam releasing at all locations.

Although these tables are color coded to illustrate the general pattern of degree days breakup events, these tables are not particularly useful. There is ultimately too much overlap in degree days of thaw between events at all sites to glean any useful patterns in addition to what the analysis of dates has already revealed.

Table Q.1: Total degree days (*TDD*) between first cracking at all locations.

Reference Site	Border	Isl	Grumb	MC	AF	Esc	Ent	PG	GC	PPB
First crack anywhere										
First crack @ Border										
First crack @ Island			0-9							
First crack @ Grumb		-9-0								
First crack @ MC										
First crack @ AF						-7-0				
First crack @ Esc					0-7					
First crack @ PG										
First crack @ Golf C.										-7-0
First crack @ WSC HR				-9-0					0-7	-3 - 0
First crack @ PPB									0-7	

General pattern:
- before
- mostly before
- during
- mostly after
- after
- - N/A

Ie: when blue,
event in hz axis
happens AFTER
event in vt axis

Table Q.2: Total degree days (*TDD*) between jamming at sites on x axis and cracking at sites on y axis.

Reference Site	Border	Isl	Grumb	MC	AF	Esc	Ent	PG	GC	PPB	*Do*	*Dp*
First crack anywhere												
First crack @ Border												
First crack @ Island												
First crack @ Grumb	7-11											7-15
First crack @ MC				0-9		4-9				0-9	4-14	
First crack @ AF	0-7											
First crack @ Esc												
First crack @ PG								0-8				
First crack @ Golf C.				-4-0		-4-0			0-7	-7-0	0-5	0-10
First crack @ WSC HR				0-7		0-7				0-4	3-7	
First crack @ PPB				0-7		0-7				0-4	3-8	

Table Q.3: Total degree days (*TDD*) between jam releasing at sites on x axis and cracking at sites on y axis.

Reference Site	Border	Isl	Grumb	MC	AF	Esc	Ent	PG	GC	PPB
First crack anywhere										
First crack @ Border			17-26							
First crack @ Island									5-14	
First crack @ Grumb	7-15		7-11				7-15			
First crack @ MC										
First crack @ AF	4-7									
First crack @ Esc										
First crack @ PG	0		-4-0			-3-2	0-9		-3-0	
First crack @ Golf C.	0-7		-4-3	0			0-9		0-7	0-8
First crack @ WSC HR			0-7	0-7						4-8
First crack @ PPB			0-7	0-7						4-8

General pattern:

- before
- mostly before
- during
- mostly after
- after
- \- N/A

Ie: when blue,
event in hz axis
happens AFTER
event in vt axis

Table Q.4: Total degree days (*TDD*) between first cracking at sites on x axis and jamming at sites on y axis.

Reference Site	Border	Isl	Grumb	MC	AF	Esc	Ent	PG	GC	PPB
Jam @ Border			-11- -7		-7-0					
Jam @ Grumbler										
Jam @ Mink Creek				-9-0					0-4	-7-0
Jam @ Alex Falls										
Jam @ Escarpment				-9--4					0-4	-7-0
Jam @ Enterprise										
Jam @ PG								-8-0		
Jam @ Golf Course									-7-0	
Jam @ PPB									0-7	-4-0
Do @ Delta				-14--4					-5-0	-8--3
Dp @ Delta			15--7						-10-0	

General pattern:
- before
- mostly before
- during
- mostly after
- after
- \- N/A

Ie: when blue, event in hz axis happens AFTER event in vt axis

Table Q.5: Total degree days (*TDD*) between jamming at all locations.

Reference Site	Border	Isl	Grumb	MC	AF	Esc	Ent	PG	GC	PPB	*Do*	*Dp*
Jam @ Border			0						0-5			2-6
Jam @ Grumbler	0								0-5			2-7
Jam @ Mink Creek						0			0-7	-8-0	0-5	0-10
Jam @ Alex Falls												
Jam @ Escarpment				0			0-7		0-7	-7-0	0-5	0-9
Jam @ Enterprise						-7-0						
Jam @ PG												
Jam @ Golf Course	-5-0		-5-0	-7-0		-7-0					-7-0	0-7
Jam @ PPB				0-8		0-7					0-7	
Do @ Delta				-5-0		-5-0			0-7	-7-0		0-9
Dp @ Delta	-6--2		-7--2	-10-0		-9-0			-7-0		-9-0	

Table Q.6: Total degree days (*TDD*) between jam releasing at sites on x axis and jamming at sites on y axis.

Reference Site	Border	Isl	Grumb	MC	AF	Esc	Ent	PG	GC	PPB
Jam @ Border	0-5		0			2-4	0-4	4-11	0-5	
Jam @ Grumbler	0-5		0-7			2-4	0-7	4-11	0-5	
Jam @ Mink Creek	0-7			0-4			0-9		0-7	0-8
Jam @ Alex Falls										
Jam @ Escarpment	0-7			0-4		0-9	0-9		0-7	0-4
Jam @ Enterprise							0-8			
Jam @ PG			-4-0				-10-0	0-5		
Jam @ Golf Course	0		-5-3	-7-0			-5-3		0	
Jam @ PPB				0-7						0-8
Do @ Delta	0-7		-5-3	-5-0					0-7	0-5
Dp @ Delta	-2-0			-10-0			-10-0		-3-0	-9-0

General pattern:
- before
- mostly before
- during
- mostly after
- after
- - N/A

Ie: when blue,
event in hz axis
happens AFTER
event in vt axis

Table Q.7: Total degree days (*TDD*) between first cracking at sites on x axis and jam releasing at sites on y axis.

Reference Site	Border	Isl	Grumb	MC	AF	Esc	Ent	PG	GC	PPB
Jam Release @ Border			-15--7						-7-0	
Jam Release @ Grumb			-15--7		-7--3				-7-0	
Jam Release @ MC									0	-7-0
Jam Release @ Esc										
Jam Release @ Ent			-15--7						-9-0	
Jam Release @ PG										
Jam Release @ GC									-7-0	
Jam Release @ PPB									-8-0	-8--4

General pattern:
- before
- mostly before
- during
- mostly after
- after
- - N/A

Ie: when blue, event in hz axis happens AFTER event in vt axis

Table Q.8: Total degree days (*TDD*) between jamming at sites on x axis and jam releasing at sites on y axis.

Reference Site	Border	Isl	Grumb	MC	AF	Esc	Ent	PG	GC	PPB	*Do*	*Dp*
Jam Release @ Border	-5-0		-5-0	-7-0		-7-0			0		-7-0	0-2
Jam Release @ Grumb			-7-0				-3-4	0-4	-3-5	-3-4	-3-4	0-6
Jam Release @ MC				-4-0		-4-0			0-7	-8-0	0-5	0-10
Jam Release @ Esc	-4--2		-4--2			-9-0						
Jam Release @ Ent	-4-0		-7--4	-7-0		-7-0	-8-0	0-10	-3-5			0-10
Jam Release @ PG	-11--4		-11--4					-5-0				
Jam Release @ GC	-6--2		-8--2	-9-0		-9-0			-4-0		-9-0	-1-7
Jam Release @ PPB				-8-0		-4-0				-8-0	-5-0	0-9

Table Q.9: Total degree days (*TDD*) between jam releasing at all locations.

Reference Site	Border	Isl	Grumb	MC	AF	Esc	Ent	PG	GC	PPB
Jam Release @ Border			-5--4	-7-0		0-2	-5-0		0	-7-0
Jam Release @ Grumb	4-5			-3-4		-3-4	0-4	0-5	-3-5	-3-5
Jam Release @ MC	0-7		-4-3				0-9		0-7	0-8
Jam Release @ Esc	-2-0		-4-3						-2-0	
Jam Release @ Ent	0-5		-4-0	-9-0				0-10	-3-5	
Jam Release @ PG			-5-0				-10-0			
Jam Release @ GC	0		-5-3	-7-0		0-2	-5-3			-7-0
Jam Release @ PPB	0-7		-5-3	-8-0					0-7	

General pattern:

red	before
orange	mostly before
green	during
light blue	mostly after
blue	after
black	- N/A

Ie: when blue,
event in hz axis
happens AFTER
event in vt axis

Appendix R: Reach based lookup tables for total degree days of thaw (*TDDT*) between sites and stages of breakup, color coded by years of available data.

This Appendix contains the reach based lookup tables for total degree days of thaw (*TDDT*) between sites and stages of breakup, color coded by years of available data. Only combinations of sites and breakup events that occur within 2 days range for all years of data are included. Only combinations of sites and breakup events with more than two years of data are included. The nine tables in Appendix R are:

As mentioned in Appendix Q, these tables are not particularly useful. There is ultimately too much overlap in degree days of thaw between events at all sites to glean any useful patterns in addition to what the analysis of dates has already revealed, regardless of how many years of data are available.

Table R.1: Range of total degree days (*TDD*) between first cracking at all locations, color coded by years of data.

Reference Site	Border	Isl	Grumb	MC	AF	Esc	Ent	PG	GC	PPB
First crack anywhere										
First crack @ Border										
First crack @ Island			0-9							
First crack @ Grumb		-9-0								
First crack @ MC										
First crack @ AF						-7-0				
First crack @ Esc					0-7					
First crack @ PG										
First crack @ Golf C.										-7-0
First crack @ WSC HR				-9-0					0-7	-3 - 0
First crack @ PPB									0-7	

Years of Data:

- 5 years
- 4 years
- 3 years
- 2 years
- N/A

Table R.2: Total degree days between jamming at sites on x axis and cracking at sites on y axis, color coded by years of data

Reference Site	Border	Isl	Grumb	MC	AF	Esc	Ent	PG	GC	PPB	*Do*	*Dp*
First crack anywhere												
First crack @ Border												
First crack @ Island												
First crack @ Grumb	7-11											7-15
First crack @ MC				0-9		4-9				0-9	4-14	
First crack @ AF	0-7											
First crack @ Esc												
First crack @ PG								0-8				
First crack @ Golf C.				-4-0		-4-0			0-7	-7-0	0-5	0-10
First crack @ WSC HR				0-7		0-7				0-4	3-7	
First crack @ PPB				0-7		0-7				0-4	3-8	

Table R.3: Total degree days (*TDD*) between jam releasing at the sites on x axis and cracking at sites on y axis, color coded by years of data.

Reference Site	Border	Isl	Grumb	MC	AF	Esc	Ent	PG	GC	PPB
First crack anywhere										
First crack @ Border			17-26							
First crack @ Island									5-14	
First crack @ Grumb	7-15		7-11				7-15			
First crack @ MC										
First crack @ AF	4-7									
First crack @ Esc										
First crack @ PG	0		-4-0			-3-2	0-9		-3-0	
First crack @ Golf C.	0-7		-4-3	0			0-7		0-7	0-8
First crack @ WSC HR			0-7	0-7						4-8
First crack @ PPB				0-7						4-8

Years of Data:

- 5 years
- 4 years
- 3 years
- 2 years
- N/A

Table R.4: Total degree days between first cracking at sites on x axis and jamming at sites on y axis, colored by years of data

Reference Site	Border	Isl	Grumb	MC	AF	Esc	Ent	PG	GC	PPB
Jam @ Border			-11- -7		-7-0					
Jam @ Grumbler										
Jam @ Mink Creek				-9-0					0-4	-7-0
Jam @ Alex Falls										
Jam @ Escarpment				-9--4					0-4	-7-0
Jam @ Enterprise										
Jam @ PG								-8-0		
Jam @ Golf Course									-7-0	
Jam @ PPB									0-7	-4-0
Do @ Delta				-14--4					-5-0	-8--3
Dp @ Delta			15--7						-10-0	

Years of Data:
- 5 years
- 4 years
- 3 years
- 2 years
- N/A

Table R.5: Total degree days (*TDD*) between jamming at all locations, color coded by years of data.

Reference Site	Border	Isl	Grumb	MC	AF	Esc	Ent	PG	GC	PPB	*Do*	*Dp*
Jam @ Border			0						0-5			2-6
Jam @ Grumbler	0								0-5			2-7
Jam @ Mink Creek						0			0-7	-8-0	0-5	0-10
Jam @ Alex Falls												
Jam @ Escarpment				0			0-7		0-7	-7-0	0-5	0-9
Jam @ Enterprise						-7-0						
Jam @ PG												
Jam @ Golf Course	-5-0		-5-0	-7-0		-7-0					-7-0	0-7
Jam @ PPB				0-8		0-7					0-7	
Do @ Delta				-5-0		-5-0			0-7	-7-0		0-9
Dp @ Delta	-6--2		-7--2	-10-0		-9-0			-7-0		-9-0	

Table R.6: Total degree days between jam releasing at sites on x axis and jamming at sites on y axis, colored by years of data

Reference Site	Border	Isl	Grumb	MC	AF	Esc	Ent	PG	GC	PPB
Jam @ Border	0-5		0			2-4	0-4	4-11	0-5	
Jam @ Grumbler	0-5		0-7			2-4	0-7	4-11	0-5	
Jam @ Mink Creek	0-7			0-4			0-7		0-7	0-8
Jam @ Alex Falls										
Jam @ Escarpment	0-7			0-4		0-9	0-7		0-7	0-4
Jam @ Enterprise							0-8			
Jam @ PG			-4-0					0-5		
Jam @ Golf Course	0		-5-3	-7-0			-5-3		0	
Jam @ PPB			-4-3	0-7						0-8
Do @ Delta	0-7		-5-3	-5-0					0-7	0-5
Dp @ Delta	-2-0			-10-0			-10-0		-3-0	-9-0

Years of Data:

- 5 years
- 4 years
- 3 years
- 2 years
- N/A

Table R.7: Total degree days (*TDD*) between first cracking at sites on x axis and jam releasing at sites on y axis, color coded by years of data.

Reference Site	Border	Isl	Grumb	MC	AF	Esc	PG	GC	PPB
Jam Release @ Border			-15--7					-7-0	
Jam Release @ Grumb			-15--7		-7--3			-7-0	
Jam Release @ MC								0	-7-0
Jam Release @ Esc									
Jam Release @ Ent			-15--7					-9-0	
Jam Release @ PG									
Jam Release @ GC								-7-0	
Jam Release @ PPB								-8-0	-8--4

Years of Data:

- 5 years
- 4 years
- 3 years
- 2 years
- N/A

Table R.8: Total degree days (*TDD*) between jamming at sites on x axis and jam releasing at sites on y axis, color coded by years of data.

Reference Site	Border	Isl	Grumb	MC	AF	Esc	Ent	PG	GC	PPB	*Do*	*Dp*
Jam Release @ Border	-5-0		-5-0	-7-0		-7-0			0		-7-0	0-2
Jam Release @ Grumb			-7-0				-3-4	0-4	-3-5	-3-4	-3-4	0-6
Jam Release @ MC				-4-0		-4-0			0-7	-8-0	0-5	0-10
Jam Release @ Esc	-4--2		-4--2			-9-0						
Jam Release @ Ent	-4-0		-7--4	-7-0		-7-0	-8-0	0-10	-3-5			0-10
Jam Release @ PG	-11--4		-11--4					-5-0				
Jam Release @ GC	-6--2		-8--2	-9-0		-9-0			-4-0		-9-0	-1-7
Jam Release @ PPB				-8-0		-4-0				-8-0	-5-0	0-9

Table R.9: Total degree days (*TDD*) between jam releasing at all locations, color coded by years of data, color coded by years of data.

Reference Site	Border	Isl	Grumb	MC	AF	Esc	Ent	PG	GC	PPB
Jam Release @ Border			-5--4	-7-0		0-2	-5-0		0	-7-0
Jam Release @ Grumb	4-5			-3-4		-3-4	0-4	0-5	-3-5	-3-5
Jam Release @ MC	0-7		-4-3				0-9		0-7	0-8
Jam Release @ Esc	-2-0		-4-3						-2-0	
Jam Release @ Ent	0-5		-4-0	-9-0				0-10	-3-5	
Jam Release @ PG			-5-0				-10-0			
Jam Release @ GC	0		-5-3	-7-0		0-2	-5-3			-7-0
Jam Release @ PPB	0-7		-5-3	-8-0					0-7	

Years of Data:

- 5 years
- 4 years
- 3 years
- 2 years
- N/A

Appendix S: Change in total degree days of thaw (*ΔTDDT*) between historic onsets of breakup, peak stages and melt outs.

This Appendix contains the change in total degree days of thaw (*ΔTDDT*) between historic onsets of breakup, peak stages and melt outs. These are color coded by severity class. The three tables in Appendix S are:

Figure S.1: Change in total degree days of thaw ($\Delta TDDT_p$) between the onset of breakup and peak stage jam in the Town of Hay River.

Figure S.2: Change in total degree days of thaw ($\Delta TDDT_m$) between the onset of breakup and melt out in the Town of Hay River.

Figure S.3: Change in total degree days of thaw ($\Delta TDDT_{m-p}$) between the peak stage and melt out in the Town of Hay River.

These figures illustrate that there is no consistency or patterns in total degree days of thaw between any of the onset of breakup dates, the dates of peak stage or the dates of melt out.

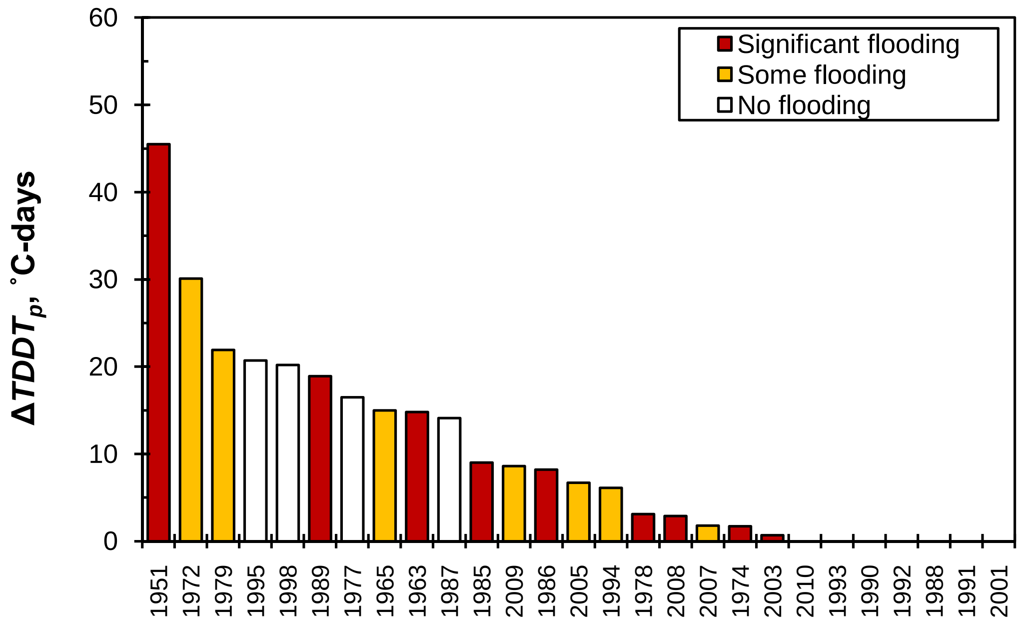


Figure S.1: Change in total degree days of thaw between the onset of breakup and peak stage ($\Delta\, TDDT_p$) in the Hay River delta for all known events between 1963 and 2010.

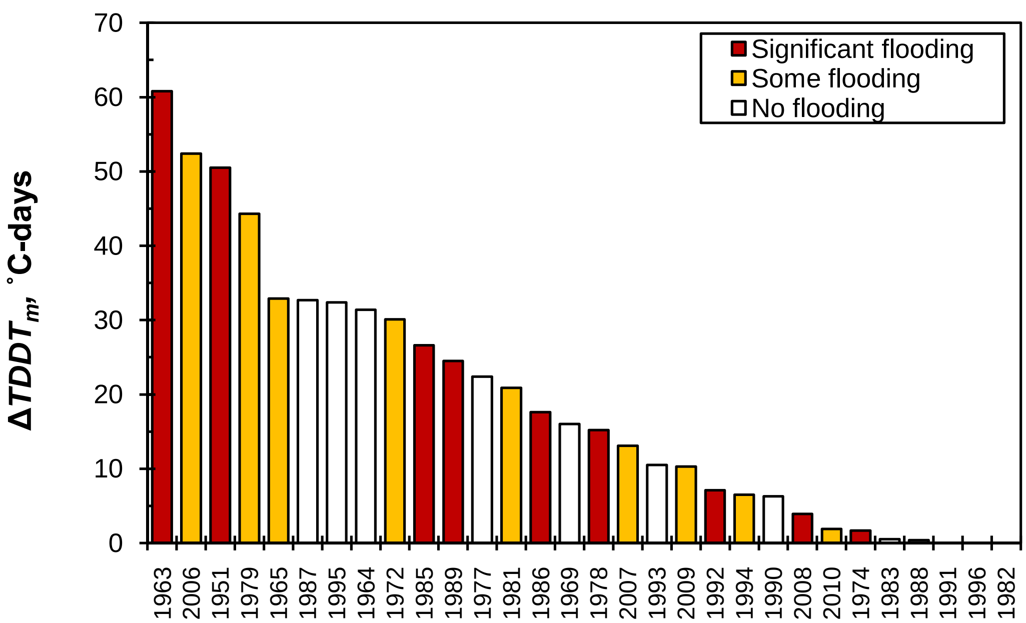


Figure S.2: Change in total degree days of thaw between the onset of breakup and ice jam melt out ($\Delta\, TDDT_m$) in the Hay River delta for all known events between 1963 and 2010.

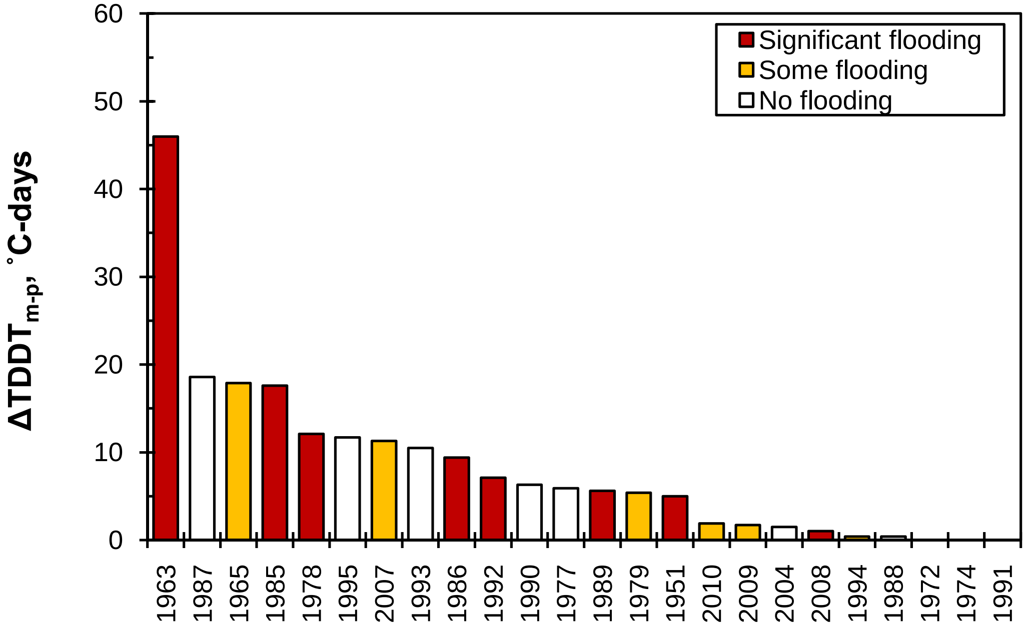


Figure S.3: Change in total degree days of thaw between peak stage jam and melt out (*Δ TDDT $_{m-p}$*) in the Hay River delta for all known events between 1963 and 2010.

Appendix T: Change in total degree days of freezing in the pre-breakup period ($\Delta TDDF$) between historic onsets of breakup, peak stages and melt outs.

This Appendix contains the change in total degree days of freezing in the pre-breakup period ($\Delta TDDF$) between historic onsets of breakup, peak stages and melt outs. These are color coded by severity class. The three tables in Appendix T are:

Figure T.1: Change in total degree days of freezing in the pre-breakup period between the onset of breakup and peak stage jam ($\Delta TDDF_p$) in the Town of Hay River.

Figure T.2: Change in total degree days of freezing in the pre-breakup period ($\Delta TDDF_p$) between the onset of breakup and melt out in the Town of Hay River.

Figure T.3: Change in total degree days of freezing in the pre-breakup period ($\Delta TDDF_{m-p}$) between the peak stage and melt out in the Town of Hay River.

These figures illustrate that there is no consistency or patterns in total degree days of freezing in the pre-breakup period between any of the initial breakup date, the date of peak stage or the date of melt out.

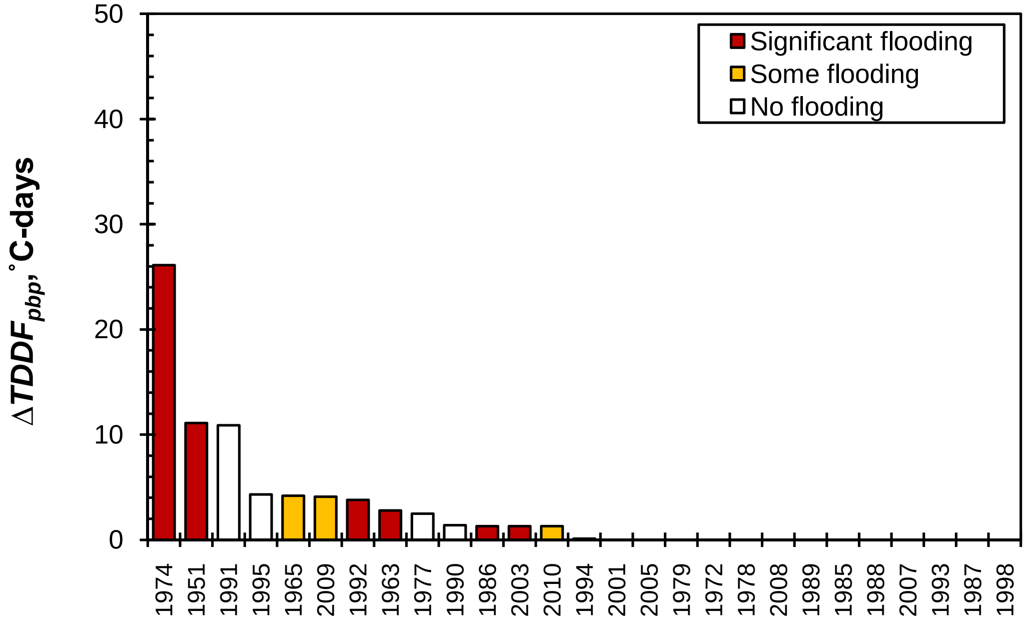


Figure T.1: Change in total degree days of freezing in the pre-breakup period between the onset of breakup and peak stage ($\Delta\ TDDF_p$) in the Hay River delta, for all known events between 1963 and 2010.

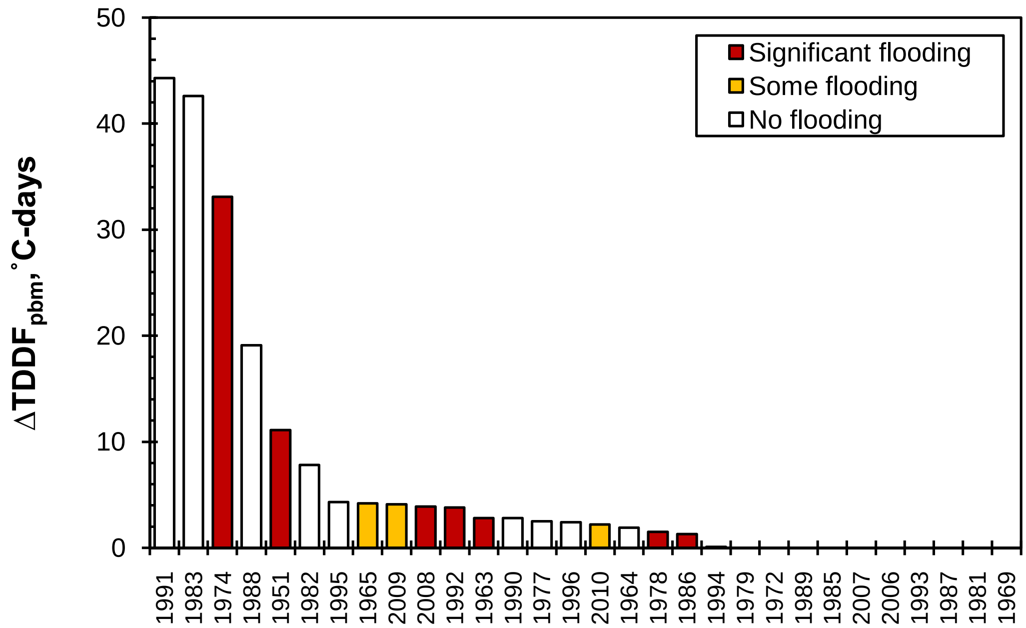


Figure T.2: Change in total degree days of freezing in the pre-breakup period between the onset of breakup and melt out ($\Delta\ TDDF_m$) in the Hay River delta, for all known events between 1963 and 2010.

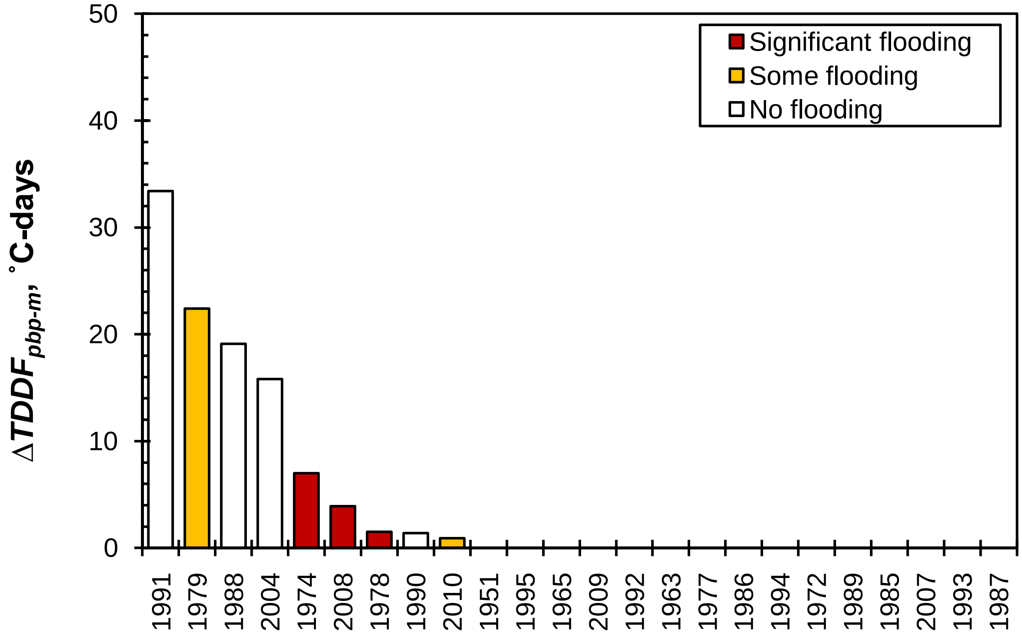


Figure T.3: Change in total degree days of freezing in the pre-breakup period between the peak stage and melt out (*Δ TDDF* $_{p-m}$) in the Hay River delta, for all known events between 1963 and 2010.

Appendix U: Patterns of Hay River and High Level total degree days (*TDDT*) from 15-Apr to 20-May.

This Appendix contains the Hay River and High Level total degree days of thaw (*TDDT*) plotted for all years. The dates of initiation of breakup and peak stage are included on the graph.

The figures are grouped by severity class to aid in identifying patterns in the total degree days. The following table lists the 36 figures in Appendix U.

Significant Flooding		**Some Flooding**		**No Flooding**	
Figure	**Year**	**Figure**	**Year**	**Figure**	**Year**
Figure U.1	1951	Figure U.11	1965	Figure U.22	1964
Figure U.2	1963	Figure U.12	1972	Figure U.23	1969
Figure U.3	1974	Figure U.13	1979	Figure U.24	1977
Figure U.4	1978	Figure U.14	1994	Figure U.25	1982
Figure U.5	1985	Figure U.15	1997	Figure U.26	1983
Figure U.6	1986	Figure U.16	2001	Figure U.27	1987
Figure U.7	1989	Figure U.17	2005	Figure U.28	1988
Figure U.8	1992	Figure U.18	2006	Figure U.29	1990
Figure U.9	2003	Figure U.19	2007	Figure U.30	1991
Figure U.10	2008	Figure U.20	2009	Figure U.31	1993
		Figure U.21	2010	Figure U.32	1995
				Figure U.33	1996
				Figure U.34	1998
				Figure U.35	2002
				Figure U.36	2004

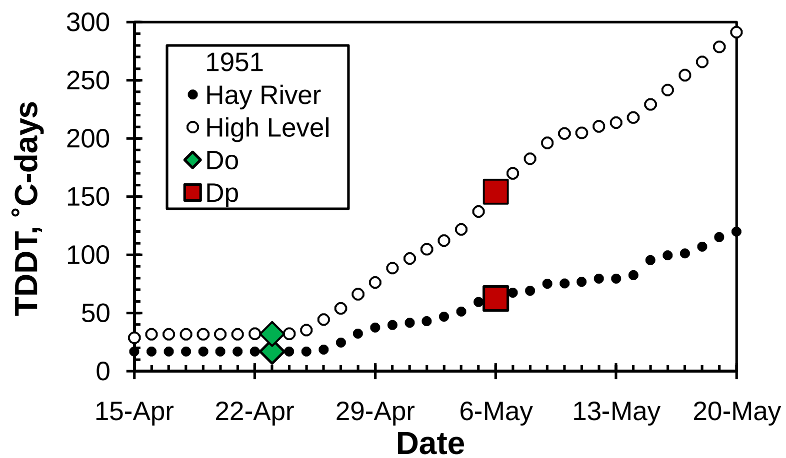


Figure U.1: *TDDT* during breakup in 1951 (significant flooding).

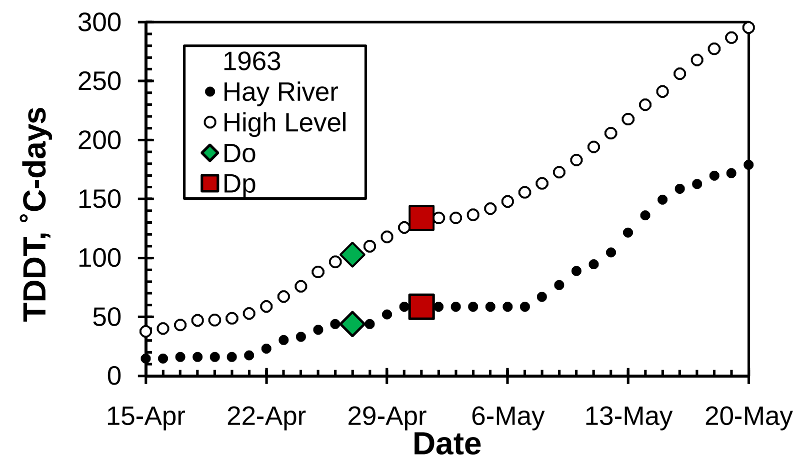


Figure U.2: *TDDT* during breakup in 1963 (significant flooding).

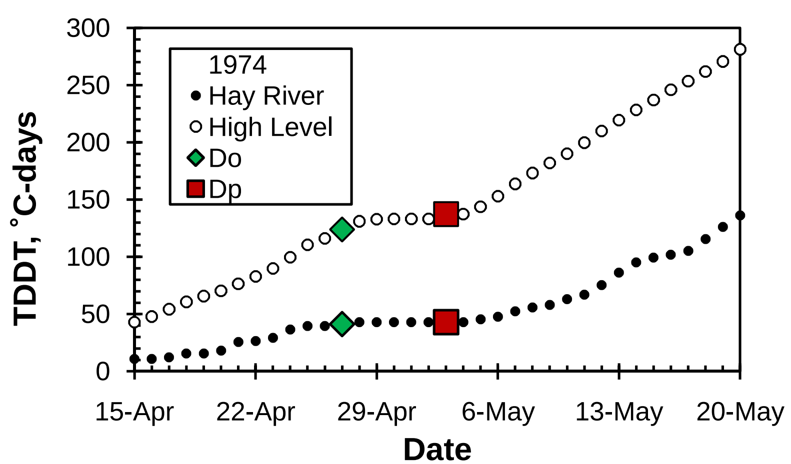


Figure U.3: *TDDT* during breakup in 1975 (significant flooding).

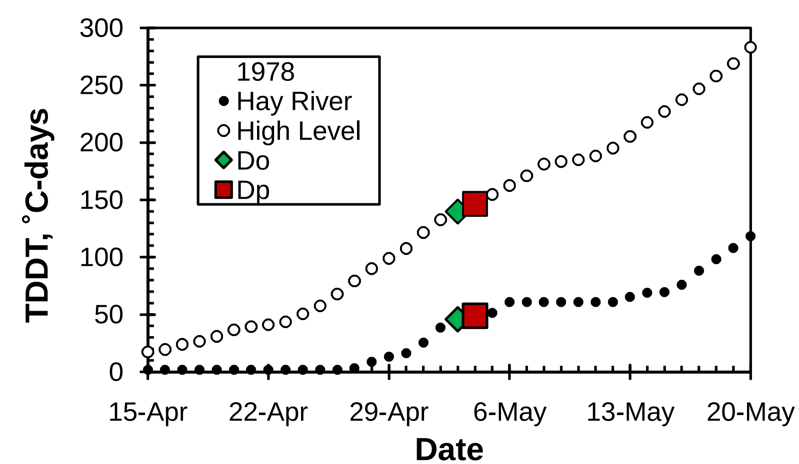


Figure U.4: *TDDT* during breakup in 1978 (significant flooding).

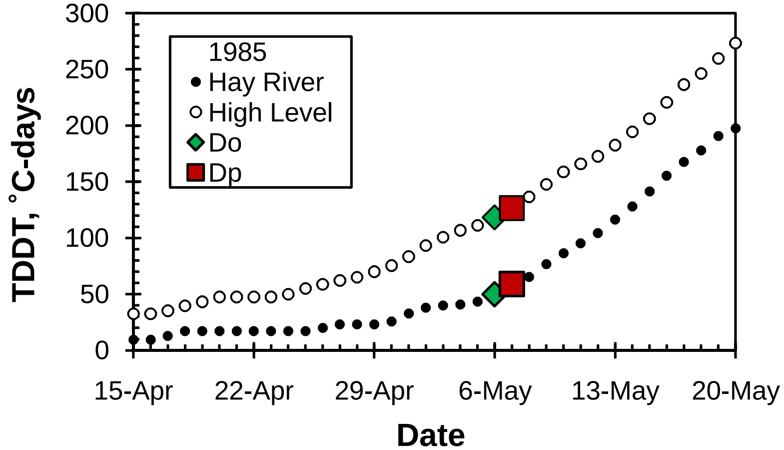


Figure U.5: *TDDT* during breakup in 1985 (significant flooding).

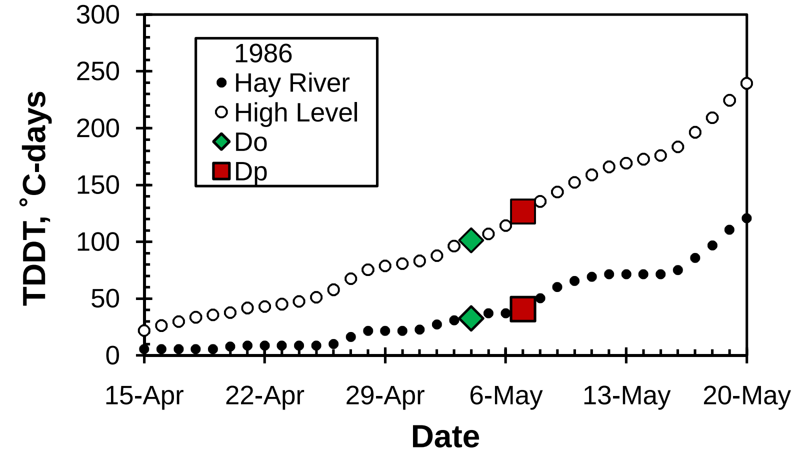


Figure U.6: *TDDT* during breakup in 1986 (significant flooding).

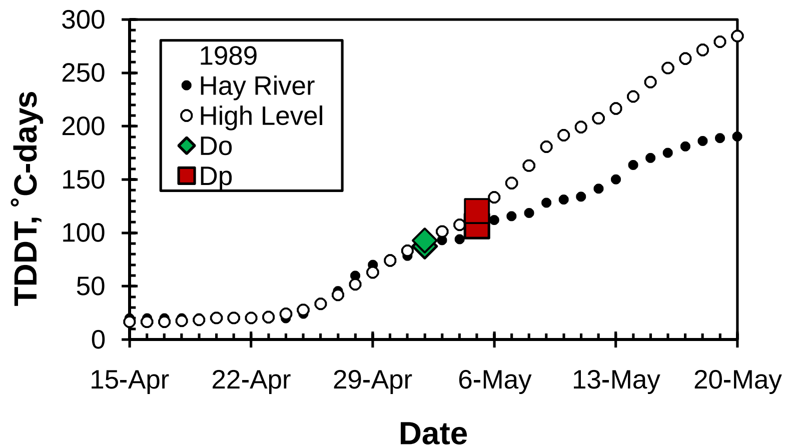


Figure U.7: *TDDT* during breakup in 1989 (significant flooding).

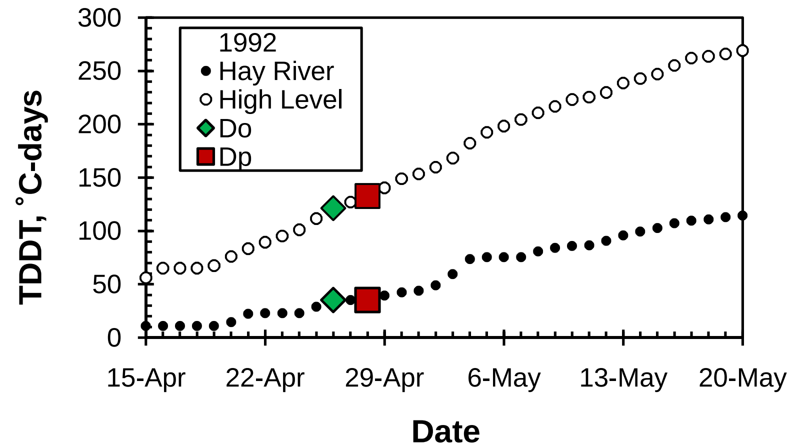


Figure U.8: *TDDT* during breakup in 1992 (significant flooding).

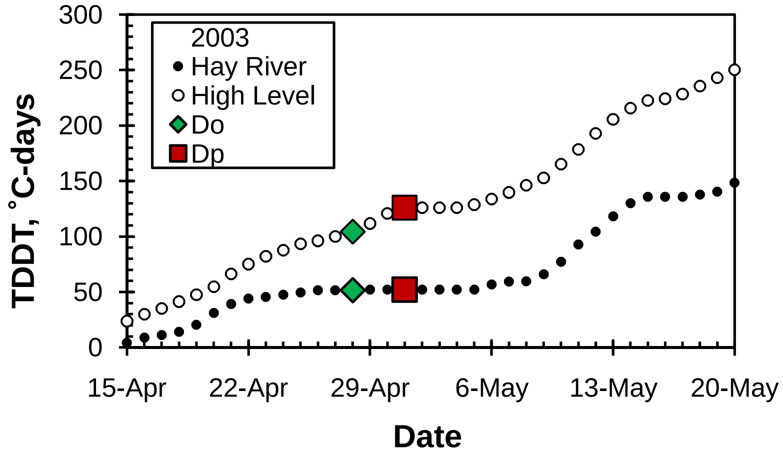


Figure U.9: *TDDT* during breakup in 2003 (significant flooding).

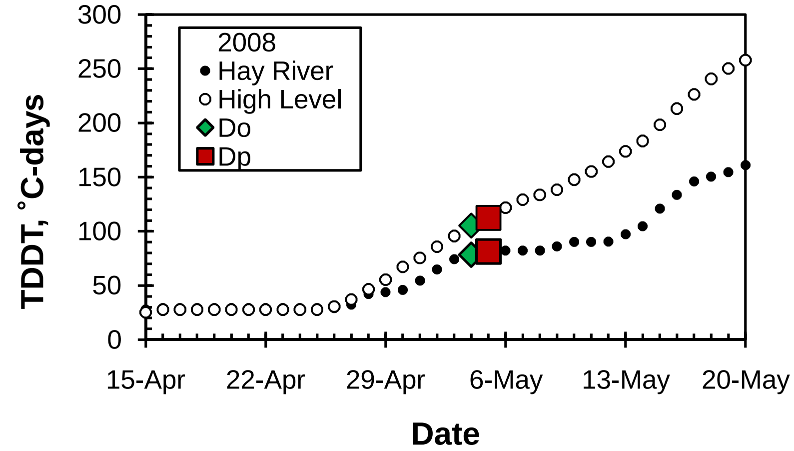


Figure U.10: *TDDT* during breakup in 2008 (significant flooding).

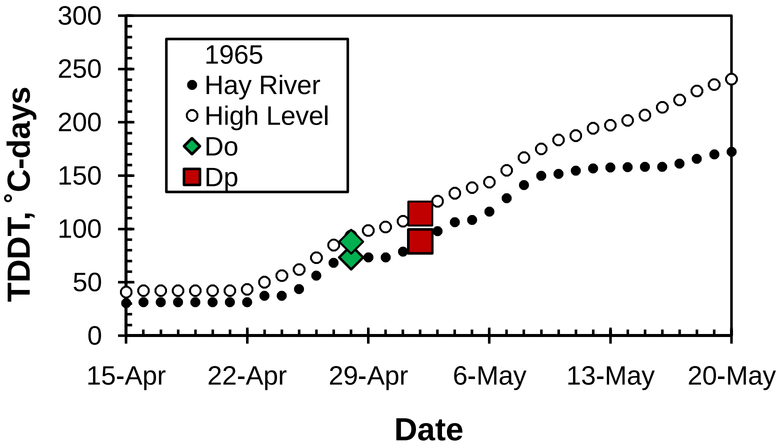


Figure U.11: *TDDT* during breakup in 1965 (some flooding).

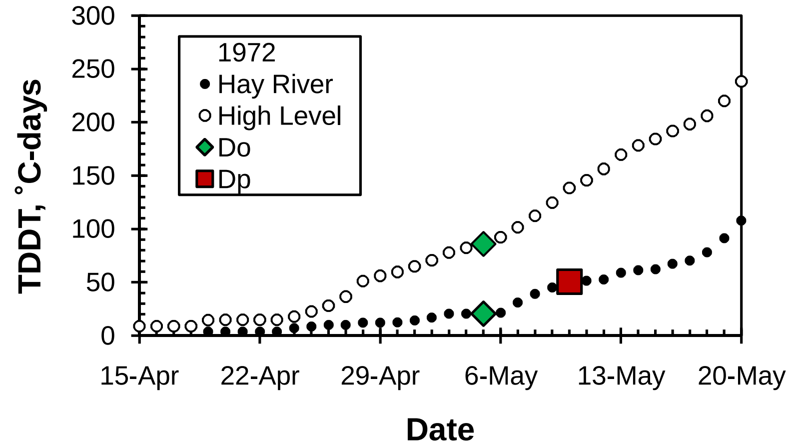


Figure U.12: *TDDT* during breakup in 1972 (some flooding).

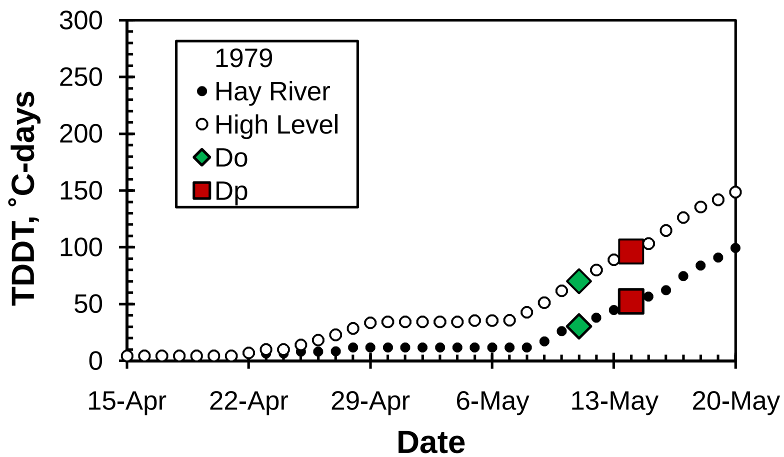


Figure U.13: *TDDT* during breakup in 1979 (some flooding).

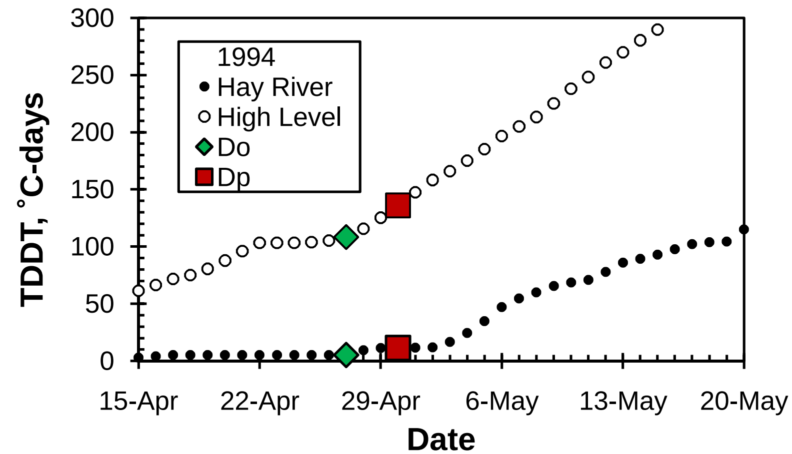


Figure U.14: *TDDT* during breakup in 1994 (some flooding).

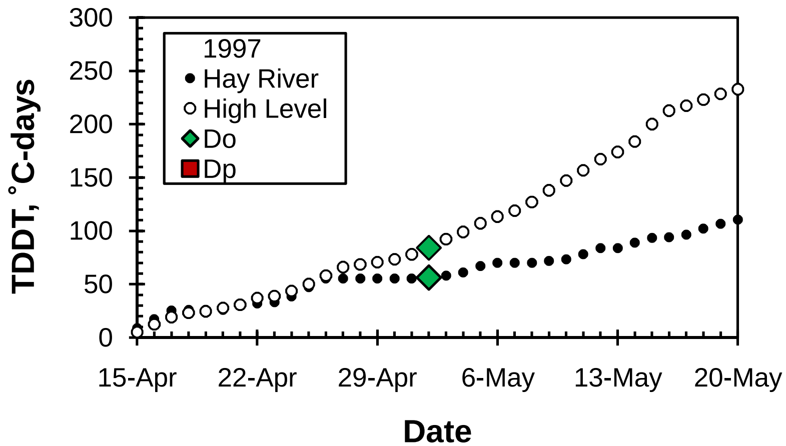


Figure U.15: *TDDT* during breakup in 1997 (some flooding).

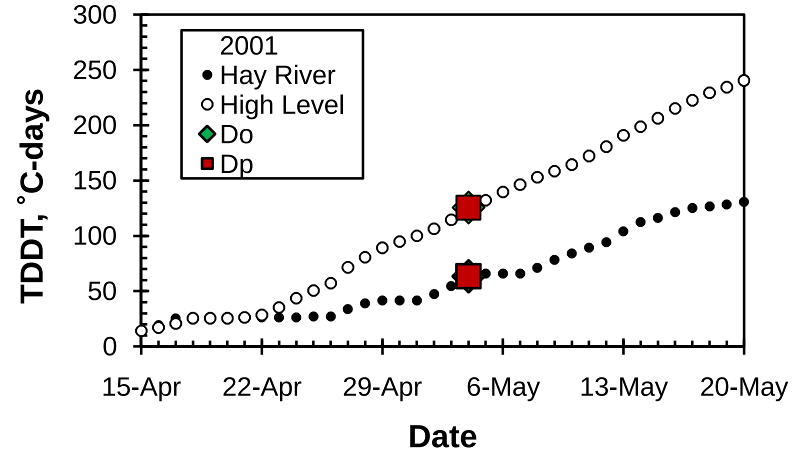


Figure U.16: *TDDT* during breakup in 2001 (some flooding).

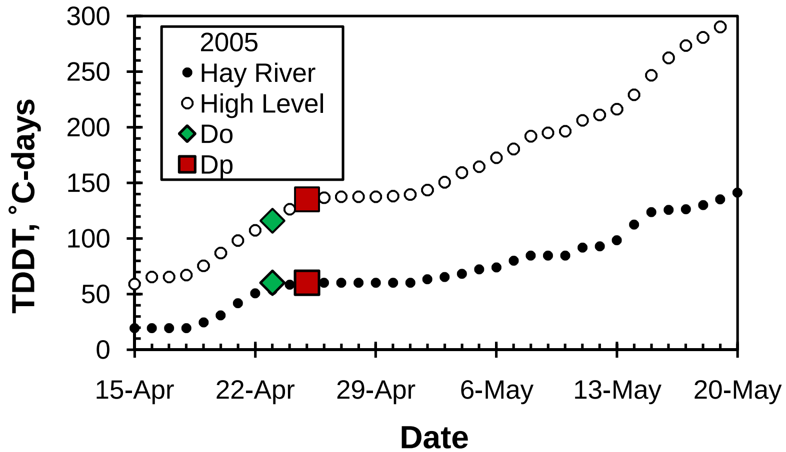


Figure U.17: *TDDT* during breakup in 2005 (some flooding).

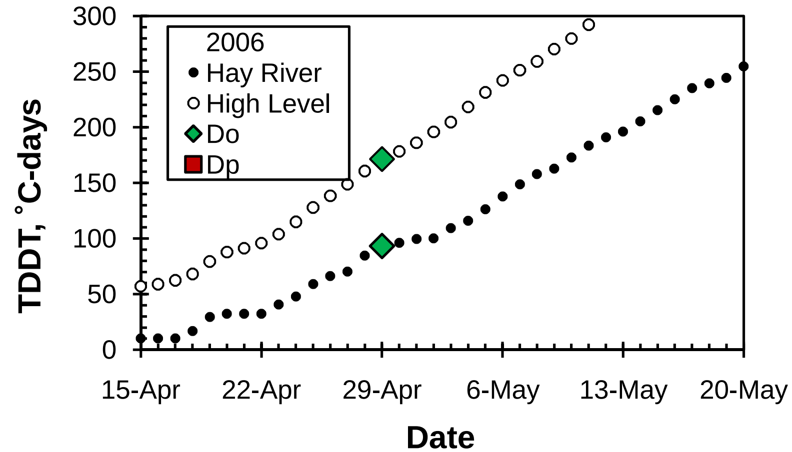


Figure U.18: *TDDT* during breakup in 2006 (some flooding).

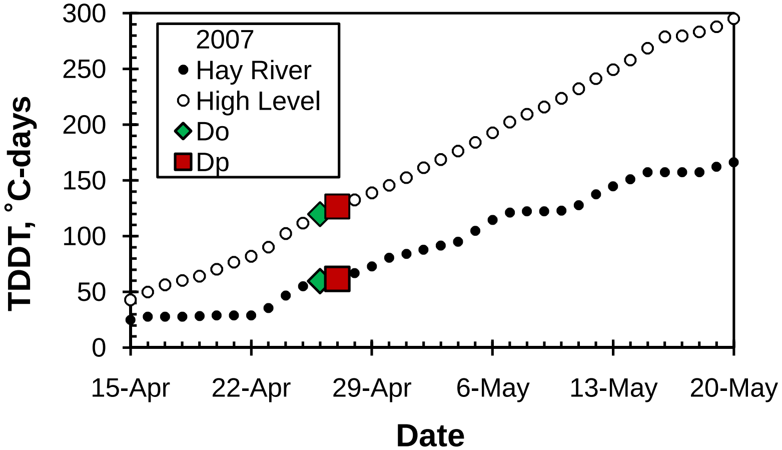


Figure U.19: *TDDT* during breakup in 2007 (some flooding).

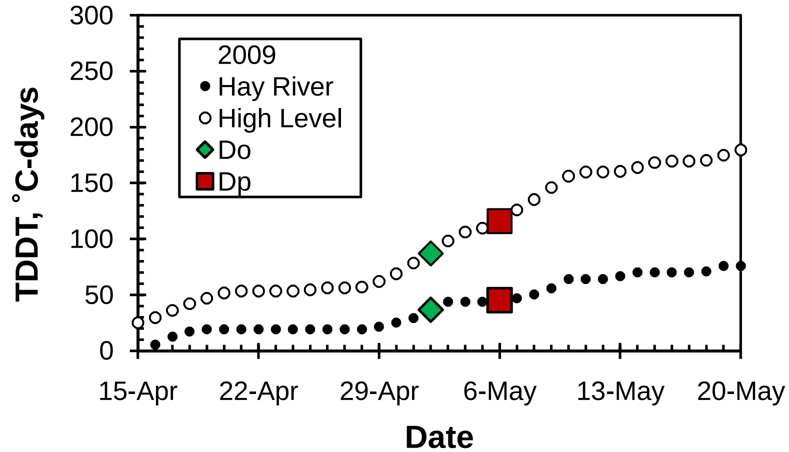


Figure U.20: *TDDT* during breakup in 2009 (some flooding).

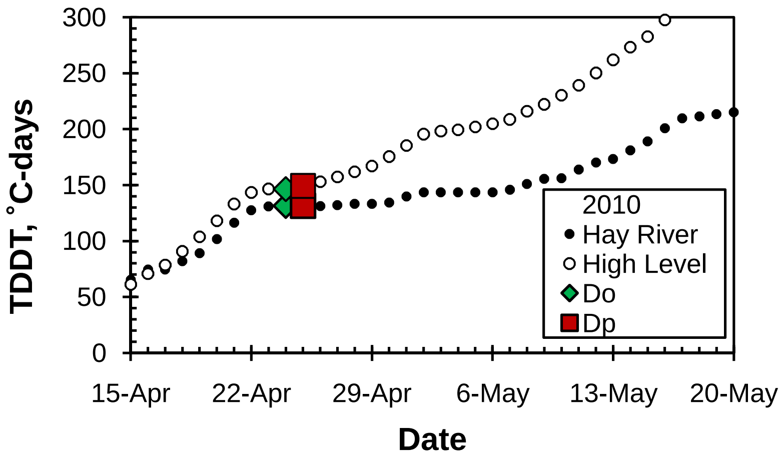


Figure U.21: TDDT during breakup in 2010 (some flooding).

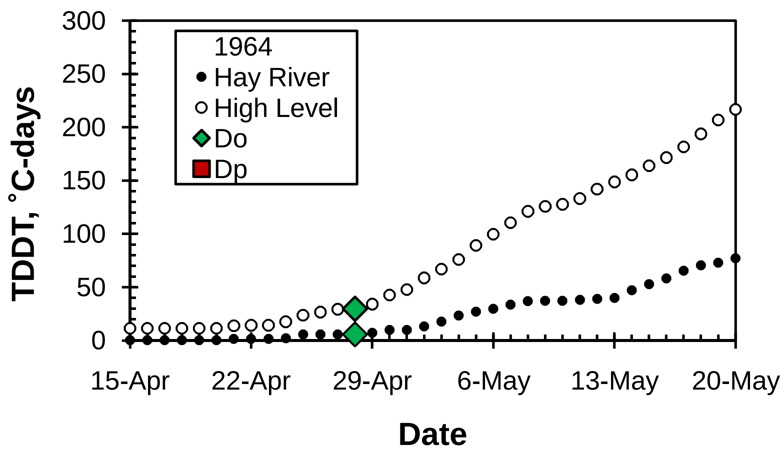


Figure U.22: *TDDT* during breakup in 1964 (no known flooding).

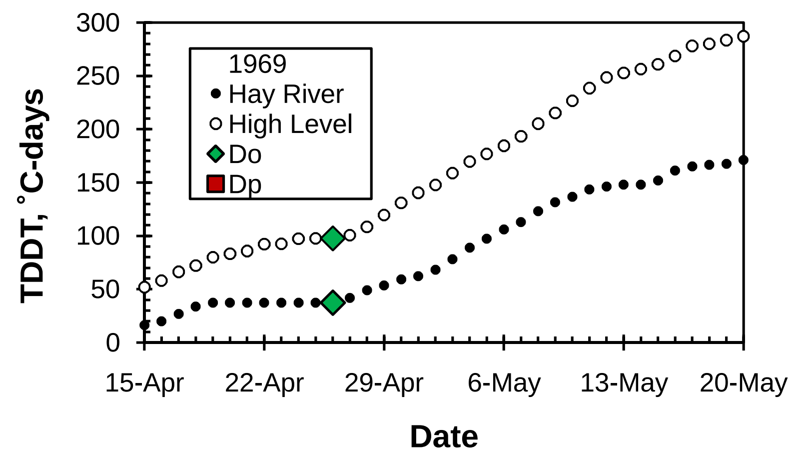


Figure U.23: *TDDT* during breakup in 1969 (no known flooding).

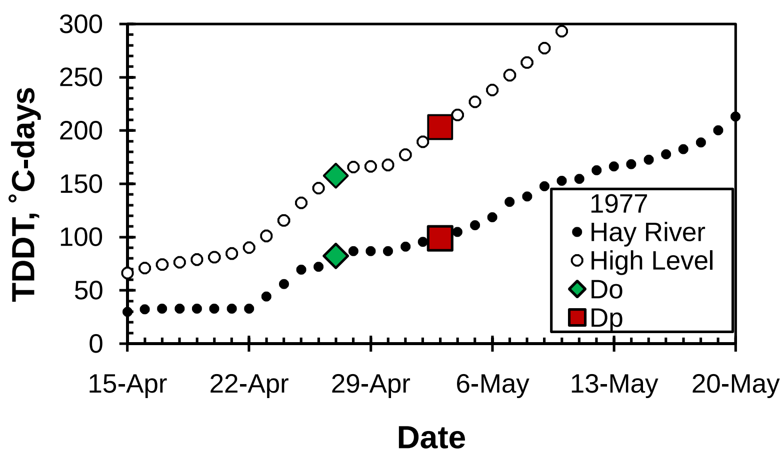


Figure U.24: *TDDT* during breakup in 1977 (no known flooding).

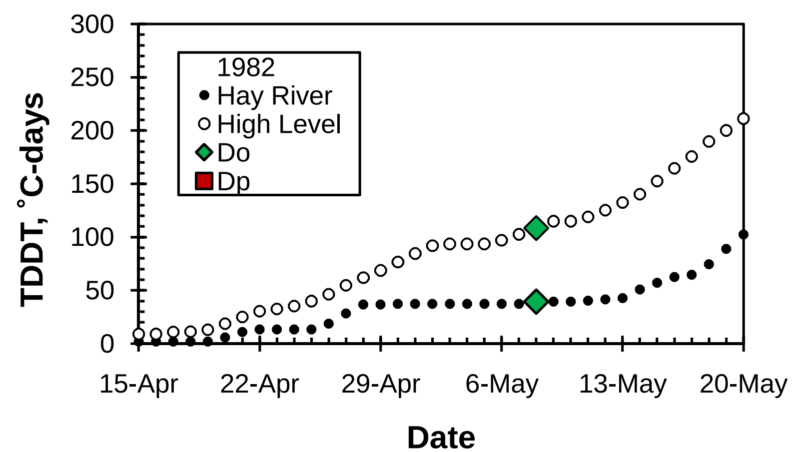


Figure U.25: *TDDT* during breakup in 1982 (no known flooding).

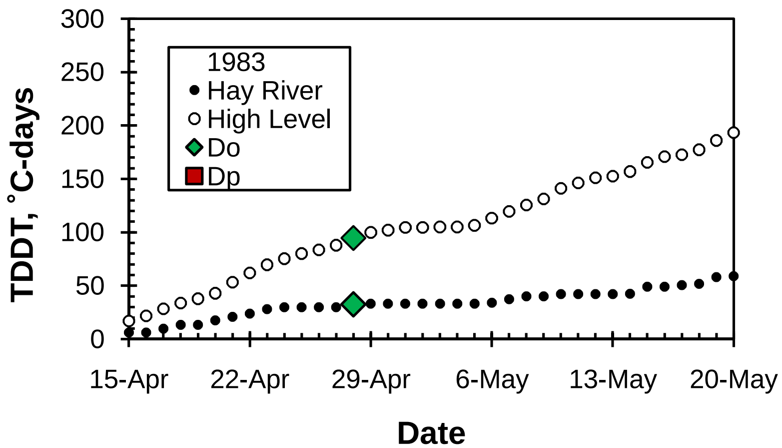


Figure U.26: *TDDT* during breakup in 1987 (no known flooding).

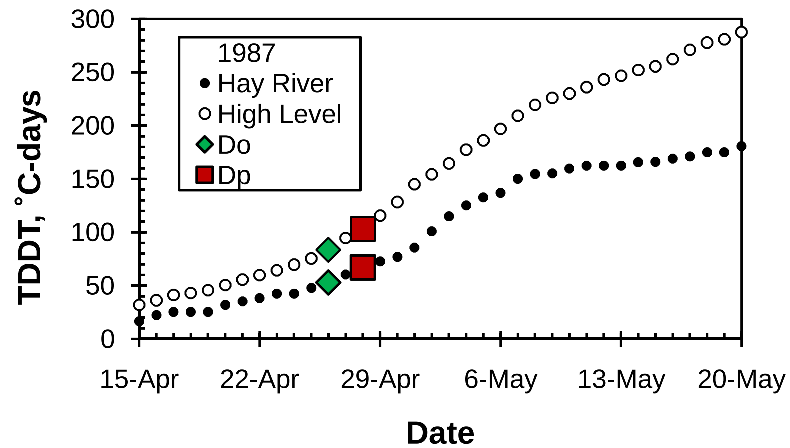


Figure U.27: *TDDT* during breakup in 1988 (no known flooding).

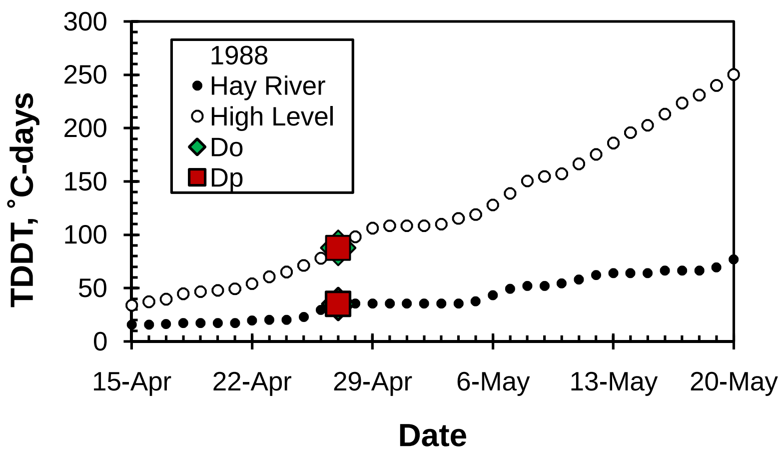


Figure U.28: *TDDT* during breakup in 1990 (no known flooding).

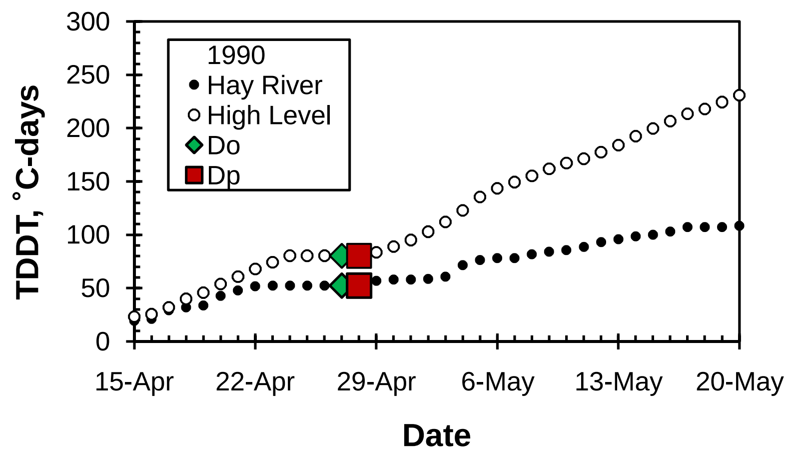


Figure U.29: *TDDT* during breakup in 1991 (no known flooding).

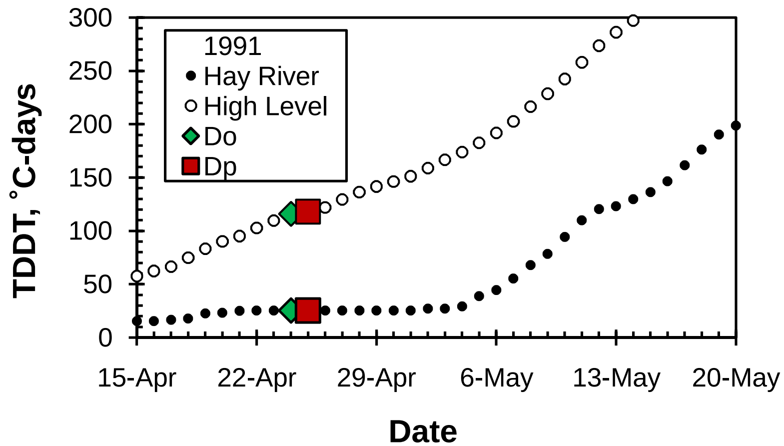


Figure U.30: *TDDT* during breakup in 1991 (no known flooding).

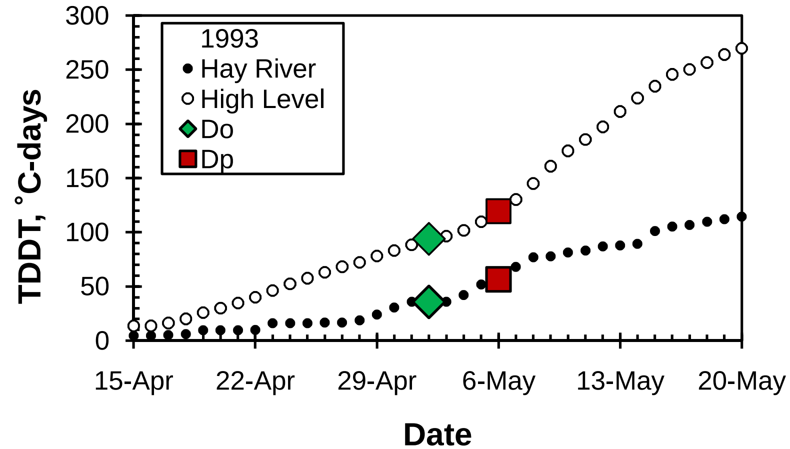


Figure U.31: *TDDT* during breakup in 1993 (no known flooding).

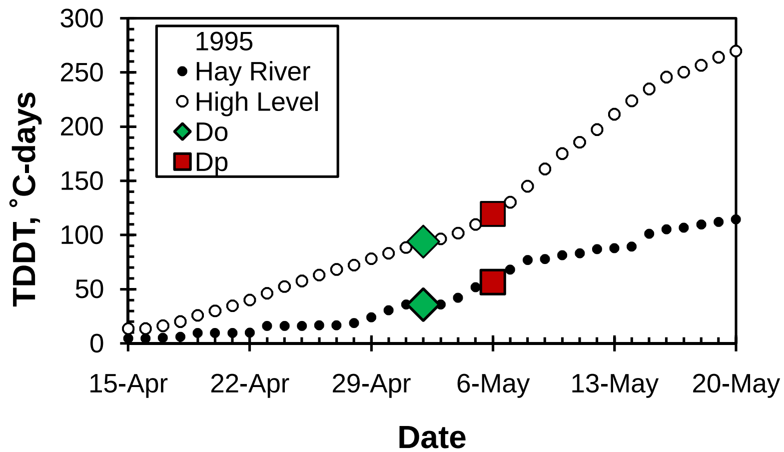


Figure U.32: *TDDT* during breakup in 1995 (no known flooding).

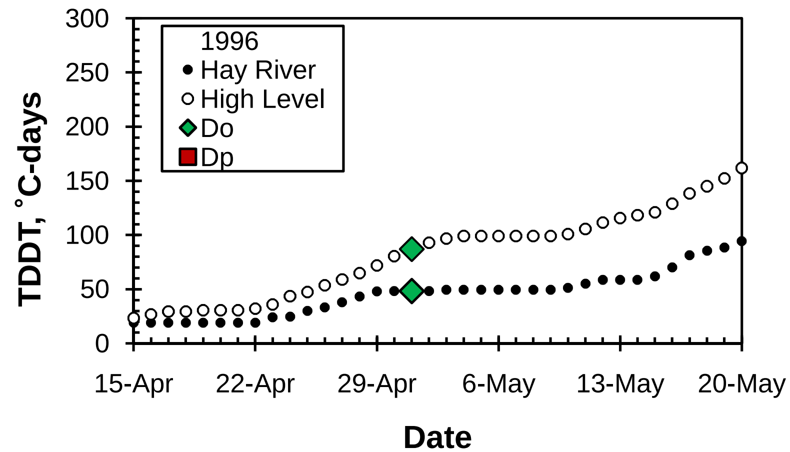


Figure U.33: *TDDT* during breakup in 1996 (no known flooding).

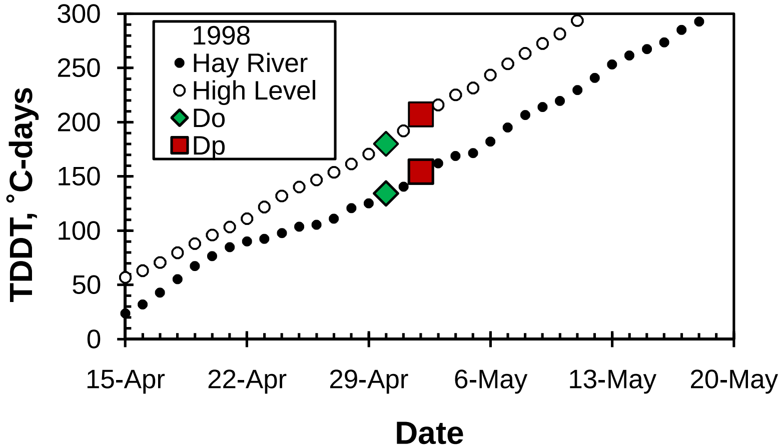


Figure U.34: *TDDT* during breakup in 1998 (no known flooding).

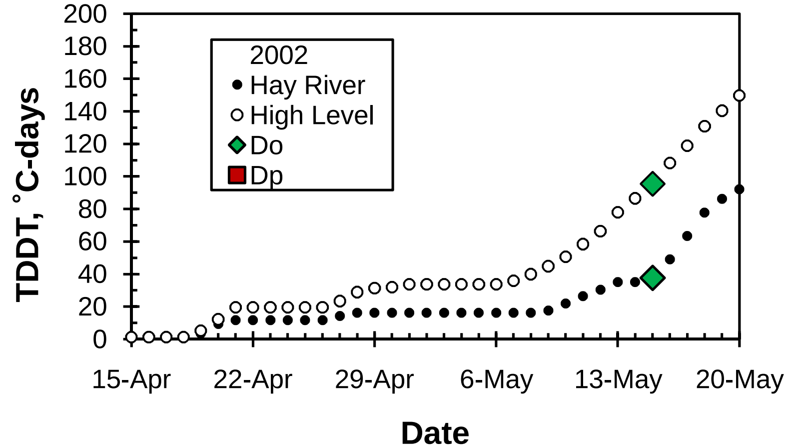


Figure U.35: *TDDT* during breakup in 2002 (no known flooding).

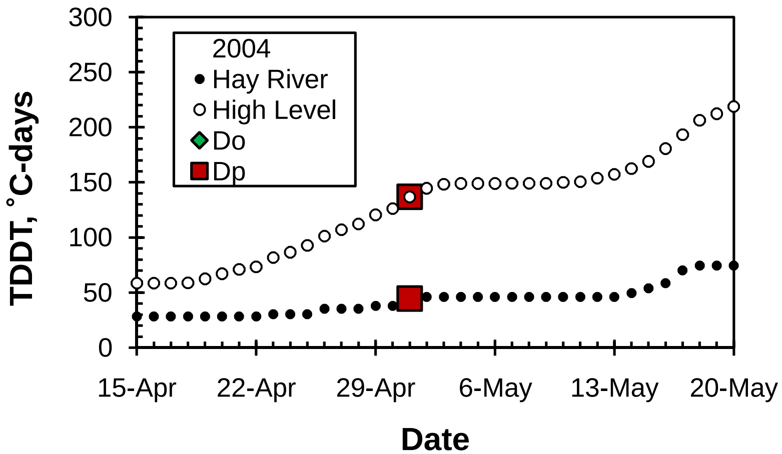


Figure U.36: *TDDT* during breakup in 2004 (no known flooding).

Appendix V: Summary of ranges of water level thresholds during stages of breakup and increases in gauge height between stages of breakup at six water level gauge stations in the Hay River study reach.

This Appendix contains the results of the site specific analysis of the water level gauge stations. The two Tables in Appendix V are:

Table V.1: Ranges in water levels during stages of breakup at each of the six water level gauge stations in the Hay River study reach.

Table V.2: Increase in gauge height between stages of breakup at each of the six water level gauge stations in the Hay River study reach.

The tables summarize the water level thresholds and increases at all sites, regardless of how consistent the ranges are.

Table V.1: Ranges in water levels during stages of breakup at each of the six water level gauge stations in the Hay River study reach.

	Gauge height on dates of occurence, m											
	Day of First Crack (H_c)				Day of Ice Jam (H_j)				Day of Ice Jam Release (H_r)			
Site	Min	Max	Range	# Years	Min	Max	Range	# Years	Min	Max	Range	# Years
NWT/AB Border	0.38	2.34	1.96	5	0.92	4.27	3.35	5	2.24	4.41	2.17	3
Alexandra Falls	0.28	0.95	0.67	3	0.63	2.00	1.37	5	0.63	2.00	1.37	5
Paradise Gardens												
WSC @ HR	3.17	4.25	1.08	5	3.88	6.23	2.35	5	4.77	7.49	2.79	5
Pine Point Bridge	-0.60	2.19	2.79	5	0.24	4.14	3.90	5	0.24	4.92	4.68	5
Onset of breakup WCB					1.29	3.75	2.47	5				
Peak stage jam WCB					3.76	5.27	1.51	5				

Table V.2: Increase in gauge height between stages of breakup at each of the six water level gauge stations in the Hay River study reach.

	Increase in gauge height between events, m											
	From First Crack to Ice Jam (ΔH_{cj})				From Crack to Ice Jam Release (ΔH_{cr})				From Ice Jam Formation to Release (ΔH_{jr})			
Site	Min	Max	Range	# Years	Min	Max	Range	# Years	Min	Max	Range	# Years
NWT/AB Border	0.54	2.69	2.15	3	1.87	3.74	1.87	3	0.00	1.32	1.32	3
Alexandra Falls	0.05	0.90	0.85	3	0.05	0.90	0.85	3				
Paradise Gardens	1.07	3.23	2.16	5	0.64	3.20	2.56	5	-0.43	0.00	0.43	5
WSC @ HR	0.69	1.97	1.28	5	1.21	4.33	3.12	5	0.00	3.61	3.61	5
Pine Point Bridge	0.24	1.94	1.70	5	0.84	4.55	3.71	5	-0.52	4.00	4.52	5
Onset of breakup WCB												
Peak stage jam WCB												