

Spatial and Temporal Variations of River-ice Break-up, Mackenzie River Basin, Canada

by

Laurent Paul de Rham
B.Sc., University of Victoria, 2003

A Thesis Submitted in Partial Fulfillment
of the Requirements for the Degree of

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in the Department of Geography

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Abstract

Hydrological data extracted directly from Water Survey of Canada archives covering the 1913-2002 time period is used to assess river ice break-up in the Mackenzie River basin. A return-period analysis indicates that 13 (14) of 28 sites in the basin are dominated by peak water-levels occurring during the spring break-up (open-water) period. One location has a mixed signal. A map of flooding regimes is discussed in terms of physical, hydrological and climatic controls. Annual break-up is found to progress from south to north, over a period representing $\sim\frac{1}{4}$ of the year. Average annual duration is ~ 8 weeks. The at site break-up period, recognized as the most dynamic time of the year on cold-regions river systems is found to last from 4 days to 4 weeks. Break-up timing (1966-1995) is found to be occurring earlier in the western portions of the basin (~ 3 days/decade), concurrent with late 20th century warming.

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CHAPTER 1: INTRODUCTION

1. INTRODUCTION

It has recently been noted that over half (60%) of rivers in the northern hemisphere experience ice conditions over the annual period (Prowse, 2005). On these northern river systems, the break-up period represents a brief but crucial event of the annual regime (Beltaos, 1997). During this time, ice break-up can result in significant biological (e.g. Prowse and Culp, 2003; Cunjak *et al.*, 1998) and morphological effects (e.g. Mackay and Mackay, 1977). One of the most persistent effects of the ice break-up period is the occurrence of high-water events, often augmented by ice jamming conditions (Watt, 1989; Gerard, 1990). In Canada, costs associated with break-up and jamming are \$60 million CDN dollars (Gerard and Davar, 1990) while American estimates exceed \$100 million US dollars (White and Eames, 1999). Due to the significant effects and high costs, much research has, and continues to be, focused on better understanding the dynamics of the spring break-up period.

2. RESEARCH UNKNOWNNS

As previously described by Smith (1980), the vast majority of research on flood regimes has historically focused on the open-water period (e.g. Wolman and Leopold 1957; Dury, 1970, 1974). More recently, the importance of ice to river hydrology have been highlighted in a series of reviews including *Hydrological Processes* (2002), *Canadian Journal of Civil Engineering* (2003) and manuscripts by Beltaos (2000) and Morse and Hicks (2003). While much progress has been made in both understanding and

predicting ice break-up events, several research gaps remain. Recent reviews of the climate control on river ice hydrology (Prowse and Beltaos, 2001; Beltaos and Prowse, 2002) indicate that a major research unknown continues to be a quantification of ice-affected versus open-water-levels for a cold regions river system. While studies (e.g. Gerard and Karpuk, 1979; Prowse *et al.*, 2001) indicate that ice-induced flooding occurs at much lower recurrence intervals than for open-water conditions, the majority of previous work is site specific. The major reason why a large-scale quantification has never been performed is that the mandate of most hydrometric programs is to publish discharge information. In the case of ice break-up, return-period assessments of discharge, commonly used for open water flood studies, are not applicable due to the indefinable stage-discharge conditions occurring during the break-up. For locations subject to ice break-up during the spring, water-level data is required to accurately assess flood-risk.

To address this unknown, the initial phase of this type of study requires the extraction of ice break-up related water-level information from archived hydrometric data. To do so, a methodology is provided by the Working Group on River Ice Jams (Beltaos *et al.*, 1990). Variables of interest for the quantification of ice versus open-water-levels include the magnitude of the peak annual ice break-up water-levels for comparison to the magnitude of peak open-water-level events.

This type of assessment would also provide the building blocks for a regime classification of cold-regions river systems based on the dominant physical process leading to high-water events. An early cold-region regime classification was provided by Church (1974). However, this classification did not provide any spatial framework and

was qualitative in nature. Given the advances in river-ice hydrology over the past ~30 years, now would seem an appropriate time to perform a quantification of spring break-up water-levels for a cold-regions river system.

This utility of large-scale assessments of the spring break-up period has been previously noted by Gerard (1990) who indicated that while traditionally spring break-up work was site specific, researchers should not lose sight that local events are a part of the big picture of the ice regime on a river. It was indicated that to make a contribution to the science, research should be focused at the catchment-wide scale, and consider hydraulic, hydrological, mechanic and thermal aspects of the situation. While some large-scale Canadian assessments of ice break-up have been performed (e.g. Brimley and Freeman, 1997; Zhang *et al.*, 2001), these have not focused on the most basic of hydrological units, the drainage basin. In addition, these previous assessments of ice break-up timing have relied on Water Survey of Canada 'Last B dates'. As this date often only represents an estimate of overall ice-channel conditions the accuracy is limited. Some recent advancement in assessing break-up patterns at the watershed scale has been made by using remote sensing techniques (Pavelsky and Smith, 2004). However limitations to these types of studies include short data sets (<10 years), high costs, and the occurrence of atmospheric conditions which hinder observations.

It is likely that a longer term (>30 years) indication of the break-up season can be provided by the timing of the initiation of break-up and the timing of peak water-levels, which can be extracted directly from Water Survey of Canada hydrometric archives. These variables can be used in conjunction with the previously mentioned 'Last B date' for determination of time lags between the three events including the *drive*, *wash* and

duration (Deslauriers, 1968; Michel, 1971) which, in total, represent five spring break-up event/duration variables which, to the authors knowledge have never been assessed at the watershed scale. This work will represent a significant contribution to cold-regions hydrology.

3. DATA SOURCE

To perform both a spatial and temporal assessment of break-up water-levels and timing variables, a data archive of hydrometric information is required. Fortunately, data archival was undertaken by researchers at the Environment Canada's National Water Research Institute in 2001. In total 143 Water Survey of Canada hydrometric stations were selected and information pertaining to the break-up period were collected including: (1) pen recorder charts during the break-up season, (2) station description, (3) hydrometric survey notes, (4) gauge history, (5) benchmark history, (6) discharge measurement tables, (7) station analysis, and (8) water-level tables.

The extraction of ice break-up information requires careful examination of pen recorder charts during the ice break-up period. While the process is time-consuming, the database created provides valuable information which, once created can be used for a variety of research objectives pertaining to the ice break-up season.

4. STUDY AREA

While the data archive covers stations across Canada, the extraction of ice break-up information is, as previously mentioned, a time consuming process. Given the scope of a research thesis, it was decided to limit the study of break-up variables to the watershed

scale. For this study, the Mackenzie River basin, Canada's largest northwards flowing river system, was selected. Reasons for the selection include the occurrence of dramatic break-up events within the basin (e.g. see Kriwoken, 1983; Prowse, 1986; Stanley and Gerard, 1992); limiting the study to one basin assumes a continuity of flow which greatly simplifies the analysis of break-up patterns, and the large body of literature already available on various components of the hydrology, climate and geography of the basin which will assist in the analysis and discussion of findings. Major research efforts for the area over the past ~30 years include the: Mackenzie River Basin Committee (MRBC, 1981); Mackenzie Basin Impact Study (Cohen, 1994); Northern River Basins Study (NRBS, 1996); Mackenzie River Basin Board (MRBB, 2003); and the Mackenzie Global Energy and Water Experiment (GEWEX) Study (Stewart 2002).

5. SPECIFIC OBJECTIVES

The extraction of spring break-up hydrometric information and subsequent analysis of data will be used to address the two general objectives of this thesis. Objective 1, below, will be addressed in a Chapter 2, which is written as a stand-alone, journal style manuscript:

1) *Use relevant hydrometric records to quantify the frequency and magnitude of ice-induced peak water-levels versus those for open-water conditions for a suite of station under varying physical and climatic regimes.*

Objective 2, below, will be addressed in Chapter 3, again a stand-alone, journal style manuscript:

2) *Use relevant hydrometric records to assess temporal pattern and trends of the spring break-up season for a suite of stations under varying physical and climatic regimes.*

This thesis concludes with Chapter 4 which contains a summary of major findings of the two manuscripts and indicates future research directions in the field of cold-regions hydrology.

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CHAPTER 2: ASSESSMENT OF ANNUAL HIGH-WATER EVENTS FOR THE MACKENZIE RIVER BASIN, CANADA

ABSTRACT

River ice break-up is known to have important morphological, ecological and socio-economic effects on cold-regions river environments. One of the most persistent effects of the spring break-up period is the occurrence of high-water-levels. A return-period assessment of maximum-annual water-levels occurring during the spring break-up and open-water season at 28 Water Survey of Canada hydrometric sites over the 1913-2002 time period in the Mackenzie River basin (MRB) is presented. For the return-periods assessed, 13 (14) stations are dominated by peak water-level events occurring during the spring break-up (open-water season). One location is determined to have a mixed signal. A regime classification is proposed to separate ice- and open-water dominated systems. As part of the regime classification procedure, specific characteristics of return-period patterns including alignment, exceedence of the 2.33-year event, and difference between the 2 and 10-year events are used to identify regime types. A dimensionless stage-discharge plot allows for a contrast of the relative magnitudes of flows required to generate peak water-level events in the different regimes. At sites where discharge during the spring break-up is approximately $\frac{1}{4}$ or greater than the magnitude of the peak annual discharge, water-levels can be expected to exceed those occurring during the peak annual discharge event. Several physical factors (location, basin area, stream order, gradient, basin orientation, and climate) are considered to explain the differing regimes and discussed relative to the major sub-regions of the MRB.

Keywords: River-ice; Spring break-up; Return-period assessment; Mackenzie River basin; Flooding

1. INTRODUCTION

River ice break-up, an annual occurrence on cold-regions river systems, has important morphological, ecological and socio-economic effects on river environments. For example, sediment concentrations have been reported to increase by an order of magnitude during the break-up period (Beltaos *et al.*, 1994) with the related ice action producing distinctive erosional and depositional features along river channels and flood plains (MacKay and Mackay, 1977; Church *et al.*, 1997; Prowse, 2006). Prowse and Culp (2003) also identified the significant and wide-ranging effects of ice break-up on river ecology. These include: physical disturbance to vegetation (Cameron and Lambert, 1971); controls on biological production (Cunjak *et al.*, 1998) and determination of water quality. Over the last two decades, the importance of ice-induced flooding for maintaining the health of freshwater riparian ecosystems, specifically deltas, has become widely acknowledged (Marsh, 1986; Lesack *et al.*, 1991; Prowse and Lalonde, 1996; Prowse *et al.*, 2006). From an economic perspective, it has been estimated that total damages resulting from river ice break-up events across Canada exceed \$60 million (CDN) per year (Gerard and Davar, 1995), although this may be a conservative estimate given that the cost of a single break-up season in Eastern Russia in 2001 exceeded \$100 million (US) (Brakenridge *et al.*, 2001).

One of the dominant hydrologic effects of the spring break-up period is extreme high-water-levels (Watt, 1989). Unlike open-water floods, which are generally the result of catchment-scale precipitation/snowmelt events, spring break-up floods are more the result of in-channel ice processes (Gerard, 1990). For example, the addition of a stable ice cover to a river channel will result in water-level increases of approximately 30% over

open-water channel flow conditions assuming ice and channel roughness are equal (Gray and Prowse, 1993). During ice break-up and jamming events, further constriction to channel area and increases in hydraulic roughness caused by under-ice protrusions can raise water-levels well beyond the +30%-level.

Although numerous case studies of ice-affected sites are available in the literature (e.g., Egginton, 1980; Gerard and Calkins, 1984; Grover *et al.*, 1999; Kriwoken, 1983; Marsh and Hey, 1989; Petryk, 1990; Stanley and Gerard, 1992a, 1992b; Tuthill *et al.*, 1996; White, 2000), only a few have extended time-series analyses that permit evaluation of return-periods for ice versus open-water conditions (e.g., Gerard and Karpuk 1979; Prowse *et al.*, 2001). Moreover, any form of regional quantification of the relative importance of ice-affected versus open-water conditions remains a major and much needed task to be undertaken in the field of cold-regions hydrology (Beltaos and Prowse, 2001; Gerard, 1990).

The importance of conducting such research is magnified by the findings of the International Panel on Climate Change (IPCC, 2001) that projects future alteration to break-up intensity and frequency as a result of anthropogenically induced climate change. Benchmarks of broad-scale regional conditions are required to identify and quantify any future climate-induced change.

The goal of this study is to make the first broad-scale assessment of river-ice in controlling peak water-level conditions in a large cold-regions catchment. The result of such an assessment will provide the building blocks for more detailed analyses of controlling physical factors (e.g., climate, hydrology and hydraulics) and regional analyses of other cold-regions environments.

The site chosen for this initial assessment is the Mackenzie River Basin (MRB). As described in the subsequent two sections, it meets selection criteria of having a broad range in climatic, hydrologic and hydraulic characteristics and, at least within Canada, one of the longest and most spatially-intensive archives of ice and open-water-level and flow data encompassing the 1913-2002 time period.

This study has two major objectives: 1) to quantify, through the use of return-period analyses and related characteristics, the ice and open-water regimes of the MRB; and 2) to generate a regional classification of these regimes considering major spatial differences in physical factors.

2. STUDY AREA

The MRB, the largest cold-regions drainage basin in North America ($1.8 \times 10^6 \text{ km}^2$), extends across 16° of latitude from 54° N to 70° N and 37° of longitude from 103° W to 140° W (Figure 1). Within these boundaries it contains a wide range of physical conditions. It is unique among cold-regions basins in North America in that it contains over half (8/15) of the ecozones identified in Canada, and encompasses portions of 5 permafrost zones. By land cover type, the basin coverage includes 79% forest, 7% arctic and alpine tundra, 7% lakes and rivers, while barren lands and agriculture cover 5% and 2% of the basin respectively.

Elevations in the MRB range from sea level at the Beaufort Sea to $\sim 3300 \text{ m}$ in its headwaters at the Rocky Mountains. Four distinct physiographic regions are identified in the basin including the Western Cordillera (mountain chains, valleys and high plateaus); Canadian Shield (rolling terrain with lakes and wetlands); Interior Plains (wetlands, lakes

and grassland in south to boreal forest to tundra); and the delta environment at the river mouth (Mackenzie Delta $\sim 12,000 \text{ km}^2$). Other internal-MRB deltas include the Peace-Athabasca River Delta (PAD) (3800 km^2) and the Slave River Delta (640 km^2).

Two climate regimes are found in the MRB: the tundra, covering the north-eastern and higher attitudes of the Western Cordillera, while the remainder of the basin is classified as sub-arctic (MRBC, 1981). The Mackenzie Valley region has a milder climate than neighbouring areas to the east and west. From south to north, the (1971-2000) daily average temperature at Athabasca ($\sim 54^\circ \text{ N}$) is 2.1° C while at Inuvik ($\sim 68^\circ \text{ N}$) it is -8.8° C (Environment Canada, 2006). Precipitation in the MRB decreases from the west to the northeast with $\sim 1000 \text{ mm/yr}$ occurring in the southwest to $\sim 500 \text{ mm/yr}$ in the northwest (Hydrological Atlas of Canada, 1978). Snowfall is identified as the major source of precipitation in the basin, with many parts of the MRB being snow covered over half of the year. It is noted by Woo and Thorne (2003) that most rivers in the southern basin peak in May, while delayed snowmelt and freshet peaks occur later in the higher altitude and latitude locations. Additionally, autumn rainfall events can give rise to secondary annual peaks.

The major tributaries of the Mackenzie River system include the Athabasca, Peace and Liard Rivers (Figure 1). These river systems flow from the Western Cordillera towards their outlets on the Interior Plateau where dramatic spring break-up events are common. These ice jam prone locations, previously classified as the *subarctic nival regime* (Church, 1974), include the Athabasca River at Fort McMurray (Kowalczyk and Hicks, 2003); the Peace River as it enters the PAD (Peters and Prowse, 2001); the town of Hay River, Northwest Territories (Stanley and Gerard, 1992a, 1992b); the confluence of the

Liard and Mackenzie Rivers at Fort Simpson (Prowse, 1986) and the Mackenzie River delta (Marsh and Hey, 1989). A recent assessment of ice duration in the MRB identified that the spring break-up clearance lasts ~8 weeks in the MRB, occurring over an average of $\frac{1}{4}$ of the annual period (de Rham, 2006).

3. BACKGROUND: COLD-REGIONS FLOW REGIME

Four distinct flow regimes are identified for ice-affected river systems over the annual period (Davar, 1979). These include: open-water, autumn freeze-up, mid-winter, and spring break-up. This manuscript deals with extreme water-level events occurring during the open-water and spring break-up periods. Although high-water-levels are also known to occur during freeze-up (Keenhan *et al.*, 1980), and mid-winter (Prowse *et al.*, 2002), the latter are often of a transient, irregular nature and spring break-up levels typically exceed those during freeze-up.

Break-up processes on ice-affected rivers are described as: *thermal* (overmature) or *mechanical* (dynamic) (Gray and Prowse, 1993). In the thermal case, the ice-cover strength deteriorates due to solar radiation and warming temperatures, and downstream forces as dictated by the spring flood wave are limited. As a result, the break-up events tend to be relatively quiescent. Conversely, mechanical break-ups occur when the strength of the ice sheet has not deteriorated considerably, and a flood wave of sufficient magnitude occurs which is able to rapidly break-up the ice cover. The cover tends to fragment into large pieces producing a hydraulic roughness that is often many times the bed roughness. As such, water-levels increase well beyond the +30%-level (see Gray and Prowse, 1993) associated with hydraulically smooth ice experienced during the period of

intact ice cover. Water-levels can increase by 3-4 times because of the very high ice roughness occurring during such mechanical events. Some enhanced elevation of water-levels also occurs during thermal events (e.g., Beltaos, 2003), since the above classification only represents the ‘end points’ in a description of the break-up process.

In general, the potential for mechanical break-up events is lower on rivers flowing in a direction opposite to that of regional warming. This is due to the significant thermal decay of the downstream cover that can occur prior to the onset of upstream spring melt (Lawford *et al.*, 1995). The MRB, however is generally classified as a “northward” flowing river.

4. DATA SOURCE AND METHODOLOGY

4.1. Station Selection

The water-level data used in this analysis originate from the Water Survey of Canada (WSC) hydrometric archives. Although the WSC regularly publish discharge data, water-level data are primarily kept as archive information. In the case of ice-affected data, the information is rarely extracted into publicly available formats and only remains on the original pen-chart or digital recordings. The WSC keeps on file for each station: (1) pen recorder charts during the break-up season, (2) station description, (3) hydrometric survey notes, (4) gauge history, (5) benchmark history, (6) discharge measurement tables, (7) station analysis and (8) annual water-level tables.

There are 652 WSC stations, past and current, located within the MRB. Of these, 108 have a drainage basin area $\geq 10,000 \text{ km}^2$. For this study, MRB stations were only included if they fit the following criteria: a minimum $10,000 \text{ km}^2$ drainage basin (ensures

formation of free floating ice cover) and representative of upstream to downstream locations on the major tributary and mainstem river systems.

Using this filtering process, 28 stations, with similar temporal coverage, and the requisite 10-year record length for return-period assessments (see Water Survey of Canada, 1970) were finally selected (Figure 1). These stations covered a broad range of physical environments found in the MRB, encompassing the 1913-2002 time period (Figure 2).

4.2. Data Extraction Procedures

To determine return-periods and assess the stage-discharge relationships for selected stations in the MRB, the magnitude and discharge of the maximum-annual instantaneous break-up water-level (H_M) and maximum annual instantaneous open-water-level (H_O) were required. The specific procedures for extracting the data from the original archives are discussed below.

4.2.1. Maximum Annual Instantaneous Break-up (H_M) and Open (H_O) Water-level

Data extraction of H_M (Figure 3) followed procedures outlined in Beltaos (1990). To determine H_M , a review of original, water-level recording charts (pre ~1996) and digital water-level recording data (post ~1996) was performed. These H_M events can be caused by: (1) flood peaks from the break-up of an upstream jam (attenuated effects or surge effects), (2) the backwater from a distant downstream ice jam, (3) evolving ice jams which release before building to their maximum flood depth at equilibrium (e.g., see Beltaos, 1995), (4) ice jams which cannot be sustained beyond a given flow rate (i.e., an

ice clearing discharge), (5) ice jams which result in spillage over dykes or banks into the flood plain, and/or (6) ice jams which have their development limited by the available ice from upstream (Ontario Ministry of Natural Resources, 1990). Unfortunately, damage to water-level recording instrumentation is common during the break-up period. This includes over pressuring of water-level pressure transducer lines and/or their shearing by ice. As such, recorded H_M values are not available for many years when stations were “operational”. Under these circumstances, if available, daily-mean water-levels were used. H_O values were obtained from either the mean-daily water-level tables, or converted to stage using a published maximum instantaneous or daily discharge. While daily water-level are not as accurate as instantaneous events in defining an at site flooding regime, inclusion of these events provides a larger dataset set to be assessed at the site of interest.

To assess data quality, a rating scheme was employed. A 0-1-2 confidence rating scale was used on the extracted data to indicate high confidence (0) to low confidence (2) in the accuracy of the final values. A published or extracted maximum instantaneous water-level was rated a 0; a mean-daily water-level extracted from a continuous daily water-level record was rated a 1; and a mean-daily water-level extracted from a limited daily water-level record was rated as 2. Data ratings were used to assess the quality of all H_M and H_O events used in the return-period analyses.

For the extracted H_M (H_O) magnitudes, daily or where available, instantaneous discharge, Q_M (Q_O), as published by the WSC, was obtained. The WSC does not publish instantaneous discharges during the break-up period because they are virtually impossible

to determine during the highly dynamic and transient flow conditions that characterize break-up.

4.3. Return-period Assessment

4.3.1. Return-period Analyses

To determine the return-period of events occurring during the open-water and spring break-up seasons, the Weibull Method (Weibull, 1939) was used for calculation:

$$[1] \quad R = n+1/m$$

where R is the return-period of event (in years), n is the number of annual water-level records in the data series and m is the magnitude rank of the given annual event. The H_O and H_M datasets (two sub-populations) were assessed separately according to the above equation. Resultant data for each site were plotted on a single return-period (logarithmic) vs. stage (arithmetic) plot as has been used in other hydrologic and ice-jam flood analysis employing stage or discharge (e.g., Grover *et al.*, 1999; McCuen, 2003)

Based on the calculated return-periods, the associated magnitudes under break-up and open-water condition were determined for a range of (frequent to rare) year intervals including the 2, 5, 10, 15, 20, 25 and 30-year events. Also included was a commonly used flood index, the mean-annual flood, which represents the arithmetic mean of all maximum yearly discharges and statistically refers to the 2.33-year event (Ritter *et al.*, 1995). Interpolation between bounding events using a linear equation was employed if no measured water-level was available for the specified return-period. Due to the sensitivity of ice-affected water-levels to overbank flow (see Beltaos and Prowse, 2001; Gerard and Karpuk, 1979), data extrapolation, common in discharge-based return-period analysis, was not used. As such, the temporal record limited the determination of return-periods.

The resulting data set, H_M' and H_O' , for the specified return-periods, was then classified according to the dominant regime, return period line patterns, exceedence of the 2.33-year open-water event; and the difference in magnitude between the 2 and 10-year event.

4.4. Regime Classification

4.4.1. Dominant Regime Classification

The results of the basin return-period analyses were used to identify peak water-level regimes that were dominantly controlled by either break-up (R_B) or open-water (R_O) conditions. To perform this classification, the ratios of the return-period values for maximum water-levels for break-up (H_M') and open-water (H_O') for all selected and equal return-periods were calculated. If H_M'/H_O' was ≥ 1.00 (< 1.00) for all selected return-periods (2, 2.33, 5, 10, 15, 20, 25, 30-year), the station was classified as dominantly R_B (R_O). If the return-period ratios were mixed, that is some ratios were ≥ 1.00 and some < 1.00 , maximum water-levels may be produced by either break-up or open-water events and the locations were identified as mixed regime (R_M).

4.4.2. Classification of Return-Period Line Patterns

A previous assessment of flood events generated by two distinct processes (i.e., two sub-populations) identified differing patterns of return-period lines (Woo and Waylen, 1984). More recent work by Prowse *et al.* (2001) hypothesized that differing alignments (converging, diverging, and parallel) of the H_M and H_O return-period lines among sites were likely the result of differing hydro-climatic and morphological controls. To quantify the differing alignments, a classification scheme was developed for the return-period line

patterns at the 28 study sites. Alignment of the return-period lines was evaluated using the H_M'/H_O' data.

A divergent, D, (convergent, C) pattern was considered to apply when H_M'/H_O' values show a steady increase (decrease) across all return-periods and the difference between the $H_M'/H_O'_{2\text{-year}}$ and the $H_M'/H_O'_x$, (where x denotes the largest return-period assessed) equates to a $\geq 10\%$ ($< 10\%$) difference. C and D superscripts to the R_O and R_B regimes denote their convergent or divergent character respectively. If the increase or decrease was $< 10\%$, or an increase then decrease in H_M'/H_O' values was observed, the regime was classified as parallel (P), herein referred to R_B^P and R_O^P . It is worthwhile to note that the choice of 10% was selected following an iterative process of data examination that provided a good separation of regime types. As such, it is not representative of any physical principle, rather, it provides a simple, quantifiable classification method.

4.4.3. Exceedence of 2.33 year Open-Water Event

To assess the significance of the spring break-up period in the MRB, the return-period of the H_M' event (2, 2.33, 5, 10, 15, 20, 25, and 30-year), herein referred to the ' $H_M'_{\text{Event}}$ ', that equalled, or exceeded the magnitude of the 2.33-year H_O' event was determined for each station. For a special comparison to open-water flood conditions, the differences in water-levels between the 2.33-year H_O' and the $H_M'_{\text{Event}}$ magnitude were calculated.

These are herein referred to the $\Delta H_{2.33}$.

4.4.4. Difference in Magnitude between the 2 and 10-Year H_M' and H_O'

To quantify, and be able to compare, the difference in water-level of low to high return-period event during the spring break-up and open-water season at each site, the magnitude of the 2-year H_M' and H_O' (representative of a frequent event) was subtracted from the 10-year (i.e., more rare event) H_M' and H_O' at each station. The resultant data are identified as $\Delta H_M'_{2}$ and $\Delta H_O'_{2}$. The 10-year event was selected as it allowed for an assessment of similar return-period water-level differences at all 28 stations, given the varying record lengths.

4.5. Stage-discharge Classification

To quantify the average magnitude of the discharge occurring during both the spring break-up and open-water events for each station, mean ice-affected ($\overline{Q_I}$) and open-water ($\overline{Q_O}$) discharge and stage ($\overline{H_I}$, $\overline{H_O}$) were determined. Ratios for the discharge ($\overline{Q_I} / \overline{Q_O}$) and stage ($\overline{H_I} / \overline{H_O}$) for each station were calculated and plotted on a synthetic stage-discharge ratio plot incorporating data from the 28 stations.

4.6. Regime Map and Physical Characteristics

To assess the spatial distribution of the dominant regime and return-period line classifications identified in the MRB, a map was produced showing the major river networks, elevation and dominant regime classification. From previous case studies, it is known that numerous physical and meteorological factors govern the ice break-up and jamming processes (Beltaos and Prowse, 2001). As a first evaluation of the relative

importance of a potential myriad of physical factors, on ice break-up and open water-levels it was decided to use six readily available and quantified characteristics. These include (*characteristic*, major control on related hydrologic, hydraulic or climatic variable; source of data): (1) *latitude*: radiative inputs (Aguado and Burt, 1999), WSC archives; (2) *basin area*: flow magnitudes (Murphey *et al.*, 1977), WSC archives; (3) *channel slope*: water velocities (Beltaos, 1995), Hydro1K database (USGS, 2005); (4) *elevation*: radiative warming and cooling (Aguado and Burt, 1999), GTOPO30 DEM (USGS, 2005); (5) *stream order*: hierarchy in drainage network (Strahler, 1952), Hydro1K database (USGS, 2005); (6) *river orientation*: mechanical vs. thermal break-up (Gray and Prowse, 1993), extracted from map

4.7. Data Assumptions and Limitations

A major assumption of return-period analysis is a stationary climate. It has been indicated by previous research that the MRB has experienced increasing temperatures over the past 30 to 50 years (Serreze *et al.*, 2000; Zhang *et al.*, 2000). Such changes on the ice and flow regime, however, are assumed to have an insignificant effect on the regional evaluation of this ice versus open-water regime analysis. Detection of any possible climatic effects on high-water events at the stations is reserved for future research focusing specifically on this issue.

It is also worth noting that data employed for the station Mackenzie River *at* Arctic Red River (station identifier: 10LC014) were treated as homogenous for the 29 years of record assessed. Prior to 1985, the hydrometric station Mackenzie River *above* Arctic Red River (10LA003) was located ~16 km upstream of 10LC014. To create a

homogenous data series, a WSC water-level adjustment factor was applied to the pre-1985 data. While the adjustment factor was designed for medium flows occurring under open-water conditions, it was assumed that this adjustment factor was also appropriate for ice conditions.

Finally, for the two locations along the Peace River mainstem, only data after and including 1972 (i.e., post WAC Bennett dam construction and reservoir infilling) were assessed. This was done to ensure a consistent regulation signal. It was assumed that further downstream on the Mackenzie main stem, regulation effects became relatively minor, thus all available data were used at these locations.

5. RESULTS AND DISCUSSION

5.1. Regime Classification

5.1.1. Dominant Regime Classification

The magnitude and values of H_M'/H_O' ratios for the eight return-period intervals are shown in Table 1. Notably, almost half (13 of the 28) of the stations assessed in the MRB are identified as R_B whereby for all assessed return-periods, H_M'/H_O' ratios are ≥ 1.00 . At these locations peak annual high-water events are considered to always occur during the spring break-up season. For all return-periods considered ratios vary between a low 1.03 at the Wabasca River to a high of 2.09 at the Mackenzie River. Notably, water-level differences between the H_M' and H_O' values for the 25-year return-period at the latter location exceed 9 m, a value even greater than the open-water value (8.42 m).

A contrasting open-water regime prevails at 14 stations in the basin. At these locations, all H_M'/H_O' ratios are < 1.00 (Table 1) and identified as R_O . Here, events occurring during the open-water season produce the annual high-water condition. Ratios vary

between a low of 0.28 at the Kechika River above Boya Creek to a high of 0.99 at the Little Smoky River. At the former location, the 2-year events (H_O' vs. H_M') differ by approximately 2.5 m (3.51 m vs. 0.98 m) while at the latter the 30-year events differ by less than 0.1 m (6.61 m vs. 6.56). Thus, at some R_O locations, during the spring break-up, large return-period (i.e., more rare) break-up events are still capable of producing water-levels similar to those resulting from large return-period events during the open-water season.

One location in the basin, the Pembina River Jarvie, is classified as R_M where events at the assessed return-periods vary between < 1.00 and ≥ 1.00 (Table 1). While the 2, 2.33, and 10-year return-period H_M' events are of a greater magnitude, H_O' values for other return-periods are larger. The specific reason for this remains unclear and requires a detailed site investigation, particularly of channel geometry related to the flow/level conditions, to identify possible causes.

5.1.2. Classification of Return-Period Line Patterns

For the 13 R_B locations in the MRB, 8 are identified as R_B^D , 1 as R_B^C , and 4 as R_B^P (Table 1). Sample return-period plots depicting the diverging (D), converging (C) and parallel (P) patterns of the R_B and R_O regimes are shown on Figures 4a-4f. For R_B^D locations the steady increases in H_M'/H_O' ratios are clearly evident indicating that the magnitude of ice events increasingly exceeds those of open-water events (Gerard and Karpuk, 1979; Prowse *et al.*, 2001). For example, at the Liard River near the Mouth (Figure 4a), the difference between the 2-year events is less than 3 m (9.54 m vs. 6.64m) while for the 25-year events it is > 6 m (15.11 m vs. 8.69 m). By contrast, the single R_B^C

location, at the Arctic Red River (Figure 4b), shows at higher return-periods, the magnitude of H_M and H_O events become similar. Notably, however, the highest magnitude H_O event, only rated a 2 on the confidence scale and this one event of questionable data quality defines the pattern at this station. If this one event was eliminated from the analysis, the station would become R_B^D .

Four locations in the basin are identified as R_B^P (e.g. Figure 4c) - three occur on the Peace River system and one is on the Peel River. Interestingly, three of the four locations exhibit an enhanced divergence (i.e., H_M'/H_O' ratio) at the 10-year return-period whereas the greatest divergence occurs at the 15-year return-period on the Wabasca River. This divergence may at least be partly controlled by aspects of channel geometry, particularly related to flow containment and over-bank spillage occurring at the aforementioned return periods for ice events. For example, Smith (1980) noted that the return-period for ice break-up over bank flooding on several Alberta sites is close to decadal while Henoch (1960) discussed the importance of channel bank elevations on flood levels along the Peel River. As such, it is possible that this divergence relates to over-bank flooding events. However, examination of channel cross-section would be necessary to more fully explain this occurrence and is reserved for future research.

Of the 14 R_O locations in the MRB, three are identified as R_O^D , seven as R_O^C , and four as R_O^P (Table 2). At the R_O^D locations, steady decreases in H_M'/H_O' ratios are evident. For example, at the Wapiti River (Figure 4d), the difference between the 2-year events is < 1 m (2.41 m vs. 3.23 m) but the 30-year event is almost 6 m (3.34 m vs. 9.29 m). The pattern at R_O^D locations shows that at larger return-periods (i.e., more rare events) the magnitude of H_O events increasingly exceeds those of H_M events.

At the seven R_O^C locations, the magnitudes of H_M' and H_O' for larger period events show a lower difference than for the more frequent events. For example, at the Kechika River at the Mouth (Figure 4e), the 2-year events differ by approximately 1.5 m (2.33 m vs. 3.75 m), while the 20-year return-period difference is < 1 m (4.61 m vs. 4.67 m). Hence, although not dominant, ice effects are still important at the R_O^C locations, particularly in the larger return-periods (i.e., more rare events).

The remaining four R_O locations in the basin are identified as R_O^P . These sites show similar differences in water-levels at both large and small return-periods. As an example, at the Frances River near Watson Lake (Figure 4f), the difference between the 2-year and 30-year H_M' to H_O' event magnitudes is 2.0 m and 1.36 m respectively.

Finally, at the single R_M location (Figure 4g), events less than and equating to the 15-year return-period (except the 5-year event) are H_M' dominated while at the 5, 20, 25, and 30-year time intervals, H_O events dominate. The specific causes of this pattern are unknown but again are likely related to channel morphometric characteristics controlling flow and water-levels.

5.1.3. Exceedence of 2.33 year Open-Water Event

The return-period of the break-up event (H_M' Event) which exceeds the respective 2.33-year H_O' are shown in Table 2. Also included, if applicable, is the difference in water-level for the two events, $\Delta H_{2.33}$.

For all R_B locations, the magnitude of the 2.33-year H_M' , exceeds the 2.33-year H_O' . In fact, at all stations except the Wabasca River, the more common 2-year H_M' magnitude event exceeds the 2.33-year H_O' . Differences in water-levels ($\Delta H_{2.33}$) range from 0.16 to

5.07 m (Table 2). Given that 2.33-year mean annual event is based on open-water flood investigations (Ritter *et al.*, 1995), its appropriateness for flood-related studies on ice-affected waterways should be carefully scrutinized.

At the R_O locations, exceedence of the 2.33-year H_O' value varies station to station. For example at the Smoky River, the 5-year H_M' value exceeds this event by 0.79 m, while at eight of the 14 stations, none of the assessed H_M' return-period values exceed the 2.33-year H_O' . At these stations, use of the 2.33-year H_O event for determining the mean annual flood level may be suitable.

Lastly, at the single R_M location, the 2-year H_M' value exceeds the 2.33-year H_O' by 0.27 m. While this station is identified as mixed, the 2.33-year exceedence is similar to the R_B locations.

5.1.4. Difference in Magnitude between the 2 and 10-Year H_M' and H_O'

The results of a comparison of the difference between the 2 and 10-year H_M' and H_O' values is shown in Table 2. Overall, at all the R_B locations, $\Delta H_M'_{2}$ is greater than $\Delta H_O'_{2}$. For example, at the Liard River near the Mouth, $\Delta H_M'_{2}$ is 4.52 m compared to 1.57 m for $\Delta H_O'_{2}$. The R_O locations have a less obvious dominance of H_O' and H_M' magnitudes at the return-periods assessed. Interestingly, at all four R_O^P locations greater differences occur during the break-up period (i.e., $\Delta H_M'_{2}$) while at all three R_O^D locations, $\Delta H_O'_{2}$ show greater differences. At the remaining seven R_O^C locations four (three) locations show greater differences for $\Delta H_M'_{2}$ ($\Delta H_O'_{2}$) events. Stream network factors may be attributable to these as both locations in the Fort Nelson Basin have greater differences for $\Delta H_O'_{2}$, while both sites along the Kechika River differences are greater for $\Delta H_M'_{2}$. On

the Pembina River (R_M), greater differences occur between $\Delta H_O'$, albeit compared to $\Delta H_M'$, the change is small, being on the order of 0.2 m (2.28 m vs. 2.02 m).

The difference in the 2 and 10-year H_M' and H_O' magnitudes allows for equal return-periods to be assessed at all stations. It is found that approximately 70% of the stations (21/29) in the MRB show greater differences in water-levels during ice-conditions as opposed to open-water conditions. These results are important as they indicate the relevance of ice on water-levels at the vast majority of stations in the basin.

5.2. Stage-Discharge Classification

Figure 5 is a plot of mean ice and open-water discharge ($\overline{Q_I} / \overline{Q_O}$) and stage ($\overline{H_I} / \overline{H_O}$) ratios for the 28 stations in the MRB. Incorporated into the plot are the dominant regime classifications. An obvious distinction between the two regimes (R_B and R_O) is evident, while a logarithmic equation, fitted to the data, provides an acceptable fit ($R^2 = 0.83$). When all available data were employed, ($n= 779$) the R^2 was reduced to 0.58. Based on the assumption that mean values of each of the four variables, are representative of each regimes, several noteworthy characteristics are evident.

The first is that ice effects are evident at R_O locations. For example, a spring break-up flow ($\overline{Q_I}$) of only 1/10 of the open-water flow ($\overline{Q_O}$) will still produce a stage of at least 50% of that for open-water conditions. This is a testament to the importance of ice conditions on cold-regions river systems, even during low-flow conditions. Moving towards larger spring break-up ($\overline{Q_I}$) events, a flow equivalent to approximately 1/4 of the open-water discharge ($\overline{Q_O}$) will produce an equivalent water-level (i.e., $\overline{H_I} / \overline{H_O} =$

1.00) conditions. Thus, it can be concluded that during the spring break-up at the R_O locations, discharge events are on average $< \frac{1}{4}$ of the open-season or mean-annual peak flow events. Conversely, at the R_B locations, discharge events are on average $\geq \frac{1}{4}$ the magnitude of the open-water season event. These R_B locations are characteristic of the *sub-arctic nival regime* (Church 1974; Prowse 1994) whereby ice break-up and high-water events occur during the spring break-up, preceding the peak snowmelt runoff event. At the extreme end of Figure 5, when the spring break-up flow event is equal to that occurring during the open-water season (i.e., $\overline{Q_I} / \overline{Q_O} = 1.00$), an approximate 60% increase over the latter water-levels occur. These increases represent twice those occurring under a hydraulically smooth, competent ice cover (30%), and are indicative of the significance of ice break-up on water-levels on a large, northwards flowing river system.

5.3. Regime Map and Physical Characteristics

A map of the MRB, with station regime classifications, is shown in Figure 6, while physical characteristic data is included in Table 3. In the subsequent discussion, site locations, as shown on Figure 6, are indicated by [#], where # refers to the ID column in Table 2.

In describing the spatial distribution of the dominant regimes, it is evident that all R_B (R_O) locations, are located north of 56° (south of 61°) and represent a longitudinal band covering 62% (38%) the width of the MRB. The R_O locations are concentrated in the south and western portion of the basin (i.e., Western Cordillera and upper Interior Plateau). To the east, R_B sites occur on the downstream reaches of the Athabasca [4],

Peace [8, 9, 10], and Liard [22, 23] systems, while further north, the entire Mackenzie Interior Plateau mainstem [24, 25, 27] is R_B , as are the northernmost tributaries of the Arctic Red [26] and Peel [28] Rivers. A line drawn on Figure 6 depicts the obvious spatial distinction between the two dominant regimes in the basin. Given this distinction several physical, hydraulic, and climatic characteristics are used to compare and contrast the regimes.

5.3.1. Basin Area

While the R_B designations typify a full range of basin sizes, (1.85×10^4 to 1.68×10^6 km^2), the smaller R_O catchments (1.1×10^4 to 1.19×10^5 km^2) are concentrated in the upstream portions of the major MRB tributaries (Table 3). During the open-water season, in the smaller R_O catchments, flood response times are *flashy*, resulting in the peak annual water-levels. For example, locations on the plains and on the east slopes of the Rocky Mountains (i.e., Athabasca and Peace tributaries) exhibit steep flood-frequency curves where, during extreme events, a high proportion of basin area contributes directly to runoff (Watt, 1989). Further north, rivers draining the east slopes of the Rocky Mountains often experience summer rain floods, producing peaks which exceed those occurring during snowmelt (Watt, 1989). For example, a severe summer rainstorm that affected the Fort Nelson and Muskwa Rivers has been previously described by Smith (1975).

The full range of drainage basin sizes at R_B locations indicate the relative importance of flood response and climatic conditions at these sites: during the open-water season, the larger basin sizes and channel area result in *sluggish* response times, whereby locally

produced rainfall events are readily incorporated into channel flows with little effects on water-levels. Conversely, during the spring break-up period, antecedent winter climatic conditions (i.e., development of thick ice cover), and the spring-melt flood pulse, are important controls in the development of peak water-level events. It can thus be concluded that for open-water flood studies (i.e., R_O locations), basin area is closely related to flow magnitudes (Ritter *et al.*, 1995) and peak-water-level events, while for cold-regions flood studies (i.e., R_B locations), basin area is independent of peak-water-level events during the spring break-up period. However, it should be noted that for cold-regions basins of $< 10,000 \text{ km}^2$, the development of a stable ice cover, and hence peak water-level occurrence during the spring break-up, is unlikely.

5.3.2. Elevation

Radiation inputs are known to be an important factor in the ice break-up (Ashton, 1986) and snowmelt runoff process (Marsh, 1990). A control on radiation warming and cooling at the earth's surface is elevation: during the day, low elevation areas warm faster than high elevation areas, while during the night, low elevation areas cool slower than high elevation areas (Aguado and Burt, 1999). For the MRB, it is noteworthy that all R_B (R_O) locations are located $\leq 350 \text{ m.a.s.l.}$ (290 to 739 m) (Table 3). This said a comparison of elevation effects using an east-west transect in the MRB is possible: the R_O dominated Upper Liard (Western Cordillera, W.C.) versus the R_B dominated Great Slave Lake region (Interior Plateau, I.P.).

Assuming that R_B (R_O) sites are generally subject to mechanical (thermal) events, with all things being equal, during the day, the thinner, low elevation I.P. (thicker, high

elevation, W.C.) snow pack (see Environment Canada, 1986) melts more quickly (more slowly), while during the night, slow (rapid) cooling in the I.P. (W.C.) results in a less cooled snow pack, and a greater propensity for melting the following day (may effectively stop snowmelt). Thus a more rapid snowmelt pulse, and mechanical type event is more likely in the low elevation Interior Plateau (R_B) region relative to higher elevation, Western Cordillera (R_O) region.

5.3.3. Stream Order

Stream order allows for the determination of drainage basin composition, by identifying similar stream reaches in a drainage hierarchy (Ritter et al., 1993). For the MRB, R_O locations occur on 2nd to 4th order reaches, while the R_B sites, occur on 2nd to 6th order reaches (Table 3). It appears that, for the MRB, a northwards flowing river system, the importance of river ice break-up in controlling peak water-levels increases towards higher order streams in the drainage hierarchy. While not directly related to stream order, an upstream to downstream importance of the spring break-up season severity is qualitatively described on large, northward flowing rivers of the Former Soviet Union including the Lena, Ob, and Yenseii rivers (Antonov et al., 1972). It may thus be concluded, that, on northern flowing river systems, the spring break-up period, has an increasing importance in controlling peak-annual water-levels, towards higher order streams in the drainage hierarchy.

5.3.4. Channel Slope

Channel slope is an important control on water velocities and break-up processes on cold-regions rivers (Beltaos, 1995). In general, a higher channel slope results in a more rapid flushing of ice on a river channel, thus decreasing the likelihood of mechanical ice break-up events. During the break-up river-ice cover failure has been categorized into prefrontal and frontal modes (Prowse and Demuth, 1989). Prefrontal modes of break-up result in large ice sheet expanses during break-up initiation, while frontal modes occur during surge wave and ice runs during the later stages of break-up. Shen (2003) notes that on relatively steep, non-meandering reaches, the transition from the prefrontal modes to frontal modes is almost undistinguishable. Conversely, on low-slope meandering river systems, the time lag from prefrontal to frontal modes of progression is greater. Thus, in the latter case, the possibility of peak water-level events caused by mechanical ice jamming and release surges is greater.

For the 28 MRB locations, 12 of 13 R_B (12 of 14 R_O) locations have gradients < 0.00056 (> 0.00570) (Table 3). Thus, the R_B regimes typically occur on low slope, meandering (mechanical prone) reaches while R_O regimes typically occur on the steeper, non-meandering (thermal prone) reaches.

5.3.5. Flow Direction

The orientation of a river catchment, relative to spring-time atmospheric warming, is an important control on the severity of break-up water-levels (Lawford *et al.*, 1995). Within the MRB, flow direction at the R_B locations varies from the northwest to the east, with the majority occurring on northwards flowing systems (Table 3). At the latter

orientations, the spring melt and break-up progress upstream together, thus, the occurrence of mechanical type break-up events is common. Several R_O locations also flow north, however, factors such as elevation (i.e., alpine) and catchment size result in the dominance of open-season events. On southwards flowing R_O locations, ice cover deterioration generally precedes catchment runoff, and break-up events are quiescent.

5.3.6. Other Factors

Several other factors, besides those discussed above, are useful for comparing and contrasting the various regimes. Ice jam favourable morphologies, including channel constrictions, rapid changes in slope, sharp river bends, and shoal areas (Mackay and Mackay, 1973, Beltaos and Prowse, 2001) are traits common to the 13 R_B sites (e.g., see Hensch, 1960 ; Kellerhals *et al.*, 1972; Mackay and Mackay, 1977; Stanley and Gerard 1992a; Prowse, 1986; Peters and Prowse, 2001).

Channel morphology is also an important physical control for the R_O regime. For example, at the two upstream locations on the Athabasca River [1, 3], the split, semi-braided channels result in an ice clearance process whereby excess water can flow around arrested ice fragments, and mechanical event are unlikely (MRBC, 1981). However, spring break-up can still lead to high-water-levels at these locations, as is evidenced by the 10-year H_M ' magnitude exceeding the 2.33-year H_O ' magnitude for both sites (Table 2). Further north, locations along the R_O Smoky River [7] were used by Beltaos (1983) for field verification of ice break-up theory, indicating the significance of spring break-up levels.

Given the similar upstream to downstream return-period line patterns on the Mackenzie main stem, it is interesting to note that Gerard and Calkins (1984) in discussing the site specific nature of ice break-up related water-levels noted the difference in probabilities (i.e., return-periods) for proximal sites on river systems. Two factors may explain the similarities identified in this study: The WSC generally selects straight river channel sections, devoid of any major obstacle for locating hydrometric stations (Prowse, 1985). As such, the similar return-period lines may reflect the similar morphologies at these sites. Additionally, Mackay and Mackay (1977) note that on the Mackenzie, during large ice-jam years, jamming is less common, however when jamming occurs it does so at higher magnitudes. As such, on the Mackenzie main stem, it is the low frequency, high magnitude events, which likely define the similar H_M ' return-periods.

The single R_M location, the Pembina River at Jarvie, is the second most southern site in the basin and occurs in a small ($1.31 \times 10^4 \text{ km}^2$) basin in addition it has a high elevation (619 m.a.s.l) and a relatively low gradient (0.000173). Given the unique classification of this station, further work is needed to more fully account for the occurrence of peak water-level events. Interestingly the station occurs on an agricultural watershed, and shows and obvious meandering channel.

6. CONCLUSIONS AND FUTURE RECOMMENDATIONS

This manuscript presented results of the first ever regional classification of river ice break-up regimes. Using archived water-level data at 28 Water Survey of Canada hydrometric stations in the Mackenzie River basin, return-period event magnitudes, for both maximum instantaneous water-levels during break-up, and maximum open water

periods, were determined. The relative importance of high-water events at each site was assessed at the 2, 2.33, 5, 10, 15, 20, 25, and 30-year return-periods.

In total, nearly half, 13 of the 28, sites were classified as *spring break-up regime dominated* (R_B), while 14 of the 28 sites were classified as *open-water season regime dominated* (R_O). At one location the dominance of high-water-levels was not clear, it was classified as *mixed break-up/open-water regime* (R_M). Further distinction of the R_B and R_O return-period lines identified diverging, converging and parallel alignments which are likely a result of local channel morphology. Using the magnitude of the 2.33-year mean annual open-water events as a baseline, it was found that the magnitude of the 2.33-year spring break-up event at all R_B locations exceeded that of the former. At the R_O locations, exceedence of the 2.33-year open-water event varied from station to station. In assessing the difference in the magnitude of the 2 and 10-year events, it was found that 70% of the stations in the basin experience greater water-level differences during the spring break-up period.

A dimensionless stage versus discharge plot was used to compare mean spring break-up and open-water magnitudes at the R_B and R_O sites. It was found that spring break-up effects are evident even at R_O sites, while a flow equivalent to only $\frac{1}{4}$ of the open-water discharge will produce an equivalent water-level during spring break-up. At the extreme end, an equivalent discharge will produce an approximate 60% increase in water-level during the spring break-up.

The spatial arrangement of the different regimes in the MRB was described using several physical, hydraulic and climatic characteristics. R_O locations tend to be concentrated in the south and western portions of the basin corresponding to the Western

Cordillera and upper Interior Plateau region while R_B sites occur on the Interior Plateau and northern portions of the basin. Basin area, commonly used as an indicator of flood potential, is shown to be independent of peak water-levels at R_B sites. In comparing the elevation of sites, it is determined that lower-elevation R_B sites in the basin are likely subject to more mechanical break-up events due to radiation cooling and warming effects on snowmelt. Examination of stream order indicates that on northward flowing river systems, the significance of ice in controlling peak annual water-levels increases with higher order (downstream) reaches. Another important factor in the regime classification was found to be channel slope, which is known to affect ice break-up progression. In general low (high) slope meandering (straight) reaches are typical of the R_B (R_O) regime due to the likely occurrence of mechanical (thermal) events. Finally, the importance of flow direction relative to atmospheric warming and local factors such as channel morphology were also found to be important controls on return period line patterns and resultant regime classifications.

In conclusion, the results of this study provide a spatial framework of the importance of ice-affected water-levels in a cold-regions watershed, and provide some first order physical explanations for the return-period line patterns observed. Based on the results of this manuscript, several recommendations for future research are provided below:

- (1) In the initial extraction phase of the project, the limiting nature of hydrometric information during the break-up period became evident. The major cause of this is instrument malfunction. Given the importance of spring break-up water-levels in the basin, it is recommended that an increased focus be placed on the collection of information during this period. This would include visual observation by field crews

during break-up, and research, design and investment in more resilient equipment. It is encouraging to note that as of 2002, the WSC began publishing maximum water-level data for several northern locations.

(2) The spatial distribution and major controls of high-water events in the MRB have been described. However, only a limited number of hydrometric sites were used for this assessment. It is recommended that ice and open-water return-periods be determined for other sites in the basin and this type of assessment be expanded to the national and international scale.

(3) It is recommended that physical factors discussed in this manuscript, along with other potentially significant variables (i.e., permafrost, landcover, aspect, soil type, gridded climate data) be used in a multivariate analysis to quantitatively determine the major controls on high-water events of the MRB and other cold-region areas.

(4) The major assumption in this return-period assessment is a stationary climate. Given recent work indicating changes in temperature in the MRB (e.g., Serreze *et al.*, 2000; Zhang *et al.*, 2000) and climate variability in the northern hemisphere (e.g., Bonsal and Prowse, 2003) it is recommended that the changes of the timing of the spring and summer events be assessed to address flood event severity.

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Table 1. Return-period assessment results for 28 Water Survey of Canada hydrometric stations in the MRB. Columns ‘ H_M ’ and ‘ H_O ’ show total years of data assessed for determination of return periods. Columns labeled ‘x-year’ (i.e., ‘x’ is 2, 2.33, 5-year etc.) denote H_M/H_O values (m) and the ratios. Dominant Regime and Return-Period Line Classification also included.

Table 2. Return-period assessment results for 28 Water Survey of Canada hydrometric stations in the MRB. Table shows return-period line classification, return-period (H_M^{Event}) and water-level difference ($\Delta H_{2.33}$ (m)) by which 2.33-year H_O event is exceeded by. Also shown is difference in water-level (m) between the 2 and 10-year H_M and H_O events, and denoted is events during which difference is greater in ‘greater’ column.

Table 3. Physical characteristics for 28 Water Survey of Canada hydrometric stations in the MRB and regime classification. Column 1, ID, are shown on Figure 6.

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Figure 1. The Mackenzie River basin, Canada with locations of hydrometric stations used in this study.

Figure 2. Temporal records for 28 Water Survey of Canada hydrometric stations in the Mackenzie River basin. Grey denotes spring break-up events, black denotes open-water events.

Figure 3. Schematic of instantaneous water-level (stage) pen recorder chart during spring break-up period (after Beltaos, 1990). H_M denotes maximum instantaneous water-level during the period.

Figure 4a-4g. Sample return-period plots regimes for the 7 return-period line classifications identified at Water Survey of Canada hydrometric stations in the MRB. Plots show data quality rating (0-2) where applicable. (a) spring break-up – diverging (R_B^D) (b) spring break-up – converging (R_B^C) (c) spring break-up – parallel (R_B^P) (d) open water – diverging (R_O^D) (e) open water – converging (R_O^C) (f) open water – parallel (R_O^P) (g) mixed. (R_M)

Figure 5. Synthetic discharge ($\overline{Q_I} / \overline{Q_O}$) versus stage ($\overline{H_I} / \overline{H_O}$) curve for the 28 Water Survey of Canada hydrometric stations in the MRB. Dominant regime classification is incorporated on the plot.

Figure 6. Map of dominant regime classifications for the 28 Water Survey of Canada hydrometric stations in the MRB. Numbers relate to ‘ID’ column included in Table 3.

Table 1

NAME	H ₀	H ₁	2-year	2.33-year	5-year	10-year	15-year	20-year	25-year	30-year	Dominant Regime	Return-Period Line Classification							
ATHABASCA RIVER BELOW MCMURRAY	32	43	4.73 / 4.11	1.15	5.02 / 4.33	1.16	6.31 / 5.17	1.22	7.89 / 5.60	1.41	8.41 / 5.65	1.49	8.74 / 5.97	1.47	9.04 / 6.08	1.49	9.28 / 6.10	1.52	R ₀
HAY RIVER NEAR HAY RIVER	35	39	7.41 / 5.15	1.44	7.99 / 5.31	1.50	8.59 / 5.92	1.45	9.68 / 6.53	1.48	10.08 / 6.59	1.53	10.42 / 6.62	1.58	10.47 / 6.68	1.57	10.51 / 6.73	1.56	R ₀ ^D
BUFFALO RIVER AT HIGHWAY NO.5	12	22	3.62 / 3.34	1.08	3.83 / 3.44	1.11	4.19 / 3.69	1.13	5.82 / 3.84	1.52	- / 3.90	-	- / 3.94	-	- / -	-	- / -	-	R ₀ ^D
LIARD RIVER AT FORT LIARD	32	55	7.91 / 7.49	1.06	8.24 / 7.75	1.06	9.31 / 8.51	1.09	10.49 / 9.39	1.12	11.37 / 9.58	1.19	11.88 / 9.69	1.23	12.24 / 10.00	1.22	12.54 / 10.14	1.24	R ₀ ^D
LIARD RIVER NEAR THE MOUTH	27	29	9.54 / 6.64	1.44	10.20 / 6.99	1.46	12.17 / 7.75	1.57	14.06 / 8.21	1.71	14.44 / 8.62	1.68	14.83 / 8.67	1.71	15.11 / 8.69	1.74	- / 8.71	-	R ₀ ^D
MACKENZIE RIVER AT FORT SIMPSON	36	60	11.09 / 7.80	1.39	11.30 / 8.09	1.40	13.24 / 8.80	1.50	14.35 / 9.22	1.56	14.73 / 9.50	1.55	14.97 / 9.49	1.58	15.01 / 9.66	1.55	15.05 / 9.81	1.53	R ₀ ^D
MACKENZIE RIVER AT NORMAN WELLS	24	29	11.10 / 7.14	1.55	12.17 / 7.19	1.69	13.45 / 7.53	1.79	15.23 / 7.78	1.96	16.74 / 8.05	2.08	17.24 / 8.26	2.09	17.62 / 8.42	2.09	- / 8.55	-	R ₀ ^D
MACKENZIE RIVER AT ARCTIC RED RIVER	26	33	6.58 / 5.51	1.19	6.66 / 5.76	1.16	7.39 / 6.67	1.11	8.22 / 6.98	1.18	9.17 / 7.74	1.18	9.43 / 8.64	1.09	9.63 / 9.55	1.01	- / 10.12	-	R ₀ ^C
ARCTIC RED RIVER NEAR THE MOUTH	31	31	9.28 / 8.73	1.06	9.46 / 8.76	1.08	10.78 / 9.77	1.10	13.24 / 11.97	1.11	13.86 / 12.79	1.08	14.59 / 13.22	1.10	14.97 / 13.54	1.11	15.01 / 14.82	1.01	R ₀ ^P
PEACE RIVER AT PEACE RIVER	28	30	9.67 / 8.17	1.18	9.95 / 8.90	1.12	12.08 / 9.32	1.27	13.21 / 10.29	1.28	13.53 / 10.40	1.30	13.60 / 10.78	1.26	13.66 / 11.09	1.23	13.70 / 11.36	1.21	R ₀ ^P
PEACE RIVER AT PEACE POINT (ALBERTA)	30	32	3.52 / 3.41	1.03	3.82 / 3.56	1.07	4.56 / 3.56	1.04	6.01 / 4.96	1.21	6.35 / 5.51	1.15	6.72 / 5.81	1.16	7.04 / 5.98	1.18	7.29 / 6.11	1.19	R ₀ ^P
WABASCA RIVER AT WADLIN LAKE ROAD	31	29	11.58 / 9.36	1.24	11.96 / 9.53	1.26	13.02 / 10.38	1.25	13.92 / 11.22	1.24	14.10 / 11.59	1.22	14.56 / 12.09	1.20	15.00 / 12.48	1.20	15.35 / 12.80	1.20	R ₀ ^P
PEEL RIVER ABOVE FORT MCPHERSON																			
WAPITI RIVER NEAR GRANDE PRAIRIE	36	42	2.41 / 3.21	0.74	2.10 / 3.41	0.62	2.79 / 4.32	0.65	3.04 / 6.02	0.50	3.21 / 8.36	0.38	3.26 / 8.87	0.37	3.31 / 9.121	0.36	3.34 / 9.29	0.36	R ₀ ^D
SMOKY RIVER AT WATINO	45	48	4.22 / 4.64	0.90	4.39 / 5.01	0.88	5.17 / 6.77	0.77	4.99 / 7.59	0.72	5.72 / 9.47	0.60	5.88 / 10.08	0.58	6.02 / 10.14	0.59	6.13 / 10.19	0.60	R ₀ ^D
LIARD RIVER AT UPPER CROSSING	22	43	2.76 / 3.34	0.83	2.99 / 5.53	0.54	3.45 / 6.01	0.57	3.55 / 6.57	0.54	3.65 / 6.61	0.55	3.76 / 6.61	0.57	- / 6.65	-	- / 6.70	-	R ₀ ^D
ATHABASCA RIVER NEAR WINDFALL	31	34	2.51 / 3.50	0.72	2.64 / 3.59	0.73	3.08 / 4.03	0.76	3.66 / 4.36	0.84	3.76 / 4.40	0.85	3.93 / 4.45	0.88	4.07 / 4.48	0.91	4.18 / 4.51	0.93	R ₀ ^D
ATHABASCA RIVER AT ATHABASCA	78	83	2.58 / 3.77	0.68	2.71 / 3.96	0.68	3.86 / 4.81	0.80	4.51 / 5.71	0.79	4.67 / 6.12	0.76	4.73 / 6.37	0.74	4.88 / 6.42	0.76	4.95 / 6.59	0.75	R ₀ ^C
LITTLE SMOKY RIVER NEAR GUY	41	42	3.98 / 4.85	0.82	4.25 / 5.02	0.85	4.93 / 5.53	0.89	5.01 / 5.78	0.87	5.73 / 5.87	0.98	5.82 / 6.05	0.96	6.19 / 6.33	0.98	6.55 / 6.61	0.99	R ₀ ^C
KECHIKA RIVER AT THE MOUTH	19	23	2.33 / 3.75	0.62	2.36 / 3.90	0.60	3.36 / 4.41	0.81	4.23 / 4.45	0.95	4.45 / 4.62	0.96	4.61 / 4.67	0.99	- / 4.71	-	- / 4.75	-	R ₀ ^C
KECHIKA RIVER ABOVE BOYA CREEK	21	27	0.98 / 3.51	0.28	1.04 / 3.61	0.29	1.41 / 3.82	0.37	1.72 / 3.99	0.43	1.91 / 4.17	0.46	1.98 / 4.24	0.47	- / 4.29	-	- / -	-	R ₀ ^C
FORT NELSON RIVER ABOVE MUSKWA RIVER	11	23	2.62 / 5.34	0.49	2.83 / 5.75	0.49	3.99 / 6.23	0.64	4.86 / 7.72	0.63	- / 9.40	-	- / 10.43	-	-	-	- / -	-	R ₀ ^C
MUSKWA RIVER NEAR FORT NELSON	23	55	1.79 / 4.95	0.36	1.88 / 5.22	0.36	3.50 / 6.82	0.51	4.40 / 8.09	0.54	5.04 / 9.46	0.53	5.67 / 9.69	0.59	- / 9.72	-	- / 9.82	-	R ₀ ^P
FRANCES RIVER NEAR WATSON LAKE	31	39	1.75 / 3.75	0.57	1.84 / 3.12	0.59	2.17 / 3.30	0.66	2.36 / 3.44	0.69	2.41 / 3.70	0.65	2.42 / 3.73	0.65	2.42 / 3.76	0.64	2.42 / 3.78	0.64	R ₀ ^P
LIARD RIVER AT LOWER CROSSING	34	56	10.63 / 13.37	0.80	10.72 / 13.43	0.80	11.31 / 13.90	0.81	11.87 / 12.46	0.82	12.15 / 14.87	0.82	12.33 / 14.87	0.83	12.50 / 14.87	0.84	12.65 / 14.91	0.85	R ₀ ^P
LIARD RIVER ABOVE BEAVER RIVER	18	24	9.18 / 11.04	0.83	9.36 / 11.23	0.83	10.38 / 12.01	0.86	10.80 / 12.46	0.87	10.99 / 12.70	0.87	- / 12.79	-	- / 12.87	-	- / -	-	R ₀ ^P
LIARD RIVER ABOVE KECHIKA RIVER	18	26	21.43 / 23.49	0.91	21.71 / 23.55	0.92	22.36 / 23.90	0.94	22.69 / 24.54	0.92	22.83 / 24.67	0.93	- / 24.81	-	- / 12.87	-	- / -	-	R ₀ ^P
PEMBINA RIVER AT JARVIE	38	44	3.70 / 3.15	1.17	3.87 / 3.40	1.14	4.68 / 4.87	0.96	5.72 / 5.44	1.05	5.75 / 5.90	0.98	5.80 / 6.89	0.84	6.04 / 7.33	0.82	6.23 / 7.37	0.85	R ₀

Table 2

NAME	Return-Period	2.33-year H_0 Exceedence		2 versus 10-year Event		
	Line Classification	H_M^1 Event	$\Delta H_{2.33}$ (m)	ΔH_M^2 (m)	ΔH_{10}^2 (m)	greater
ATHABASCA RIVER BELOW MCMURRAY	R_B^D	2	0.40	3.16	1.49	H_M
HAY RIVER NEAR HAY RIVER	R_B^D	2	2.10	2.26	1.39	H_M
BUFFALO RIVER AT HIGHWAY NO. 5	R_B^D	2	0.18	2.20	0.49	H_M
LIARD RIVER AT FORT LIARD	R_B^D	2	0.16	2.58	1.90	H_M
LIARD RIVER NEAR THE MOUTH	R_B^D	2	2.55	4.52	1.57	H_M
MACKENZIE RIVER AT FORT SIMPSON	R_B^D	2	3.00	3.25	1.25	H_M
MACKENZIE RIVER AT NORMAN WELLS	R_B^D	2	5.07	1.97	0.77	H_M
MACKENZIE RIVER AT ARCTIC RED RIVER	R_B^D	2	3.91	4.14	0.64	H_M
ARCTIC RED RIVER NEAR THE MOUTH	R_B^C	2	0.82	1.64	1.47	H_M
PEACE RIVER AT PEACE RIVER	R_B^P	2	0.52	3.96	3.24	H_M
PEACE RIVER AT PEACE POINT (ALBERTA)	R_B^P	2	0.78	3.54	2.12	H_M
WABASCA RIVER AT WADLIN LAKE ROAD	R_B^P	2.33	0.26	2.49	1.55	H_M
PEEL RIVER ABOVE FORT MCPHERSON	R_B^P	2	2.05	2.34	1.86	H_M
WAPITI RIVER NEAR GRANDE PRAIRIE	R_O^D	none	-	1.26	2.92	H_O
SMOKY RIVER AT WATINO	R_O^D	5	0.79	0.79	3.22	H_O
LIARD RIVER AT UPPER CROSSING	R_O^D	none	-	1.15	0.86	H_M
ATHABASCA RIVER NEAR WINDFALL	R_O^D	10	0.07	0.63	2.79	H_O
ATHABASCA RIVER AT ATHABASCA	R_O^C	10	0.55	1.94	1.94	H_O
LITTLE SMOKY RIVER NEAR GUY	R_O^C	15	0.76	1.03	0.93	H_M
KECHIKA RIVER AT THE MOUTH	R_O^C	none	-	1.90	0.70	H_M
KECHIKA RIVER ABOVE BOYA CREEK	R_O^C	none	-	0.75	0.48	H_M
FORT NELSON RIVER ABOVE MUSKWA RIVER	R_O^C	none	-	2.24	2.37	H_O
MUSKWA RIVER NEAR FORT NELSON	R_O^P	20	0.46	1.26	1.06	H_M
FRANCES RIVER NEAR WATSON LAKE	R_O^P	none	-	2.61	3.14	H_O
LIARD RIVER AT LOWER CROSSING	R_O^P	none	-	0.61	0.39	H_M
LIARD RIVER ABOVE BEAVER RIVER	R_O^P	none	-	1.23	1.13	H_M
LIARD RIVER ABOVE KECHIKA RIVER	R_O^P	none	-	1.61	1.42	H_M
PEMBINA RIVER AT JARVIE	R_M	2	0.27	2.02	2.28	H_O

Table 3

ID	Station Name	Latitude (N)	Longitude (W)	Area (km ²)	Elevation (m.a.s.l)	Strahler order	Gradient	Flow Direction	Regime
4	ATHABASCA RIVER BELOW MCMURRAY	56°46'50"	111°24'0"	133000	255	4	0.000185	NW	R_B^D
11	HAY RIVER NEAR HAY RIVER	60°44'35"	115°51'34"	47900	156	3	0.000558	N	R_B^D
12	BUFFALO RIVER AT HIGHWAY NO. 5	60°42'44"	114°54'11"	18500	163	3	0.000313	N	R_B^D
22	LIARD RIVER AT FORT LIARD	60°14'26"	123°28'32"	222000	220	5	0.000178	N	R_B^D
23	LIARD RIVER NEAR THE MOUTH	61°44'34"	121°13'41"	275000	152	5	0.000398	N	R_B^D
24	MACKENZIE RIVER AT FORT SIMPSON	61°52'7"	121°21'25"	1270000	133	6	0.000203	NE	R_B^D
25	MACKENZIE RIVER AT NORMAN WELLS	65°16'18"	126°50'48"	1570000	22	6	0.000063	NE	R_B^D
27	MACKENZIE RIVER AT ARCTIC RED RIVER	67°27'22"	133°44'13"	1680000	11	6	0.000077	N	R_B^D
26	ARCTIC RED RIVER NEAR THE MOUTH	66°47'24"	133°4'54"	18600	67	3	0.000124	N	R_B^C
8	PEACE RIVER AT PEACE RIVER	56°14'41"	117°18'46"	186000	350	4	0.000245	N	R_B^P
10	PEACE RIVER AT PEACE POINT (ALBERTA)	59°7'2"	112°26'13"	293000	217	4	0.000066	E	R_B^P
9	WABASCA RIVER AT WADLIN LAKE ROAD	57°52'30"	115°23'20"	35800	312	3	0.001186	N	R_B^P
28	PEEL RIVER ABOVE FORT MCPHERSON	67°14'33"	134°53'20"	70600	91	2	0.000321	N	R_B^P
5	WAPITI RIVER NEAR GRANDE PRAIRIE	55°4'20"	118°48'10"	11300	579	3	0.000578	E	R_O^D
7	SMOKY RIVER AT WATINO	55°42'56"	117°37'19"	50300	441	3	0.001379	N	R_O^D
13	LIARD RIVER AT UPPER CROSSING	60°3'0"	128°54'0"	33400	609	3	0.000686	S	R_O^D
1	ATHABASCA RIVER NEAR WINDFALL	54°12'25"	116°3'45"	19600	739	3	0.001438	E	R_O^D
3	ATHABASCA RIVER AT ATHABASCA	54°43'20"	113°17'10"	74600	570	3	0.00022	E	R_O^C
6	LITTLE SMOKY RIVER NEAR GUY	55°27'25"	117°9'40"	11100	503	2	0.002029	NNE	R_O^C
15	KECHIKA RIVER AT THE MOUTH	59°36'55"	127°18'37"	22700	598	3	0.000333	N	R_O^C
16	KECHIKA RIVER ABOVE BOYA CREEK	59°5'54"	127°32'2"	11200	599	2	0.000605	N	R_O^C
20	FORT NELSON RIVER ABOVE MUSKWA RIVER	58°40'15"	122°38'15"	22800	322	2	0.002164	N	R_O^C
21	MUSKWA RIVER NEAR FORT NELSON	58°47'18"	122°39'33"	20300	322	2	0.001372	NE	R_O^P
14	FRANCES RIVER NEAR WATSON LAKE	60°28'26"	129°7'8"	12800	670	2	0.001965	SE	R_O^P
17	LIARD RIVER AT LOWER CROSSING	59°24'45"	126°5'50"	104000	564	4	0	ESE	R_O^P
18	LIARD RIVER ABOVE BEAVER RIVER	59°44'33"	124°28'35"	119000	290	4	0.004967	E	R_O^P
19	LIARD RIVER ABOVE KECHIKA RIVER	59°42'4"	127°13'39"	61600	566	3	0.000143	ESE	R_O^P
2	PEMBINA RIVER AT JARVIE	54°27'5"	113°59'30"	13100	619	2	0.000173	N	R_M

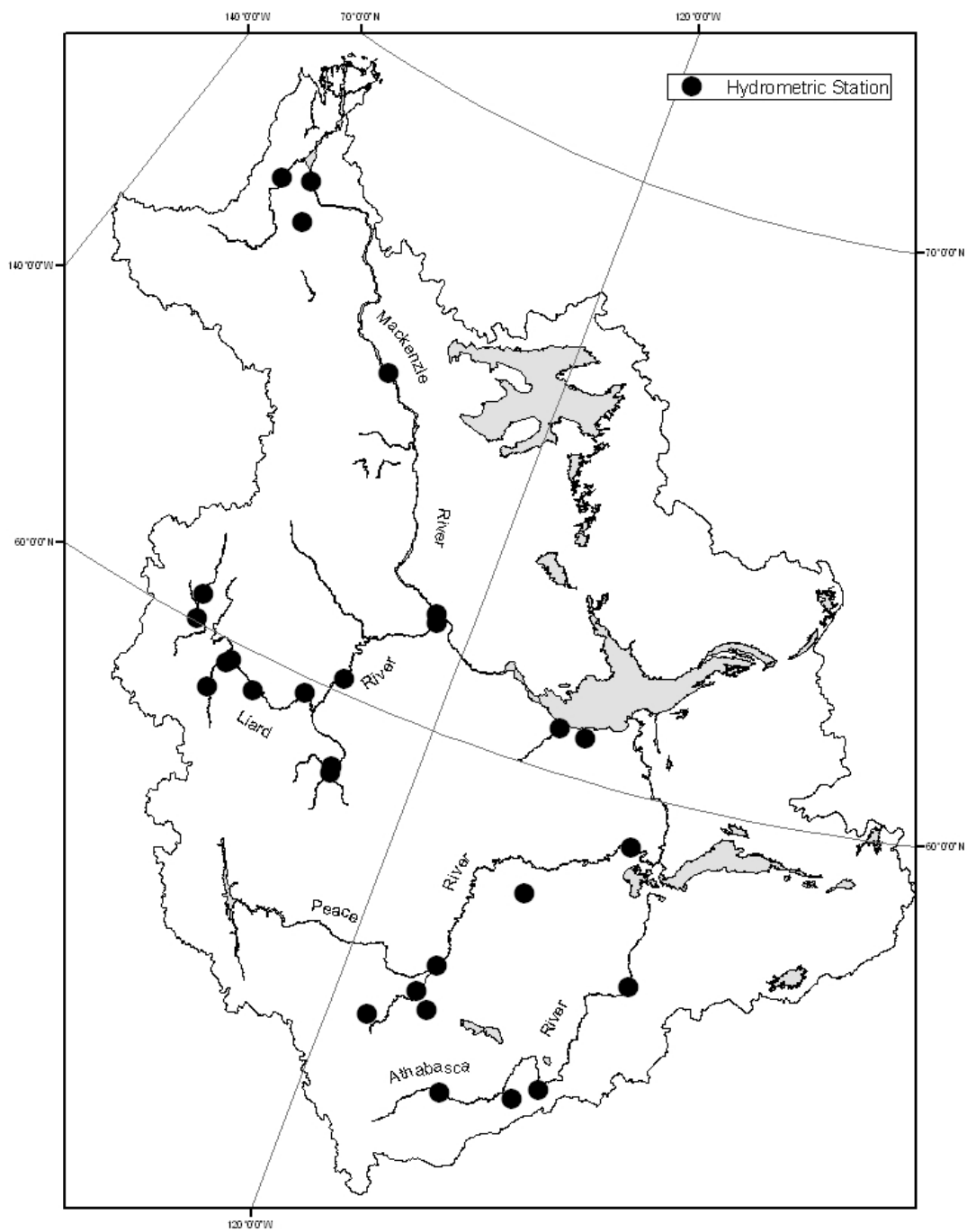


Figure 1

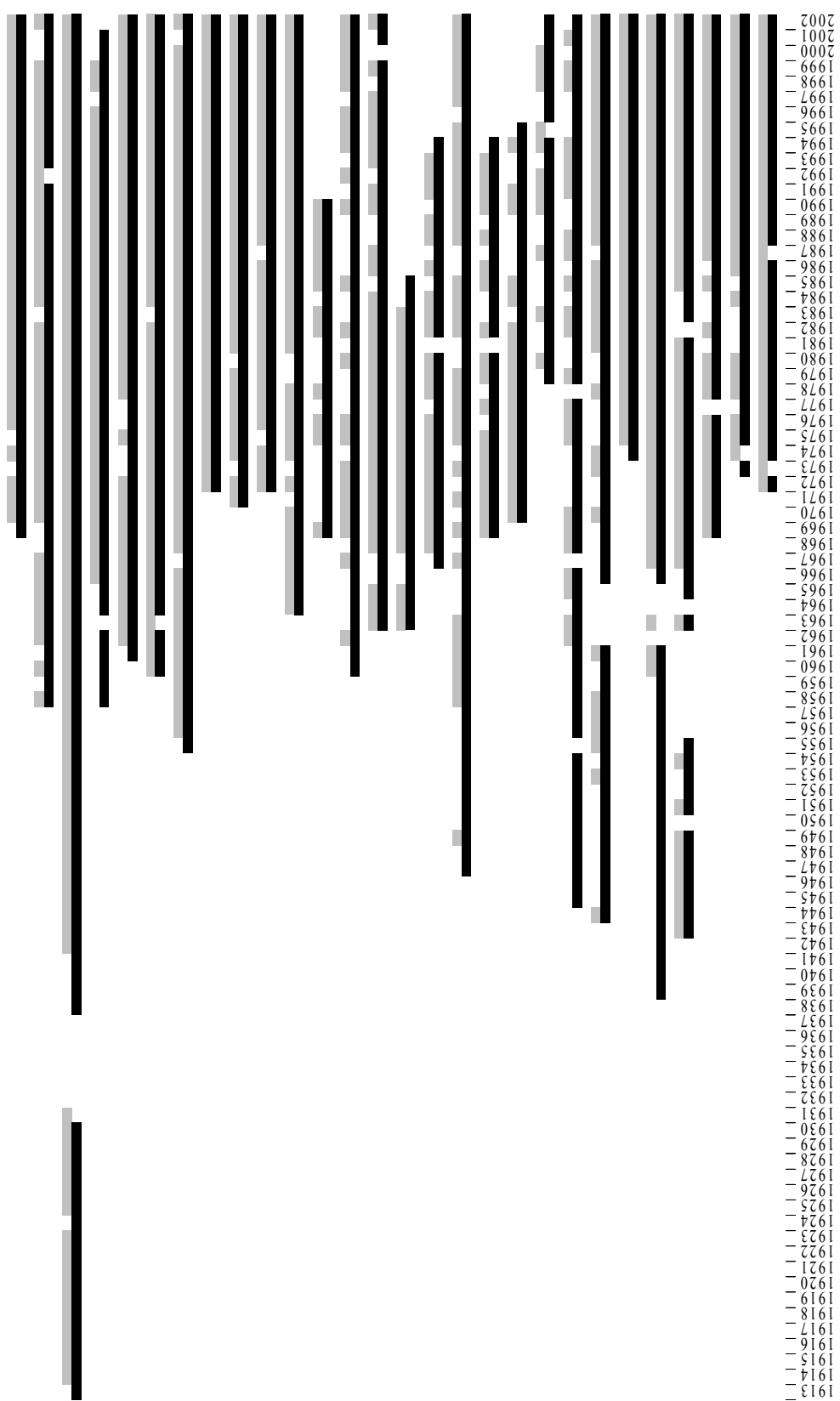


Figure 2

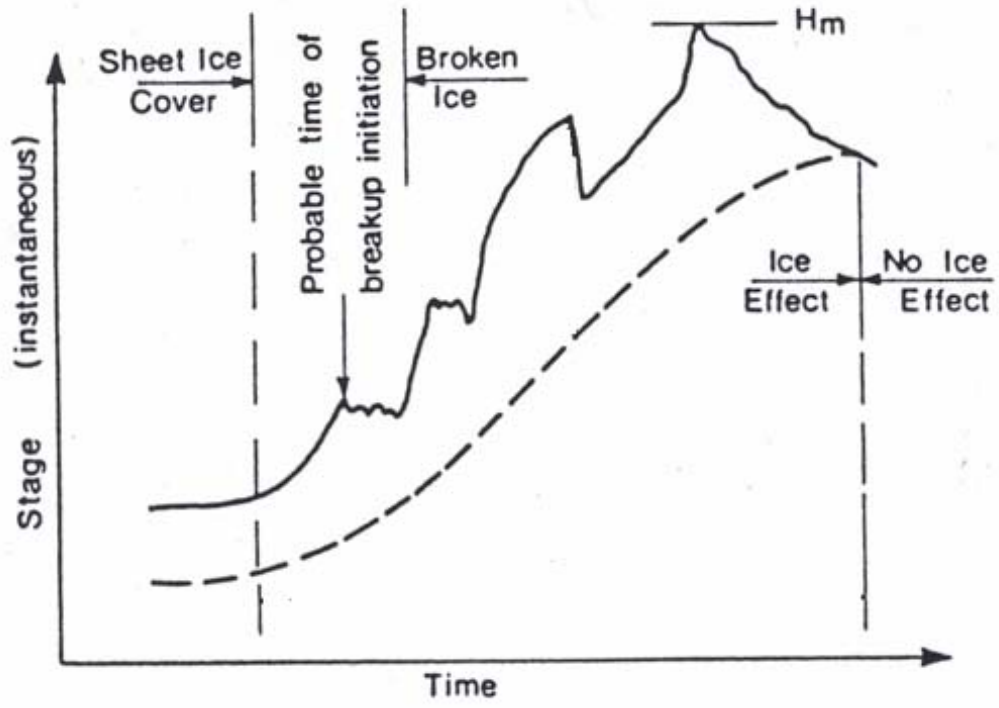


Figure 3

a) Liard River near the Mouth

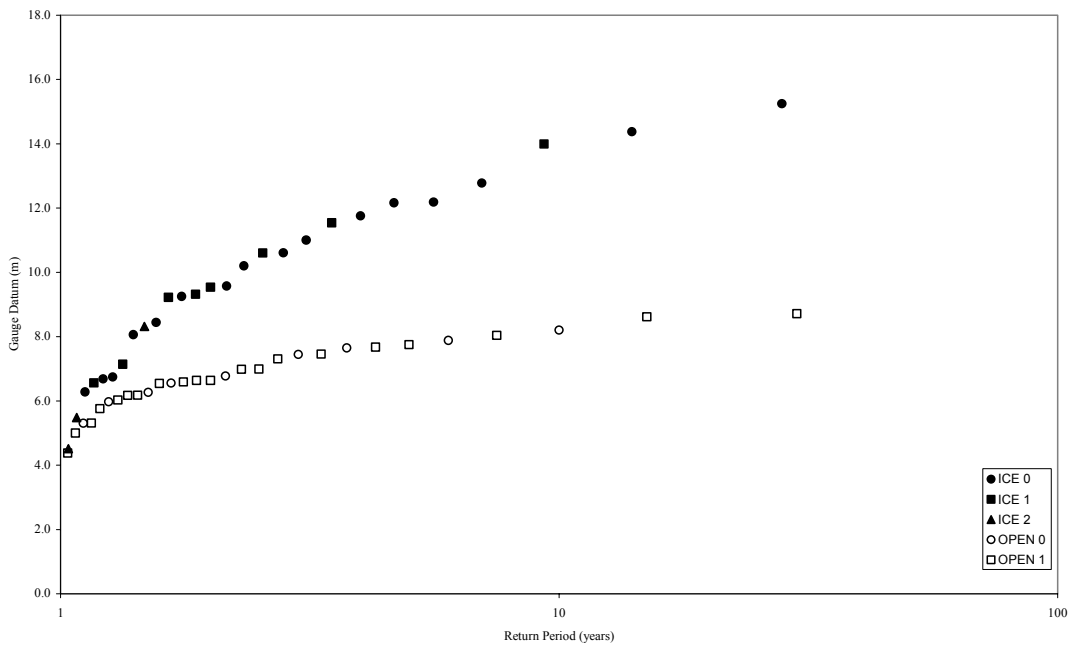


Figure 4a

b) Arctic Red River near the Mouth

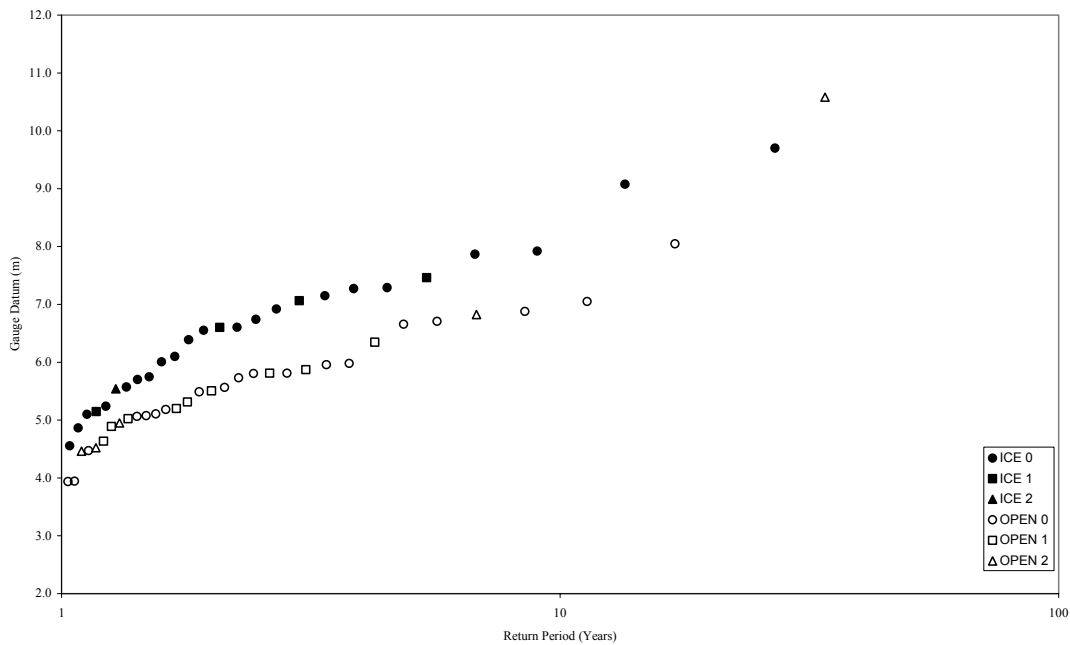


Figure 4b

c) Peace River at Peace Point

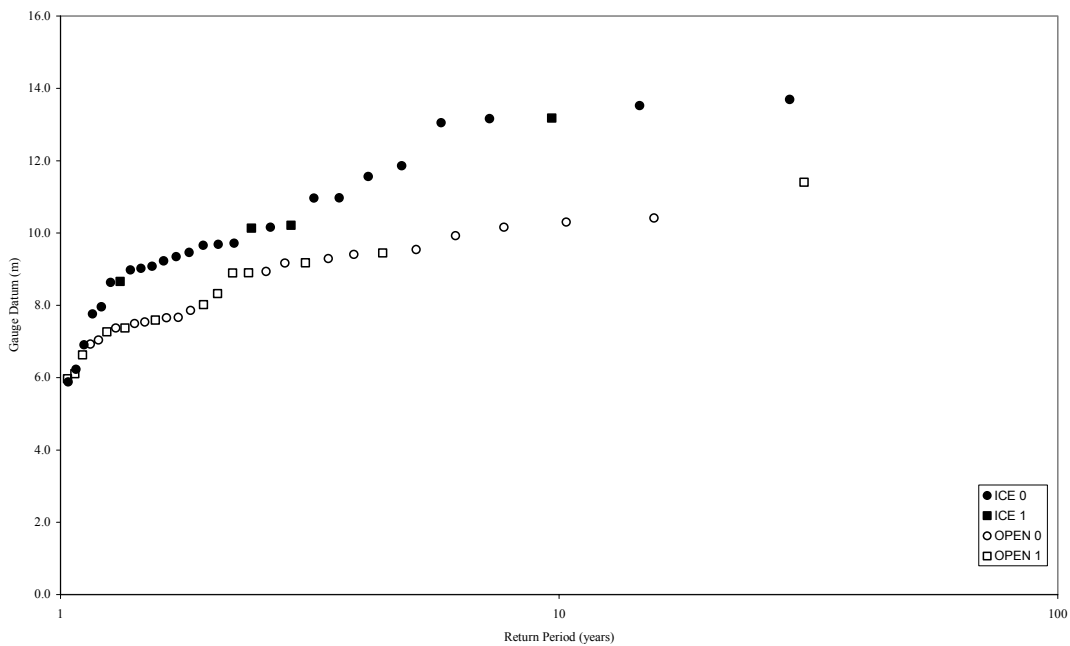


Figure 4c

d) Wapati River near Grand Prairie

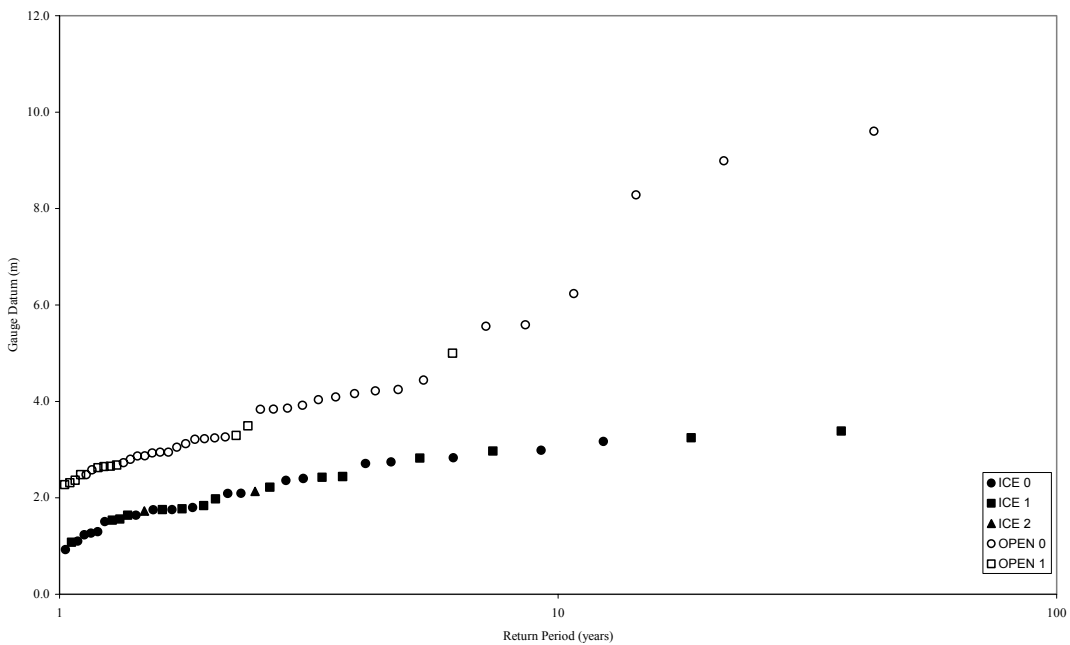


Figure 4d

e) Kechika River at the Mouth

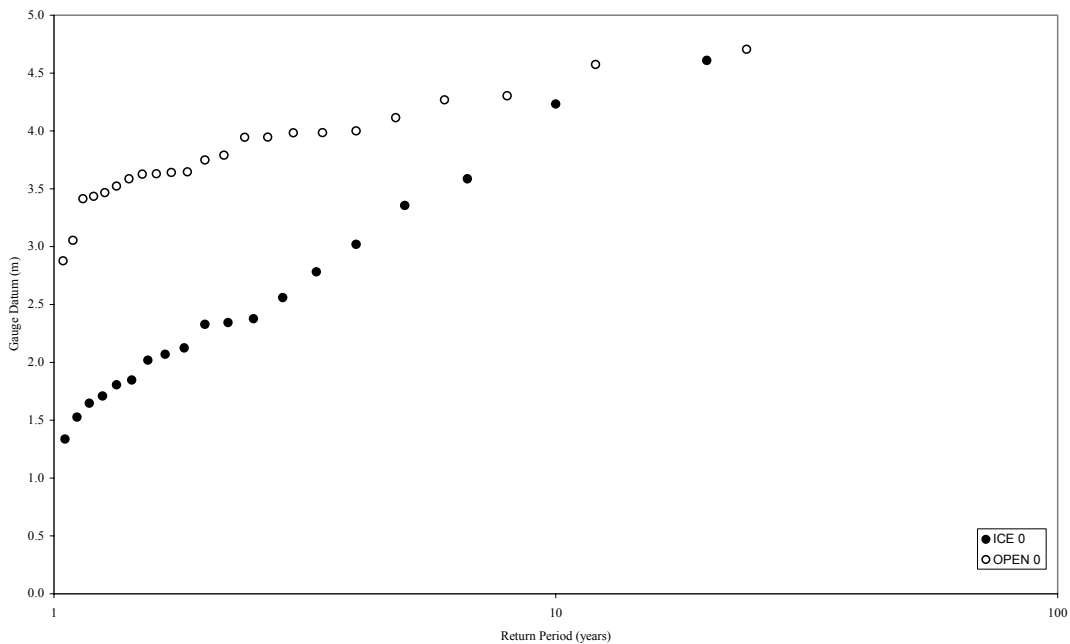


Figure 4e

f) Frances River near Watson Lake

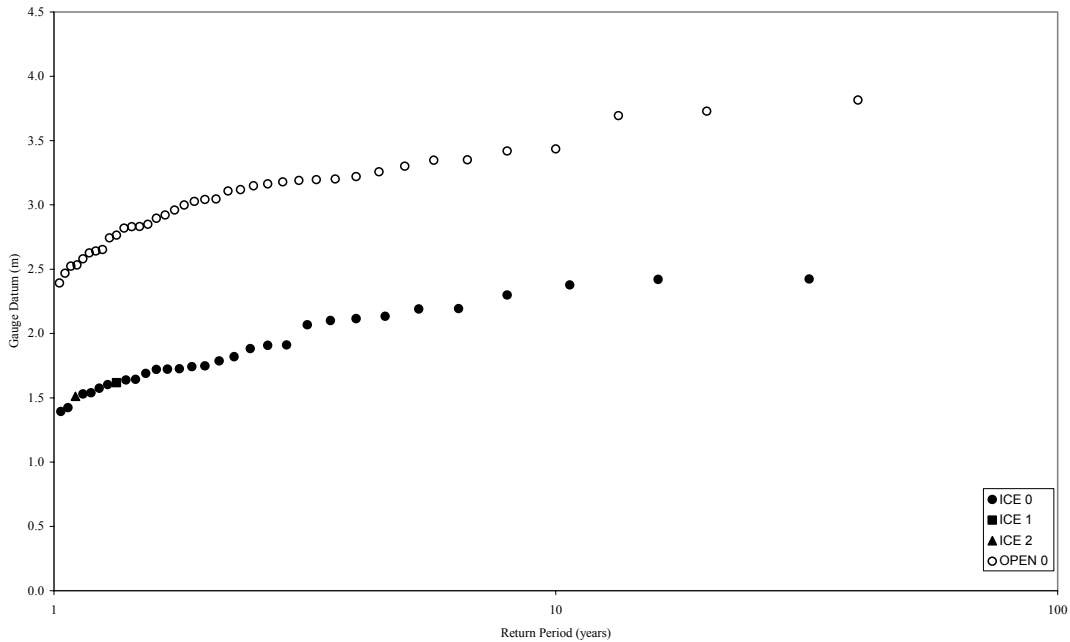


Figure 4f

g) Pembina River at Jarvie

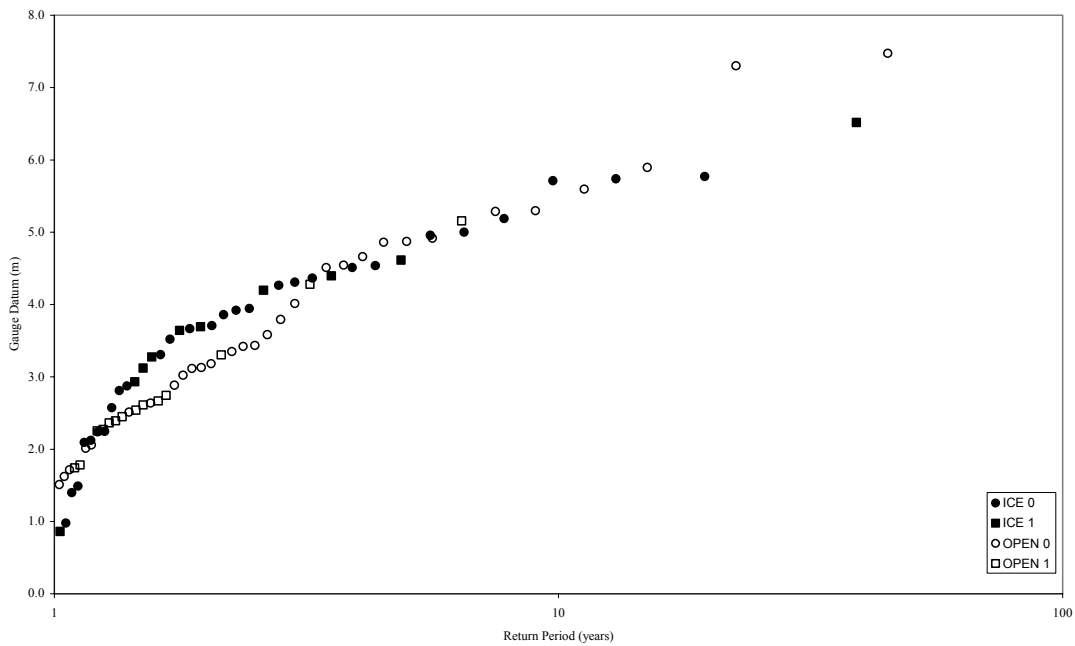


Figure 4g

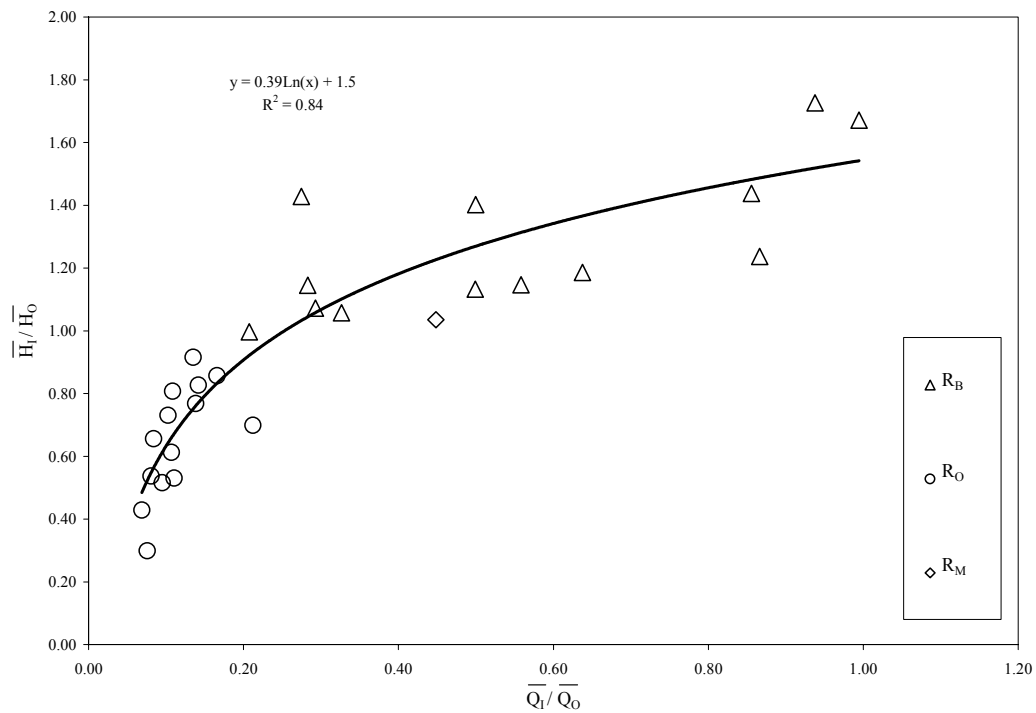


Figure 5

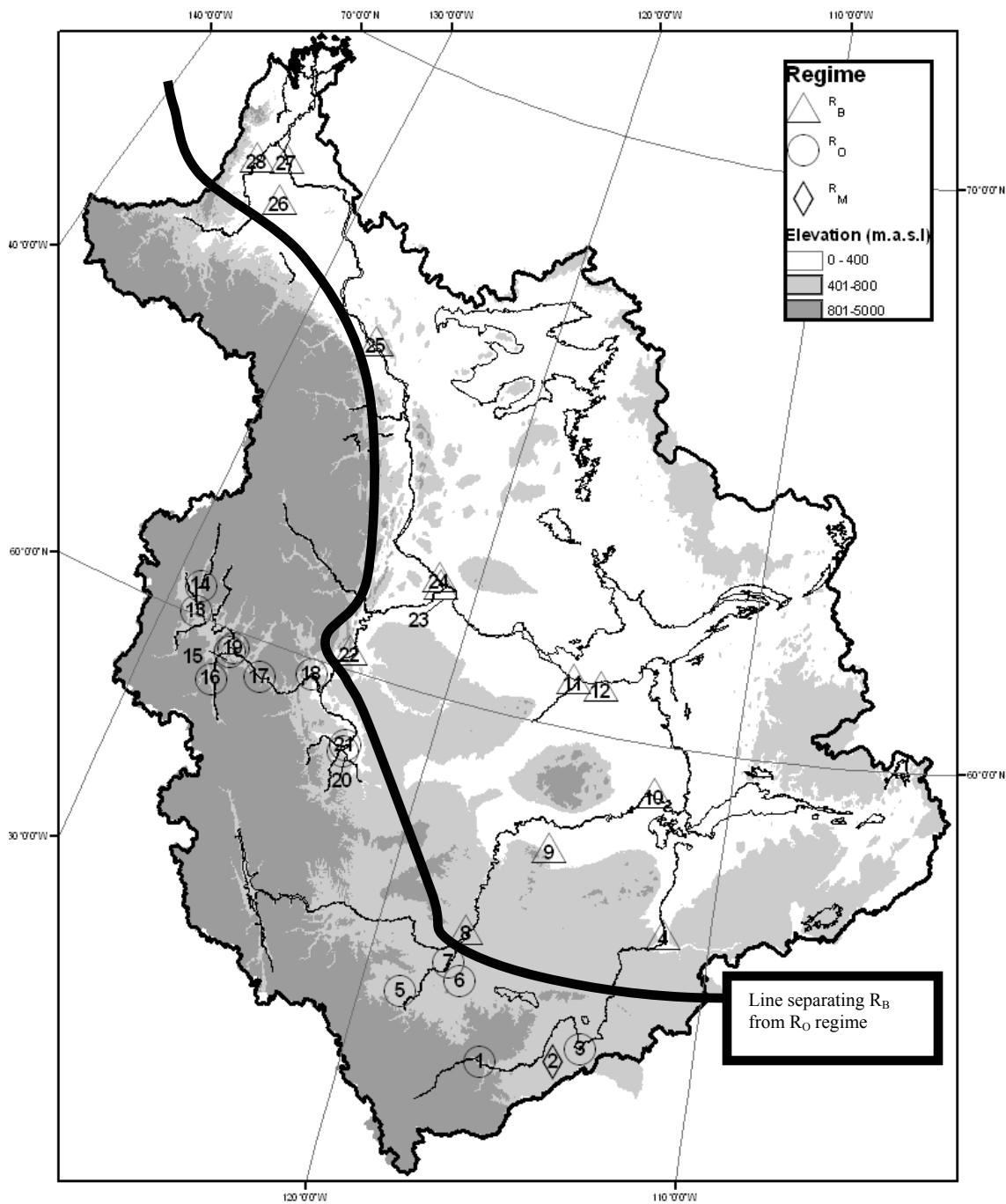


Figure 6

CHAPTER 3: TEMPORAL VARIATIONS IN RIVER-ICE BREAK-UP: THE MACKENZIE RIVER, CANADA

ABSTRACT

Climatic conditions are known to affect the development, growth and eventual decay of ice on cold-regions rivers systems. Several recent international reviews (e.g., IPCC, 2001; ACIA, 2005) have outlined that global climate may be changing. Of particular concern, are northern and arctic regions, where the spring break-up period is known to have important socio-economic, ecological and morphological effects. While the effects of break-up are reasonably well known, changes in timing and its effects on both the severity and unpredictability of events remain relatively unknown. To assess break-up timing, the Mackenzie River basin is selected as a test watershed in which to perform a baseline temporal assessment (1913-2002) of the springtime river-ice break-up season. Data employed includes the commonly assessed 'Last B date' and two hydrometric variables extracted directly from original Water Survey of Canada water-level recording charts, the timing of the: initiation of break-up (H_B) and the peak water-level during break-up (H_M). It is found that extracted variables provide a physically based, quantitative description of the break-up season in the MRB compared to the more commonly used 'Last B date' method. The northwards progressing ice break-up season, lasting on average ~ 8 weeks covers a period representative of $\sim 1/4$ of the year. An anomalously early zone of the spring break-up timing is located in the upper Peace and Athabasca region. Finally, the Mann-Kendall test for trend reveals a significantly earlier timing of the spring break-up events (~ 3 days/decade) in the upstream portions of the

major tributaries of the MRB. This shift, towards earlier events, agrees with previous work on other hydrological variables in the basin.

Keywords: River Ice Break-up, Mann-Kendall, Mackenzie River basin, climate change

1. INTRODUCTION

Climatic conditions are known to affect the development, growth and eventual decay of ice on cold-regions rivers systems. Several recent international reviews (e.g., IPCC, 2001; ACIA, 2005) have outlined that global climate may be changing. Of particular concern are northern regions where the spring break-up period is known to have important socio-economic, ecological and morphological effects.

Canadian estimates indicate that annual damage resulting from the ice break-up period exceed \$60 million (CDN) per year (Gerard and Davar, 1995), while the cost of a single break-up season in Eastern Russia in 2001 exceeded \$100 million (USD) (Brakenridge *et al.*, 2006). Although air transportation is currently ubiquitous in most northern regions, disruptions to land transport during the spring break-up still represents a major inconvenience to many communities, industries and individuals. Transportation costs, particularly for areas dependent on river transportation are increased during this period (USACE, 2002).

The spring break-up also represents a critical period for river ecology (Prowse and Culp, 2003). Effects include: physical disturbance to vegetation (Cameron and Lambert, 1971), damage to fish spawning grounds (Cunjak *et al.*, 1998), and the flooding of freshwater riparian environments including deltas (Lesack *et al.*, 1991; Marsh, 1986; Prowse *et al.*, 2006). The action of river-ice is also recognized as an important morphological agent on cold-regions river systems. During the break-up, order of magnitude increases in sediment concentrations have been reported (Beltaos *et al.*, 1994)

while distinctive erosion and deposition processes (see MacKay and MacKay, 1977; Church *et al.*, 1997; Prowse, 2006) are unique to this period of the year.

While the effects of the break-up period are well known, changes in its timing and duration, and the subsequent effects on both the severity and unpredictability of events are not well understood (Beltaos and Prowse, 2001). A region of particular concern is the Mackenzie River basin (MRB), Canada's largest cold-regions river basin which has been recognized as region of climatic warming with alterations to precipitation patterns over the latter half of the 20th century (MRBB, 2003). While changes and alterations to the timing and duration of the spring break-up period remain largely unknown for the basin, changes in the timing of numerous other hydrological variables at the Pan-Arctic scale (e.g., Magnusson *et al.*, 2000), across Canada (e.g., Zhang *et al.*, 2000) and within the MRB (e.g., Aziz and Burn 2005) indicate that a contemporary climate-change signal may already be occurring.

2. CLIMATIC TRENDS AND RIVER-ICE BREAK-UP

Freshwater ice break-up is widely acknowledged to be closely linked to climatic conditions. Previous studies have shown that, air temperature is the dominant control of the timing on lake ice break-up (see Palecki and Barry, 1986; Robertson *et al.*, 1992) and is an important factor in the river-ice break-up process (Brimley and Freeman, 1997; Duguay *et al.*, 2006; Magnusson *et al.*, 2000; Zhang *et al.*, 2001; Smith, 2000; Soldatova, 1993). As temperatures increase above 0°C the melting of channel ice and snowmelt result in the commencement of the ice break-up season.

Several analyses of river break-up dates have been conducted for regions of the circumpolar north. Magnusson *et al.* (2000) identified earlier events (6 d/100 yr) for river and lakes over the past 150 yrs, while Smith (2000) assessed several break-up variables on large Russian rivers and noted a shift towards earlier melt onset, but no shift in break-up timing. Notably, the results of the latter were opposite to those of Soldatova (1993), whose study encompassed the same region. A possible explanation for this contradiction were the differing record lengths and regional focus (see Prowse and Bonsal, 2005) employed by the studies.

Past assessments of break-up patterns across Canada indicated a distinct south to north pattern, concurrent with the timing of the 0°C isotherm (Allen, 1978). In a contemporary study, regional patterns in the 1961-1990 0°C isotherm timing were found to be likely caused by climatic contrasts in land and ocean thermal effects while earlier occurrences were identified over regions of western and northern Canada (Bonsal and Prowse, 2003). Zhang *et al.* (2001) assessed the timing of the end of break-up season across Canada for the 1947-1996 and 1957-1996 time periods. Significantly earlier break-up occurrences were found for the western portion of the country. Earlier break-up events were found to be occurring on the Yukon River over the 1896-1998 time period (Jasek, 1999). More recently, Duguay *et al.* (2006) used the 1971-2000 time period to assess trends in lake ice break-up across Canada and determined that earlier occurrences were the result of the persistence of warmer spring conditions during the time period.

Past estimates indicate that the duration of the spring break-up period is ~6 –weeks in the MRB (MRBS, 1981). While little work on the spring break-up season has been performed since this study, numerous other climatic and hydrologic investigations have

been conducted. For example, over the 1950-1998 time period, an average increase in annual air temperature of 1.5°C has been found (Zhang *et al.*, 2000) corresponding to a 5 to 10 day advance in the timing of the spring 0°C isotherm over stations in northern Canada (Bonsal and Prowse, 2003). While within this period (1968-1999) no significant changes to flow have occurred (Woo and Thorne, 2003). Over the 1966-1995 time period, Serreze *et al.* (2000) identified warming winter and spring air temperature trends over regions of the Western Cordillera, a major source of snowmelt for the entire basin (Woo and Thorne, 2003). In an assessment of hydrological variables for a similar period (1971-2000), Burn *et al.* (2004) indicated the occurrence of earlier spring freshets in the upstream regions of the basin, corresponding to the Western Cordillera. Similarly, Aziz and Burn (2005), in assessing a relatively denser hydrometric network, found an earlier onset of spring freshet, which they attributed to warmer air temperatures during the late winter and early spring.

It has been previously noted that virtually all climate-change assessments of river-ice have used only easily retrievable measures such as ice-cover dates (Beltaos and Prowse, 2001). This is especially true for Canada, where assessments have generally relied on Water Survey of Canada (WSC) 'B' date qualifiers, indicative of when channel flow hydraulics are affected by ice (Brimley and Freeman, 1997, Zhang *et al.*, 2001). More detailed and better indications of trends can be provided by data derived directly from original WSC water-level charts as used by de Rham (2006) and described later in this manuscript.

To meet the previously defined goal of assessing changes and alterations to the timing and duration of the spring break-up period in the MRB, the specific objectives of this

manuscript are as follows: (1) to determine baseline temporal patterns of the break-up season in the MRB and explain them in terms of hydrological and climatic controls and (2) to assess temporal trends in the break-up season and contrast these with the results of other researchers.

3. STUDY AREA

The MRB, the largest cold-regions drainage basin in North America ($1.8 \times 10^6 \text{ km}^2$) extends across 16° of latitude from 54° N to 70° N and 37° of longitude from 103° W to 140° W (Figure 1). Within these boundaries, it contains a wide range of physical conditions. It is unique among cold-regions basins in North America in that it contains over half (8/15) of the ecozones identified in Canada, and encompasses portions of 5 permafrost zones. By land type, the basin contains 79% forest coverage, 7% arctic and alpine tundra, 7% lakes and rivers, while barren lands and agriculture cover 5% and 2% of the basin respectively.

Elevations in the MRB range from sea level at the Beaufort Sea to $\sim 3300 \text{ m}$ in the headwaters of the Rocky Mountains. Four distinct physiographic regions are identified in the basin including the Western Cordillera (mountain chains, valleys and high plateaus); Canadian Shield (rolling terrain with lakes and wetlands); Interior Plains (wetlands, lakes and grassland in south to boreal forest to tundra); and the delta environment at the river mouth (Mackenzie Delta $\sim 12,000 \text{ km}^2$). Other internal-MRB deltas include the Peace-Athabasca River Delta (PAD) (3800 km^2) and the Slave River Delta (640 km^2).

Two distinct climate regions are found in the MRB: the tundra covers the north-eastern and higher altitudes of the Western Cordillera, while the remainder of the basin is

classified as sub-arctic (MRBS, 1981). The Mackenzie Valley region has a milder climate than neighbouring areas to the east and west. From south to north, the (1971-2000) average daily temperature at Athabasca (~54° N) is 2.1°C while at Inuvik (~68°N) it is -8.8°C (Environment Canada, 2006a) . Precipitation in the basin decreases from the west to the northeast with ~1000 mm/yr occurring in the southwest to ~500 mm/yr in the northwest (Hydrological Atlas of Canada, 1978). Snowfall is identified as the major source of precipitation in the basin, with many parts of the MRB being snow covered over half of the year. The major tributaries of the Mackenzie River system include the Athabasca, Peace, and Liard Rivers. These river systems flow from the Western Cordillera, towards their outlets on the Interior Plateau. Spring break-up is recognized as the major cause of high-water events on the lowland, Interior Plateau portions of the aforementioned river systems, including the entire Mackenzie River reach (de Rham, 2006). While investigations have identified a warming trend and earlier onset of spring freshet events in the MRB (as previously discussed in Section 2), future climate predictions indicate less pronounced warming in northern regions of the basin compared to the southern regions. This could result in major effects on the dynamics of the spring freshet and ice break-up (ACIA, 2005).

4. ICE BREAK-UP PROCESSES

The commencement of the spring break-up period occurs when the downstream force in the channel as dictated by channel flow overcomes the resistance caused by the stationary channel ice cover. The break-up process occurring on ice-affected rivers are described as: *thermal* (overmature) or *mechanical* (dynamic or premature) (Gray and

Prowse, 1993). In the thermal case, the ice-cover strength deteriorates due to solar radiation and warming temperatures, and the magnitude of the spring flood wave is limited. As a result, the break-up events tend to be relatively quiescent. Conversely, mechanical break-ups occur when the strength of the ice sheet has not deteriorated considerably, and a flood wave of sufficient magnitude occurs which is able to rapidly break-up the ice cover. The cover tends to fragment into large pieces, producing a hydraulic roughness that is often many times the bed roughness. It is typically during ice jamming associated with these mechanical-type events that annual flood risk is greatest (Watt, 1989).

In general, the potential for mechanical break-up events is lower on rivers flowing in a direction opposite to that of regional warming. This is due to the significant thermal decay of the downstream cover that can occur prior to the onset of upstream spring melt (Lawford *et al.*, 1995). The MRB, is generally classified as a “northward” flowing river.

5. DATA SOURCE AND METHODOLOGY

5.1. Data and Station Selection

The break-up timing data-set used in this analysis originates from the Water Survey of Canada (WSC) hydrometric archives. The WSC regularly publishes discharge data, and uses a ‘B’ date qualifier to annotate ice conditions. The timing of the ‘Last B date’, the final day when ice is assumed to affect channel flow conditions, is often a qualitative estimate based on a variety of indirect evidence (e.g., flow and water-level condition at distant upstream/downstream hydrometric stations), since direct observations are often unavailable during this period. A better indicator of the break-up season would be the timing of both the initiation of break-up and maximum water-levels. Unfortunately, this

information is rarely extracted into regular formats although it does exist on the original WSC pen-chart or digital recordings. The WSC keeps on file for each station: (1) pen recorder charts during the break-up season, (2) station description, (3) hydrometric survey notes, (4) gauge history, (5) benchmark history, (6) discharge measurement tables, (7) station analysis and (8) annual water-level tables.

There are 652 WSC stations, past and current located within the MRB. Of these, 108 stations have a basin area $\geq 10,000 \text{ km}^2$. For this study MRB stations were only included if they met the following criteria: a minimum of 20 years of hydrometric records (duration required for statistical climatologies (Phillips *et al.*, 2006), and a minimum $10,000 \text{ km}^2$ drainage basin (ensures formation of free floating ice cover). Despite this stringent filtering process, the final 29 stations (Figure 1) selected for analysis, still covered a broad range of physical environments found in the MRB.

5.2. Data Extraction and Analysis

5.2.1. Spring Break-up Event Variables

To assess the timing of the spring break-up season in the basin, the timing of three event-based hydrometric variables were extracted: the initiation of break-up (H_B), peak water-level during break-up (H_M), and the WSC 'Last B date'.

Determination of H_B from WSC water-level recording charts follows guidelines provided by Beltaos (1990). Figure 2 is a schematic of a typical water-level chart during the break-up period. Abrupt water-level changes during the break-up period result from hydraulic effects produced by changing ice conditions. A steeply rising limb is generally indicative of the initiation of break-up as the moving ice sheet produces an abrupt decrease in the wetted perimeter of the channel and subsequent water-level rise.

The H_M coincides with the occurrence of maximum peak water-level during the break-up period (Figure 2). This occurrence can be caused by: (1) flood peaks from the break-up of an upstream jam (attenuated effects or surge effects), (2) the backwater from a distant downstream ice jam, (3) evolving ice jams which release before building to their maximum flood depth at equilibrium (e.g., see Beltaos, 1995), (4) ice jams which cannot be sustained beyond a given flow rate (i.e., an ice clearing discharge), (5) ice jams which result in spillage over dykes or banks into the flood plain, and/or (6) ice jams which have their development limited by a limited supply of ice from upstream (Ontario Ministry of Natural Resources, 1990).

The 'Last B date' is a data qualifier used by the WSC to identify the last day when ice conditions are assumed to be affecting the channel flow hydraulics at a hydrometric station. Unlike the above mentioned variables which can be identified on pen recorder charts, the 'Last B date' are only estimates, that are only rarely based on direct site observations. For the purposes of this research it is assumed that the 'Last B date' indicates the end of the spring river ice break-up season.

The break-up of river ice is a dynamic event which can lead to the damage and destruction of hydrometric instrumentation. As a result, the H_B and H_M spring break-up annual time-series were not continuous at all stations, although the temporal coverage encompassing 1913-2002 was deemed satisfactory to meet the objectives of this manuscript.

5.2.2. Spring Break-up Duration Variables

The different phases of the break-up process have been previously identified as the *pre-breakup*, *drive*, and *wash* (Deslauriers, 1968; Michel, 1971). The latter two are used herein to describe the duration of the break-up sequence. From the dataset of annual H_B , H_M and ‘Last B date’, time intervals between events were calculated according to:

$$[1] \quad t_1 = H_M - H_B$$

$$[2] \quad t_2 = \text{‘Last B date’} - H_M$$

$$[3] \quad t_3 = \text{‘Last B date’} - H_B$$

where t_1 is the break-up *drive* (days), t_2 is the break-up *wash* (days) and t_3 is the break-up *duration* (days). The three variables are shown on Figure 2.

The *drive* is indicative of the initial stages of the break-up period. During this time, increases in snowmelt runoff, possibly augmented by rainfall, result in increasing channel discharge. Large fluctuations in water-level profiles may occur, typified by H_M events. The *drive* also represents the time during which a location is most at risk of spring break-up flooding. At sites where ice jamming is common, the duration of t_1 is likely augmented due to the travel time required for backwater effects to be registered at upstream water-level recording devices.

The *wash* provides an indication of how persistent ice clearance is after the main break-up forces have peaked. It represents the residual ice clearance, which would be expected to be large on a river where break-up occurs later on the upstream tributaries. During this period, water-levels generally decrease, however fluctuations may occur due to upstream jamming and flow releases, possibly also influenced by snowmelt and/or rainfall.

During the *duration*, channel flow hydraulics are highly variable, representing the most dynamic time of the year on many northern river systems. The *duration* indicates the total time required for ice clearance and is expected to be shortest on steep, rapidly ice clearing upstream tributaries with limited ice contributing channel areas compared to low slope, ice jam prone reaches (de Rham, 2006) with large upstream ice contributing areas.

5.2.3. General Statistics

From the time-series of variables (H_B , H_M , 'Last B date', t_1 , t_2 , t_3) at each station, the following statistics were calculated and tabulated: the mean ($\bar{\quad}$), minimum, maximum and standard deviation (\pm).

5.2.4. Isochrone Mapping

Previous work in Canada indicates a strong relationship between latitude and the timing of the spring break-up events (e.g., Allen, 1978; Prowse and Onclin, 1987). To test this, $\overline{H_B}$, $\overline{H_M}$, and $\overline{\text{'Last B date'}}$ were regressed versus the station latitude. An r^2 value was determined for each regression. To assess the spatial patterns in the MRB, isochrone maps using the six ($\bar{\quad}$) and six (\pm) variables for each station were produced. Due to the limited dataset ($n = 29$), *kriging* with the default linear variogram was used. This method is known to provide a good representation of small data sets (< 250) (Piotrowski, 2004). The maps were used to assess spatial patterns of break-up in the MRB.

5.2.5. Last 'B' Date Assessment

While the pen recorder chart variables represents actual physical processes, the 'Last B date', as mentioned earlier, is often an estimate of ice conditions on the river channel. Given that the data set of extracted values is the first of its kind, a regression of all available extracted 'Last B date' to H_B dates was performed. Considering that the 'Last B date' method has been the mainstay for previous assessments (e.g., Brimley and Freeman, 1997; Zhang *et al.*, 2001), regression results can help determine if trends in 'Last B dates' relate and correlate to H_B and H_M timing. A regression of all available H_B and H_M values was also performed to assess the relationship between these two variables.

5.2.6. Trend Analysis

The time-series of H_B , H_M , 'Last B date', t_1 , t_2 and t_3 at each station were assessed using the Mann-Kendall non-parametric test for trend (Mann 1945; Kendall 1975). The test is regularly used for work on the timing of freshwater ice variables (Duguay *et al.*, 2006; Smith, 2000; Zhang *et al.*, 2001). The following formulas and discussion follow an excellent, detailed description of the test found in Salmi *et al* (2002).

The Mann-Kendall test is applicable when the data values, x_i , of a time-series are assumed to obey the model:

$$[4] \quad x_i = f(t_i) + \varepsilon_i$$

where $f(t_i)$ is a continuous monotonic increasing or decreasing function of time and the residuals (ε_i) are assumed to be from the same distribution with zero mean. It is therefore assumed that the variance of the distribution is constant in time.

For the Mann-Kendall test, the null hypothesis, H_0 , is that the observations, x_i , are randomly ordered in time. This is tested against the alternative hypothesis, H_1 , where there is an increasing or decreasing monotonic trend. The Mann-Kendall test statistic (S) is calculated by:

$$[5] \quad S = \sum_{k=1}^{n-1} \sum_{j=k+1}^n \text{Sgn}(x_j - x_k)$$

where x_j and x_k are annual values in years j and k , $j > k$, respectively and

$$[6] \quad \text{Sgn}(x_j - x_k) = \begin{cases} 1 & \text{if } x_j - x_k > 0 \\ 0 & \text{if } x_j - x_k = 0 \\ -1 & \text{if } x_j - x_k < 0 \end{cases}$$

Because the test is based on the ranks of data, a correction must be made for the effect of data ties on the variance of S. To do so, the variance of S is computed by the following equation:

$$[7] \quad \text{VAR}(S) = \frac{1}{18} \left[n(n-1)(2n+5) - \sum_{p=1}^q tp(tp-1)2(tp+5) \right]$$

where q is the number of tied groups and t_p is the number of data values in the p^{th} group.

The values of S and VAR(S) are used to compute the test Z-statistic as follows:

$$[8] \quad Z = \begin{cases} \frac{S-1}{\sqrt{\text{VAR}(S)}} & \text{if } S > 0 \\ 0 & \text{if } S = 0 \\ \frac{S+1}{\sqrt{\text{VAR}(S)}} & \text{if } S < 0 \end{cases}$$

The standardized Z-statistic (i.e., probability) is used to determine if a statistically significant trend is present. Positive (negative) Z-values are indicative of an upward

(downward) trend. To test for an upward (later) or downward (earlier) trend, a two-tailed test at the α significance level is used (90%). The null hypothesis (i.e., no trend) is rejected if the absolute value of S is greater than $Z_{1-\alpha/2}$. $Z_{1-\alpha/2}$ is obtained from a standard normal cumulative distribution table.

Linear slope estimates for trends were determined using Sen's non-parametric method (Sen, 1968). Sen's method can be used in cases where the trend can be assumed to be linear. This means that $f(t)$ in the following equation is equal to:

$$[9] \quad f(t) = Qt + B$$

where Q is the slope and B is a constant. To determine the slope estimate, Q, the slopes of all data values pairs are calculated:

$$[10] \quad Q_i = \frac{x_j - x_k}{j - k}$$

where $j > k$.

If there are n values of x_j in the times series, the number of slope estimates Q_i is equal to $N = n(n-1)/2$. Sen's estimator of slope is the median of these N values of Q_i . The N values of Q_i are ranked from the smallest to the largest and Sen's estimator is

$$[12] \quad Q = Q_{[(N+1)/2]}, \text{ if } N \text{ is odd}$$

or

$$[13] \quad Q = \frac{1}{2}(Q_{[N/2]} + Q_{[(N+2)/2]}), \text{ if } N \text{ is even}$$

The Mann-Kendall test and Sen's slope estimate were both performed using the Excel © template MAKESENS (Salmi *et al.*, 2002).

Temporal trend analysis was performed on the six variables at the 29 sites for the 1966-1995 and 1971-2000 climate periods. These two periods were selected as they: encompass the temporal extent of the 29 WSC hydrometric stations; have been previously assessed for trends in climate and freshwater ice by Serreze *et al.*, (2000) and Duguay *et al.* (2006), respectively; provide a 5-year window, either end of which can be used to address trend analysis for differing climatic periods; give the opportunity to assess late 20th century (1995-2000) warming effects on the ice regime. Since the temporal coverage of data varied for stations in the basin, only data sets covering 2/3 of the 30-year climatologies were assessed following the criterion previously employed by Duguay *et al.* (2006).

5.3. Data Assumptions and Limitations

For the station Mackenzie River *at* Arctic Red River (10LC014), data were treated as homogenous for the 29 years of record assessed. Prior to 1985, the hydrometric station Mackenzie River *above* Arctic Red River (10LA003) was located ~16 km upstream of 10LC014. It was assumed that the distance between stations would not have a significant effect on the timing of events.

For the two locations along the Peace River mainstem, only data after and including 1972 (i.e., post WAC Bennett dam construction and reservoir infilling) were assessed to ensure a consistent regulation signal. It was assumed that further downstream on the Mackenzie main stem, regulation effects were minor, thus all available data were used at these locations.

The difficulty in interpolating (i.e., isochrone mapping) with a non-uniformly distributed data set is also acknowledged. For example, by limiting the study to one basin, no adjacent data was available for some regions – for example, adjacent to the Beaufort Sea. However, several discernable spatial patterns were found despite these limitations.

6. RESULTS AND DISCUSSION

6.1. Spring Break-up Event Variables

Table 1 is a summary of spring break-up event statistical variables for the 29 stations in the MRB. Corresponding station locations [ID] are shown in Figure 3a. Included in Table 1 are the regression values for $\overline{H_B}$, $\overline{H_M}$ and $\overline{\text{'Last B date'}}$ versus latitude of the site. Clearly, latitude is an important control on the timing of spring break-up event variables ($r^2 = 0.90, 0.89, 0.91$) which agrees with earlier findings (e.g., Allen, 1978; Prowse and Onclin, 1987). As a similar spatial progression in the timing of the three variables was found, a map of $\overline{H_B}$ Julian day isochrones for the MRB is shown in Figure 3b.

An obvious spatial pattern is the “northwards progression” of the spring break-up from south to north in the basin (Figure 3b). For the MRB, generally classified as a “northwards” flowing river system, break-up thus proceeds upstream to downstream. This event is driven predominantly by the progression of spring-time warming in the northern hemisphere. This warming results in a similar northwards pattern for 0°C isotherms, identified as a major hydro-cryospheric control (Bonsal and Prowse, 2003).

Year-to-year, break-up in the MRB is a highly variable event. Based on extracted variables, break-up initiation has occurred as early as the second week of March (Julian

day 69) [8], while ice effects may remain until the 3rd week of June (Julian day 172) [27] (Table 1). This indicates that during ~1/4 of the year, some form of spring river ice break-up activity is occurring in the MRB. On a year to year basis, the average south to north basin break-up duration is ~8 weeks, beginning on Julian day 99 [7] and ending on Julian day 154 [27]. This duration is 2 weeks longer than previous estimates of ~6 weeks (MRBS, 1981).

Within the near 3-month spring break-up time period, considerable variability occurs in H_B , H_M , and ‘Last B date’ at spatial and temporal scales. Of particular note is a zone of early $\overline{H_B}$ for the upper tributaries of both the Athabasca [1, 2, 3] and Peace [5, 6, 7, 8] River basins (Figure 3b). While it is acknowledged that H_B at the town of Peace River [8] has been modified by the effects of regulation in the headwaters (Prowse *et al.*, 2002), the occurrence of relatively earlier events on the unregulated proximal systems is indicative of some form of unique hydroclimatic signal affecting this region. Interestingly, a similar anomalous zone was depicted by Allen (1978), however, the pattern was opposite, indicating a later occurrence. A detailed climatic investigation, specifically focusing on the spring break-up period is needed to identify possible causes of this regional ‘hot-spot’.

East of this ‘hot-spot’, ice break-up proceeds from upstream to downstream. This includes the lower reaches of the Athabasca [3, 4] and Peace [8, 9, 10] rivers where the spring break-up period is identified as the principle cause of high-water events (de Rham, 2006). This downstream progression of the ice break-up contributes large volumes of ice, a pre-requisite for dramatic spring events.

Further north, the Liard River basin is a unique example of a high-alpine drainage basin which flows both opposite to (north to south), and simultaneously with (south to north), spring-time atmospheric warming. In the upstream reaches break-up progresses both opposite to [13, 14], and in accordance with [15, 16] the flow direction, while on the eastward flowing mainstem, break-up occurs at the same time along an approximate 500 km reach [15, 17, 18]. Further downstream, the Fort Nelson/Muskwa drainage [20, 21] which has been previously described as a trigger for break-up on the Lower Liard (Prowse, 1986), shows a discernable upstream [22] to downstream [23] gradient which continues to the confluence with the Mackenzie River [24].

The Mackenzie River is classified as a *prolacustrine* system, where annual flow variability is minimized due to lake storage and release effects. As such, break-up on the mainstem is generally triggered by the Liard River (Prowse, 1986). Along the mainstem, break-up proceeds upstream [24] to downstream [27] (Figure 3b), and the gradient appears to increase in a downstream direction. Notably, the total duration of the break-up season [24 to 27] is 29 days, which agrees with an early 20th century estimate of ‘nearly a month’ (Kindle, 1920).

Break-up eventually reaches the Mackenzie delta, an area recognized as dependent on spring break-up water-levels for wetlands replenishment (Marsh and Hey, 1989). Interestingly, both the Peel [28, 29] and Arctic Red [26] rivers experience early break-up timing concurrent with the more upstream reaches of the Mackenzie main stem. This pattern is similar to that of the timing of the 0°C isotherm (Bonsal and Prowse, 2003) and is likely explained by the proximity of the region to the moderating influence of the warmer Pacific Ocean air masses. In addition to this climatic influence, the presence of

the Richardson Mountains protect the Peel from large-scale wind events. While for areas of similar latitude, high winds result in the removal of the insulating snow cover along the Arctic Red and Mackenzie River and subsequent ice growth, it has been suggested by Hensch (1960) that along the Peel River, ice growth thickness is limited due to an insulating snow cover. As a result ice break-up occurs earlier on the Peel compared to the Mackenzie River. The earlier events may also be the result of anomalous warming in the region (e.g., Serreze *et al.*, 2000; MRBB, 2003) over the late 20th century.

Figure 3c depicts $\pm H_M$ for sites in the MRB. While the variability is approximately one week for the majority of stations (Table 1), for the three variables, an obvious anomaly exist at the Peace River at Peace River [8] ($\pm 13, \pm 13, \pm 11$ days). The enhanced variability at this location is likely due to regulation on the upper reaches. The ice regime at the town of Peace River is known to be sensitive to both storage and releases from the WAC Bennett Dam (Prowse *et al.*, 2002). In fact, upstream locations such as Hudson's Hope no longer experience ice conditions during the winter due to the thermal effects of the dam on water temperatures.

6.2. Spring Break-up Duration Variables

Table 2 is a summary of spring break-up duration statistical variables for the 29 stations in the MRB. The three variables: *drive* ($\overline{t_1}$), *wash* ($\overline{t_2}$), and *duration* ($\overline{t_3}$) show, on average, increasing values across Table 2. Of note, is the shorter duration of $\overline{t_1}$ over $\overline{t_2}$ for all the sites. The $\overline{t_1}$ is on average two days, however varies from 0 to 16 days. This duration is indicative of the driving forces on the downstream progression of ice at a site which can lead to peak water-level events. The duration of $\overline{t_2}$ is on average

four days, but can last up to 25 days. A similar, but longer duration is found for $\overline{t_3}$, which represents the total time break-up is progressing through the site of interest. This event can last anywhere from four days to four weeks (Table 2). This represents, at its maximum, almost one month when channel conditions can intensify ecosystem disturbances, disrupt the biotic community, abrade stream banks, change channel morphology and mixing processes, transport significant quantities of fine grained material, and interfere with navigation and hydropower production (Beltaos and Burrell, 2003).

Figure 3d shows isochrones of $\overline{t_3}$ for the Mackenzie River system. Similar patterns were found for $\overline{t_1}$ and $\overline{t_2}$. A clear spatial pattern is the increasing duration of the ice season on all major rivers of the basin from upstream to downstream. A likely explanation for the contrast is: upstream (downstream) reaches of the MRB have high (low) gradient slopes, which result in high (low) water velocities and relatively rapid (slow) ice clearance. Additionally, the propensity for ice jamming events, greater inputs of upstream ice due to larger contributing areas, and the presence of thicker ice on the lower gradient reaches result in greater ice-clearance durations. Interestingly, this pattern of increasing *duration* moving downstream, follows the general pattern of increases in *flow* moving downstream, a well-known hydrological occurrence. This is likely a common trait of all “northwards” flowing river systems.

An upstream to downstream spatial pattern for $\pm t_1$ is also evident (Figure 3e). Similar spatial patterns were also found for $\pm t_2$, and $\pm t_3$. Given that the downstream locations are more prone to mechanical (i.e., jamming) events versus the upstream locations (see de Rham, 2006), this increased downstream variability is likely a result of the frequency of

jamming events and the length of the river (Prowse and Onclin, 1987). An interesting anomaly occurs at the Liard River above Beaver River [18] ($\pm t_1 = 5$ days; $\pm t_3 = 9$ days). On this eastward flowing reach, ~35 km upstream of the outlet of the northwards flowing Beaver River, it is likely that ice congestion occurring at the confluence result in H_M events registering at the station several days after the H_B . A more detailed site investigation would be needed to confirm this occurrence.

6.3. Last 'B' Date Assessment

The extracted variables, H_B and H_M , represent two well quantified temporal indicators of the spring break-up period. As the vast majority of previous work has relied on the more readily available but often highly qualitative 'Last B date', a comparison of the three terms was performed. Figure 4 is a plot of H_B and 'Last B dates' for all available years. Data pairs were limited by H_B for which, of the 1080 'Last B dates', only 680 corresponding H_B dates were available. This is a testament to the difficulties in obtaining accurate hydrological information during the break-up period. While H_B timing is likely a better indicator of spring break-up occurrence than the 'Last B date', the relationship between the two values is strong ($r^2 = 0.90$). Thus, previous studies, which have assessed trends in 'Last B date' timing, are likely a good indicator of the trends in the initiation of break-up. Figure 4 indicates an approximate slope of 1 with a ~3 day time lag between the H_B and 'Last B date'. Compared to the results of Table 2, the average H_B to 'Last B date' (t_3) duration, calculated for the basin is 6 days. The reason for the discrepancy is likely because data in Figure 4 is biased towards years and locations where the ice

clearance is relatively rapid and quiescent, and hence damage to instrumentation is unlikely.

A stronger correlation is found between the H_B and H_M variables ($r^2=0.98$) (Figure 5). This is likely due to the fact that while H_B and H_M timing represent physical process variables extracted from hydrometric records, ‘Last B dates’ are generally estimates of channel conditions, often estimated later since direct observation are not available. The equation on Figure 5 indicates that H_M timing occurs approximately on the same day as H_B dates as the slope of the line is equal to approximately 1 and the intercept is 0.34 (i.e. ~ 0). In reference to the data in Table 2, the average time between the H_B and H_M (t_1) is two days. Thus the basin-wide assessment of break-up data presented in Figure 5 is likely biased towards locations where t_1 duration is rapid.

6.4. Temporal Trend Analysis

Table 3 presents the results of Mann-Kendall test for trend for the variables H_B , H_M , ‘Last B date’, t_1 , t_2 and t_3 the 1966-95 and 1971-2000 time period. This discussion focuses on the 1966-95 time period, the period of pronounced northern warming noted by Serreze *et al.* (2000).

Beginning with the timing of the initiation of break-up (H_B), 15 of the 16 sites assessed in the basin have earlier timing of events (average = 3 days/decade). The location of the eight significantly earlier locations is shown in Figure 6a. An obvious spatial pattern is the occurrence of these sites in the upstream reaches of the Athabasca, Peace and Liard River systems. A similar pattern is found for the timing of H_M (Figure 6b) and ‘Last B date’ events (Figure 6c) with some differences on a per station basis. For example, at the

Mackenzie River at Fort Simpson (Figure 7), H_M timing shows a significantly earlier trend (-3 days/decade) while H_B timing is earlier, although not significant (-2 days/decade). While both events show similar decreasing trends, differing record lengths (H_B $n = 20$; H_M $n = 24$) are likely the cause of the differing significance and slope values. Were the datasets of equal length, the trend significance and slope values may be more consistent on a station to station basis.

Overall in the basin, the three variables, when averaged for all sites, have a similar earlier trend (~ 3 days/decade) (Table 3). The spatial and temporal pattern show similar trends with previous hydrological and climatic studies in the MRB. For example, an assessment of discharge based variables (1961-2000, 1971-2000) was performed by Burn *et al.* (2004). Noteworthy were earlier spring freshet events for the upper reaches of the Liard and Athabasca basins. Results of a denser hydrometric network assessment by Aziz and Burn (2005) showed a similar freshet trend for a majority of the basins and were likely due to warming winter and spring temperatures. Anomalous warming regions in the western portions of the MRB during the winter and spring, found by Serreze *et al.*, (2000), are likely the cause of these earlier spring break-ups on the upstream reaches of the Mackenzie. While the results of MRB climate change on various components of the hydrological cycle are still being assessed, Brown and Braaten (1998) identified a decrease in snow depth in the basin over the 1946 – 1995 time period. Thus, earlier occurrence of the spring break-up over the basin may also be influenced by more rapid spring melt pulses due to thinner snowpacks in the region.

Interestingly, the earlier break-up signal does not appear to propagate to the downstream reaches of the Mackenzie mainstem. This is likely due to the dynamics of

the break-up season, which unlike flow, are not always transmitted downstream. An anomaly on Figure 6c is the significant increase of approximately 8 day/decade in the ‘Last B date’ on the Mackenzie River at Arctic Red River [27]. These results are noteworthy, as they directly reflect the qualitative nature of the ‘Last B date’ for river ice assessment. During data extraction, it was noted that the ‘Last B date’ methodology varied with the pre ~1990 notation being related to channel backwater conditions, while post ~1990 notation related to Mackenzie Delta backwater effects. As such, a review of hydrometric metadata is recommended for future assessments of ‘Last B date’ timing.

The result of the temporal trend analysis along the Peace River is worth discussing in light of debate regarding the influence of the WAC Bennett dam on the ice flooding regime of the PAD region (e.g., Timoney, 2001). While the upstream Peace River station shows a decreasing trend (6 a,b), likely due to regulation effects (see Prowse *et al.*, 2002), the downstream location at Peace Point shows a later trend. These results are significant as they indicate that these specific ice-regime effects on the upstream reaches of the Peace are likely not transmitted to the downstream PAD region.

Figure 6 d-f show the result of an assessment of t_1 , t_2 and t_3 variables for sites in the MRB. Significantly shorter durations are found for the *drive* (t_1) at three stations, with an average value of 0.4 days per decade (Table 3), roughly equal to a one day decrease over the 30-year climatology. Assessment of the *wash* (t_2) (Figure 6e) indicates that stations on each of the major tributaries show increasing durations, on the order of 0.6 days per decade, approximately equal to two days later over the 30-year climatology. Finally, the *duration* data shows few obvious patterns (Figure 6f). A significantly shorter trend is

found at the Peace River at Peace Point station; however, given the quality of ‘Last B date’ information, the results of the trend test are questionable.

The overall effectiveness of the Mann-Kendall and Sen’s slope estimate for determining trends in the *drive*, *wash* and *duration* are worth discussing. As data used represented the ‘day’ of events, it is likely that a less coarse temporal record (i.e., hour) may indicate more obvious spatial and temporal trends in the MRB. For example, during numerous years the duration between events was 0 days, that is, H_B and H_M occurred on the same day.

Table 3 also includes the results of the Mann-Kendall test for trend for the period 1971-2000. In general, earlier events are occurring throughout the basin. The trends in river ice agree with those found on lake ice by Duguay *et al.* (2006), who indicated that a warming climate results in earlier break-up events. The trends were most notable with earlier spring dates over most of western Canada, which correspond with regions of the MRB. Duguay *et al.* (2006) also noted that this region generally has the most consistent trends towards earlier break-up dates over all 30-year climatologies assessed.

There are a few, albeit, minor, differences found when comparing the 1966-1995 with the 1971-2000 time period. Notably, the timing of H_B and H_M indicate a roughly 1 day/decade less difference on a per decade trends (i.e., -3.1 vs. -1.8; -3.2 vs. -2.2) while ‘Last B date’ timing is approximately the same (i.e., -2.6 vs. -3.1). An example of the shifting time periods on the linear trend is shown on Figure 8. Interestingly, for the 1966-1995 (1971-2000) period, the trend of -3 days/decade (-1 day/decade) was determined to be significant (not-significant) at the 90% level. It would be expected that the later of the two periods would show greater differences due to late 20th century warming (i.e., 1996-

2000), with 1998 and 1999 ranking as two of the five warmest years in Northwest Forest and Mackenzie regions of the basin over the 1948-2005 time period (Environment Canada, 2006b), however, the results indicate the opposite. Thus, a more refined climatological analysis of the break-up period including meteorological variables (see Beltaos and Prowse, 2001) are needed to further assess the climatic controls of break-up. Interestingly this location corresponds to the anomalous zone of spring break-up shown in Figure 3b.

Results of trend tests for t_1 , t_2 and t_3 variables show some differences, with only the t_1 timing showing a 1 day later trend (i.e., 0 vs. 1.4) over the more contemporary period while the t_3 time shows an approximate one day difference over the later period (i.e., -0.9 vs. -1.6). The differing trend test results for the similar time periods are indicative of the test sensitivity as previously noted by Prowse and Bonsal (2005) whereby differing time frames and regional focus can lead to differing test for trend results. The non-continuous records, 2/3 criteria for time-series selection, and the averaging of trends are the likely cause of the results. The findings are a reminder of the problematic nature of performing statistical work with hydrometric data.

7. CONCLUSIONS AND FUTURE RECOMMENDATIONS

Given the sensitivity of river-ice regimes to climate change and variability a baseline assessment of the temporal variations of the spring river ice break-up season in the MRB was performed. The specific objectives are reiterated and relevant conclusions to each are provided below.

1) determine baseline temporal patterns of the break-up season in the MRB and explain them in terms of hydrological and climatic controls

Using a suite of previously unanalyzed hydrological variables including the timing of the initiation of break-up (H_B), peak break-up water-levels (H_M) and the more commonly used ‘Last B date’, several discernable patterns in the spring break-up season of the MRB are noteworthy. The south to north spring break-up season in the basin can occur over a time period representing approximately 1/4 of the year, while on average, break-up takes ~8 weeks to proceed through the MRB. In the upstream reaches of the Peace and Athabasca River systems, an anomalous hot spot of early spring-break-up occurs, which was evident in the timing of variables and the standard deviation. An anomalous zone also occurs in the in regions upstream of the Mackenzie delta, and is likely caused by the proximity of this region to the Pacific Ocean.

Patterns in calculated time lags between events indicate that in general, both the duration and variability of events increases downstream in the basin, likely due to increasing contributing areas, and the occurrence of ice jamming events. Notably for all sites, the break-up duration lasts on average from four days to four weeks, with an increase in duration for more northern locations.

An assessment of the extracted variables indicates that previous river-ice assessments which relied on ‘Last B dates’ are likely applicable to trends in both H_B and H_M variables. The relationship between the latter two variables indicates a strong correlation between the two physically based events.

(2) assess temporal trends of the break-up season and contrast these with the results of others researchers.

A time-series analysis of the H_B , H_M , 'Last B date' and t_1 , t_2 , t_3 indicates that the majority of significantly earlier events are occurring in the upper reaches of the Athabasca, Peace and Liard River basins. The results are important as they represent the first time physically based spring break-up variables have been assessed, rather than the more commonly used 'Last B date'. As other workers have found similar earlier trends during the open water season in the MRB, these results indicate a retrogressive shift in the timing of hydrological event is occurring in the upstream, Western Cordillera regions of the basin. A lack of obvious spatial and temporal trends for the break-up durations are likely due to the coarseness of variables extracted (day of). A comparison of two standard climatologies (i.e., 1966-95; 1971-2000) indicates the sensitivity of statistical tests to shifting time periods.

Based on the results of this manuscript, several future recommendations are described below.

(1) This first-order assessment of the break-up season relied on never before assessed temporal records of the break-up season including the H_B and H_M . When compared to the more commonly used 'Last B date' method, the extracted variables used in this assessment were not continuous. As such, it is recommended that the WSC explore more robust instrumentation to record information during the break-up period. These could include the use of tripping devices to record the timing of the initiation of break-up and digital photography equipment to provide more data during the break-up period (Beltaos, 1990). Increased personnel would also assist in obtaining a better record of the break-up season.

(2) A climatic signal is likely affecting spring break-up in the basin (i.e., earlier timing). As such, it is recommended that the dataset be used to assess how both climate change and large scale atmospheric forcing events (i.e., teleconnections) are affecting annual variability of the ice break-up regime in the MRB. In addition, examination of the severity of events (i.e., peak water-levels) in relation to the timing of variables would provide useful information for spring break-up forecasting in the basin.

(3) Finally, it is recommended that this type of study, based on physical process variables, be expanded to the entire Canadian landmass. A data archive is available; however data extraction and time-series analysis have yet to be undertaken. The results of a national study would provide a temporal indication of the break-up season, and be useful for climatic, ecological and socioeconomic assessments related to the spring break-up period.

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Table 1. Summary statistics for timing (Julian day) of the: initiation of break-up (H_B), maximum instantaneous water-level during break-up (H_M), and ‘Last B date’ for 29 Water Survey of Canada hydrometric stations in the Mackenzie River basin. Record lengths are shown in column ‘n’. Also shown are regression values (r^2) for timing of events versus station latitude.

Table 2. Summary statistics for the *drive* (t_1), *wash* (t_2) and *duration* (t_3) of the break-up season for 29 Water Survey of Canada hydrometric stations in the Mackenzie River basin. Record lengths are shown in column ‘n’.

Table 3. Result of Mann-Kendall test for Water Survey of Canada hydrometric stations in the Mackenzie River basin over the 1966-1995 and 1971-2000 time period. Test for trend is for timing of: Initiation of break-up (H_B), Maximum instantaneous water-level during break-up (H_M), ‘Last B date’ and the *drive* (t_1), *wash* (t_2) and *duration* (t_3) phases of the break-up period. Significance is at the 90% level.

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Figure 2. Schematic of water-level recording chart during break-up period adapted from Beltaos (1990). Denoted are the timing of the: initiation of break-up (H_B); maximum instantaneous water-level during break-up (H_M); ‘Last B date’; *drive* (t_1), *wash* (t_2), and *duration* (t_3).

Figure 3. The Mackenzie River basin (a) Water Survey of Canada hydrometric station locations, numbers refer to ‘ID’ column in Tables 1 and 2, (b) Isochrones of mean initiation of break-up ($\overline{H_B}$), (c) Isochrones of variability in instantaneous water-levels ($\pm H_M$), (d) Isochrones of break-up *duration* ($\overline{t_3}$), (e) Isochrones of *drive* variability ($\pm t_1$).

Figure 4. Scatter plot and linear regression of ‘Last B date’ versus initiation of break-up (H_B) timing. Plot includes all available data at 29 Water Survey of Canada hydrometric stations in the Mackenzie River basin, Canada.

Figure 5. Scatter plot and linear regression of maximum instantaneous water-levels (H_M) versus initiation of break-up (H_B) timing. Plot includes all available data at 29 Water Survey of Canada hydrometric stations in the Mackenzie River basin, Canada.

Figure 6. Results of the Mann-Kendall test for trend at 29 Water Survey of Canada hydrometric stations in the Mackenzie River basin, Canada for 1966-95 time period (a) initiation of break-up (H_B) (b) maximum instantaneous water-level during break-up (H_M), (c) 'Last B date' (d) *drive* (t_1), (e) *wash* (t_2), (f) *duration* (t_3).

Figure 7. Time series and linear trend lines for the initiation of break-up (H_B) (solid lines) and peak water-level (H_M) (dashed lines) for the station Mackenzie River at Fort Simpson.

Figure 8. Comparison of the timing of peak water-level (H_M) for the 1966-1995 (top) and 1971-2000 (bottom) time period for the station Pembina River at Jarvie. Linear trend lines are include on the plot.

Table 1

ID	Station	Latitude (N)	Longitude (W)	H _B					H _M					'Last B date'					
				n	mean	min	max	st.dev.	n	mean	min	max	st.dev.	n	mean	min	max	st.dev.	
1	ATHABASCA RIVER NEAR WINDFALL	54°12'25"	116°3'45"	31	109	91	122	8	39	109	92	122	7	42	114	96	128	7	
2	PEMBINA RIVER AT JARVIE	54°27'5"	113°59'30"	30	103	92	117	6	38	104	92	119	6	45	106	94	120	6	
3	ATHABASCA RIVER AT ATHABASCA	54°43'20"	113°17'10"	44	107	80	121	7	78	109	80	129	8	70	113	97	129	7	
4	ATHABASCA RIVER BELOW MCMURRAY	56°46'50"	111°24'0"	32	109	99	123	5	31	110	94	124	6	43	117	107	128	5	
5	WAPITI RIVER NEAR GRANDE PRAIRIE	55°42'0"	118°48'10"	28	103	90	117	7	36	106	91	120	7	42	109	95	120	6	
6	LITTLE SMOKY RIVER NEAR GUY	55°27'25"	117°9'40"	32	100	81	116	7	41	101	82	117	7	41	106	87	125	7	
7	SMOKY RIVER AT WATINO	55°42'56"	117°37'19"	34	99	79	111	7	45	102	80	117	7	47	107	89	120	6	
8	PEACE RIVER AT PEACE RIVER	56°14'41"	117°18'46"	31	100	69	120	13	31	100	70	120	13	31	105	78	125	11	
9	WABASCA RIVER AT WADLIN LAKE ROAD	57°52'30"	115°23'20"	32	110	101	120	5	28	112	103	121	5	32	114	107	128	5	
10	PEACE RIVER AT PEACE POINT (ALBERTA)	59°7'2"	112°26'13"	30	119	102	133	7	26	120	111	133	6	31	126	113	142	7	
11	HAY RIVER NEAR HAY RIVER	60°44'35"	115°51'34"	21	120	111	135	6	30	122	111	135	6	39	125	114	143	6	
12	BUFFALO RIVER AT HIGHWAY NO. 5	60°42'44"	114°54'11"	12	121	113	127	4	12	123	114	127	4	22	123	109	130	6	
13	LIARD RIVER AT UPPER CROSSING	60°3'0"	128°54'0"	11	122	115	132	6	21	124	115	134	6	42	126	111	137	7	
14	FRANCES RIVER NEAR WATSON LAKE	60°28'26"	129°7'8"	28	126	111	137	6	31	127	111	139	6	39	129	119	139	5	
15	KECHIKA RIVER AT THE MOUTH	59°36'55"	127°18'37"	24	119	99	135	8	22	120	100	133	8	26	124	107	135	7	
16	KECHIKA RIVER ABOVE BOYA CREEK	59°5'54"	127°32'2"	21	116	104	129	6	21	116	105	130	6	26	121	107	135	8	
17	LIARD RIVER AT LOWER CROSSING	59°24'45"	126°5'50"	21	119	105	130	6	34	122	105	134	6	52	127	111	151	7	
18	LIARD RIVER ABOVE BEAVER RIVER	59°44'33"	124°28'35"	17	119	107	132	7	18	126	116	137	6	23	127	115	138	6	
19	LIARD RIVER ABOVE KECHIKA RIVER	59°42'4"	127°13'39"	18	122	109	133	7	18	125	114	139	7	26	127	116	141	6	
20	FORT NELSON RIVER ABOVE MUSKWA RIVER	58°40'15"	122°38'15"	10	111	106	121	4	11	111	102	120	5	24	116	107	130	6	
21	MUSKWA RIVER NEAR FORT NELSON	58°47'18"	122°39'33"	9	113	108	121	5	23	116	108	126	5	50	118	96	139	7	
22	LIARD RIVER AT FORT LIARD	60°14'26"	123°28'32"	28	120	110	134	5	28	122	114	134	5	53	127	116	152	6	
23	LIARD RIVER NEAR THE MOUTH	61°44'34"	121°13'41"	24	123	116	136	5	27	125	119	136	5	30	131	125	148	5	
24	MACKENZIE RIVER AT FORT SIMPSON	61°52'7"	121°21'25"	25	125	117	136	4	33	127	120	140	5	41	136	124	156	7	
25	MACKENZIE RIVER AT NORMAN WELLS	65°16'18"	126°50'48"	25	136	125	144	5	38	138	128	148	5	40	143	133	152	5	
26	ARCTIC RED RIVER NEAR THE MOUTH	66°47'24"	133°4'54"	17	138	120	151	9	23	139	122	154	9	30	143	124	157	9	
27	MACKENZIE RIVER AT ARCTIC RED RIVER	67°27'22"	133°44'13"	24	143	129	152	6	23	147	134	156	5	30	154	140	172	7	
28	PEEL RIVER ABOVE CANYON CREEK	65°53'40"	136°2'10"	6	129	118	140	7	7	131	121	137	5	27	139	125	154	7	
29	PEEL RIVER ABOVE FORT MCPHERSON	67°14'33"	134°53'20"	24	138	121	153	8	31	141	125	155	8	31	149	135	167	7	
				mean	24	118	104	130	6	29	120	106	132	6	37	124	110	139	7
				min	6	99	69	111	4	7	100	70	117	4	22	105	78	120	5
				max	44	143	129	153	13	78	147	134	156	13	70	154	140	172	11
r ² (vs. Latitude)				0.90					0.89					0.91					

Table 2

ID	Station	Latitude (N)	Longitude (W)	t ₁					t ₂					t ₃					
				n	mean	min	max	st.dev.	n	mean	min	max	st.dev.	n	mean	min	max	st.dev.	
1	ATHABASCA RIVER NEAR WINDFALL	54°12'25"	116°3'45"	30	1	0	5	1	39	4	0	22	5	31	4	0	18	4	
2	PEMBINA RIVER AT JARVIE	54°27'5"	113°59'30"	30	1	0	4	1	38	2	0	9	2	30	3	0	13	3	
3	ATHABASCA RIVER AT ATHABASCA	54°43'20"	113°17'10"	44	1	0	4	1	69	4	0	24	4	44	4	0	24	4	
4	ATHABASCA RIVER BELOW MCMURRAY	56°46'50"	111°24'0"	27	2	0	13	3	28	6	0	18	5	30	8	1	15	4	
5	WAPITI RIVER NEAR GRANDE PRAIRIE	55°42'0"	118°48'10"	25	1	0	9	2	36	3	0	10	3	28	4	0	18	4	
6	LITTLE SMOKY RIVER NEAR GUY	55°27'25"	117°9'40"	32	1	0	6	2	38	4	0	25	4	30	5	1	25	4	
7	SMOKY RIVER AT WATINO	55°42'56"	117°37'19"	33	2	0	7	2	44	4	0	15	3	34	6	1	16	3	
8	PEACE RIVER AT PEACE RIVER	56°14'41"	117°18'46"	31	0	0	3	1	31	5	0	20	5	31	5	0	20	5	
9	WABASCA RIVER AT WADLIN LAKE ROAD	57°52'30"	115°23'20"	28	2	0	9	2	28	3	0	23	4	32	5	1	25	4	
10	PEACE RIVER AT PEACE POINT (ALBERTA)	59°7'2"	112°26'13"	26	2	0	10	3	26	6	0	13	3	30	7	0	14	4	
11	HAY RIVER NEAR HAY RIVER	60°44'35"	115°51'34"	21	2	0	9	2	30	3	0	11	3	21	6	2	13	3	
12	BUFFALO RIVER AT HIGHWAY NO. 5	60°42'44"	114°54'11"	10	2	0	5	2	12	3	0	11	4	12	5	2	12	3	
13	LIARD RIVER AT UPPER CROSSING	60°3'0"	128°54'0"	12	1	0	3	1	22	3	0	10	3	12	4	0	8	3	
14	FRANCES RIVER NEAR WATSON LAKE	60°28'26"	129°7'8"	29	1	0	3	1	32	2	0	9	3	29	3	0	10	3	
15	KECHIKA RIVER AT THE MOUTH	59°36'55"	127°18'37"	22	1	0	4	1	22	4	0	13	4	24	5	0	13	3	
16	KECHIKA RIVER ABOVE BOYA CREEK	59°5'54"	127°32'2"	23	0	0	1	1	22	5	0	16	6	22	6	0	16	6	
17	LIARD RIVER AT LOWER CROSSING	59°24'45"	126°5'50"	21	2	0	7	2	34	3	0	10	2	21	5	0	14	3	
18	LIARD RIVER ABOVE BEAVER RIVER	59°44'33"	124°28'35"	15	5	1	10	3	15	2	0	10	3	14	9	3	16	4	
19	LIARD RIVER ABOVE KECHIKA RIVER	59°42'4"	127°13'39"	17	2	0	12	3	18	2	0	8	3	18	5	0	14	4	
20	FORT NELSON RIVER ABOVE MUSKWA RIVER	58°40'15"	122°38'15"	8	1	0	2	1	11	1	0	5	2	10	2	0	4	1	
21	MUSKWA RIVER NEAR FORT NELSON	58°47'18"	122°39'33"	9	1	0	4	1	23	2	0	6	2	9	3	0	7	2	
22	LIARD RIVER AT FORT LIARD	60°14'26"	123°28'32"	20	1	0	5	1	28	4	0	9	2	28	6	1	15	3	
23	LIARD RIVER NEAR THE MOUTH	61°44'34"	121°13'41"	22	2	0	6	2	27	7	1	22	6	24	9	1	22	6	
24	MACKENZIE RIVER AT FORT SIMPSON	61°52'7"	121°21'25"	25	1	0	7	2	33	8	3	23	5	25	10	4	24	5	
25	MACKENZIE RIVER AT NORMAN WELLS	65°16'18"	126°50'48"	25	2	0	4	1	33	5	0	14	3	25	7	1	13	3	
26	ARCTIC RED RIVER NEAR THE MOUTH	66°47'24"	133°4'54"	17	2	0	7	2	22	4	0	23	5	17	5	0	10	3	
27	MACKENZIE RIVER AT ARCTIC RED RIVER	67°27'22"	133°44'13"	22	4	0	16	3	23	8	0	24	7	24	13	2	26	6	
28	PEEL RIVER ABOVE CANYON CREEK	65°53'40"	136°2'10"	5	2	0	3	2	7	2	0	4	2	7	4	0	7	3	
29	PEEL RIVER ABOVE FORT MCPHERSON	67°14'33"	134°53'20"	22	2	0	4	1	29	9	0	25	7	22	11	1	28	9	
				mean	22	2	0	6	2	28	4	0	15	4	24	6	1	16	4
				min	5	0	0	1	1	7	1	0	4	2	7	2	0	4	1
				max	44	5	1	16	3	69	9	3	25	7	44	13	4	28	9

Table 3

	H_B	Earlier	Average		Later	Average		
	n	n	days/decade	n-significant	n	days/decade	n-significant	no trend
1966-1995	16	15	-3.1	8	1	1.7	0	0
1971-2000	17	16	-1.8	5	0	-	-	0

	H_M	Earlier	Average		Later	Average		
	n	n	days/decade	n-significant	n	days/decade	n-significant	no trend
1966-1995	18	17	-3.2	10	1	2.1	0	0
1971-2000	19	18	-2.2	3	1	0	0	0

	Last B date'	Earlier	Average		Later	Average		
	n	n	days/decade	n-significant	n	days/decade	n-significant	no trend
1966-1995	28	24	-2.6	15	3	8	1	0
1971-2000	28	21	-3.1	9	6	1.4	2	1

	t₁	Earlier	Average		Later	Average		
	n	n	days/decade	n-significant	n	days/decade	n-significant	no trend
1966-1995	13	10	-0.4	2	3	0	0	0
1971-2000	17	8	-0.09	2	9	1.4	3	0

	t₂	Earlier	Average		Later	Average		
	n	n	days/decade	n-significant	n	days/decade	n-significant	no trend
1966-1995	18	8	-0.6	0	10	1.4	6	0
1971-2000	19	8	-0.3	1	11	1.5	6	0

	t₃	Earlier	Average		Later	Average		
	n	n	days/decade	n-significant	n	days/decade	n-significant	no trend
1966-1995	16	7	-0.9	1	9	7	1	0
1971-2000	16	4	-1.6	4	12	6	1	0

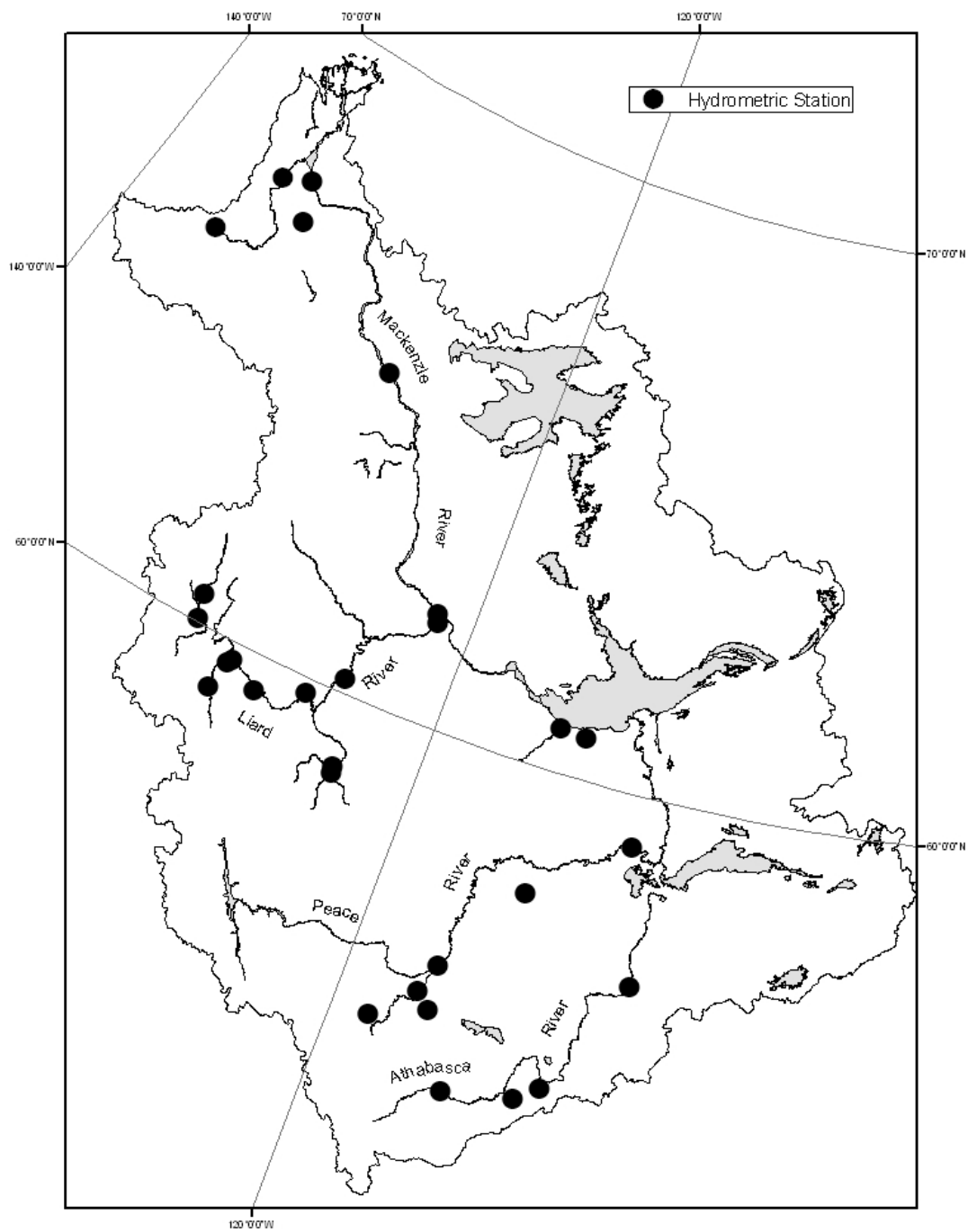


Figure 1

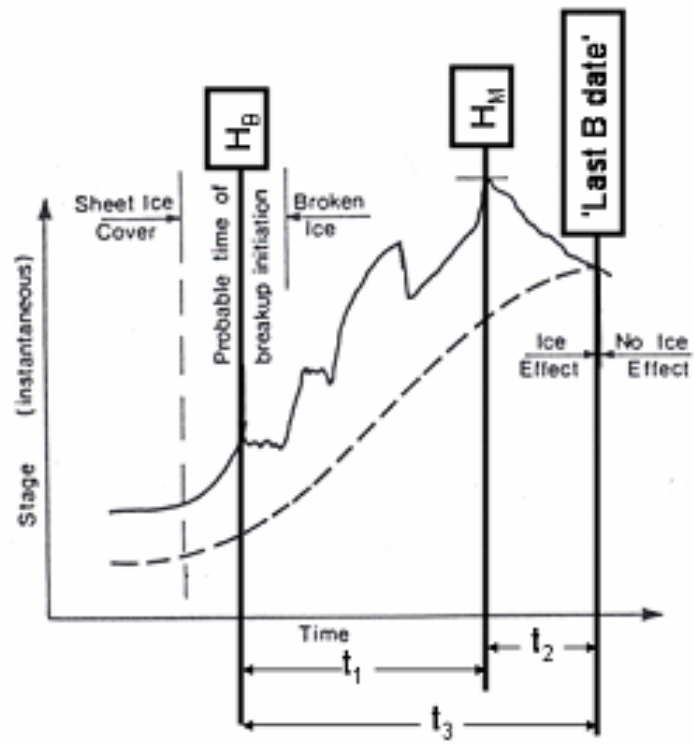


Figure 2

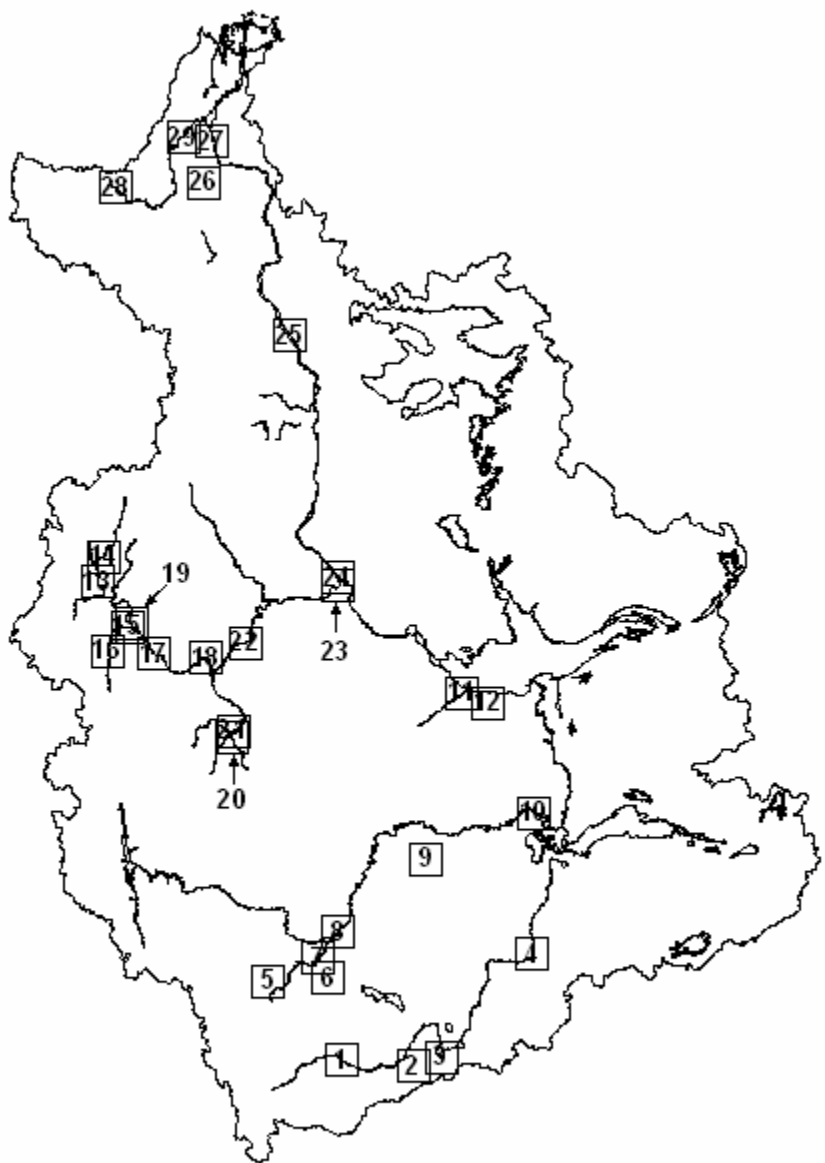


Figure 3a

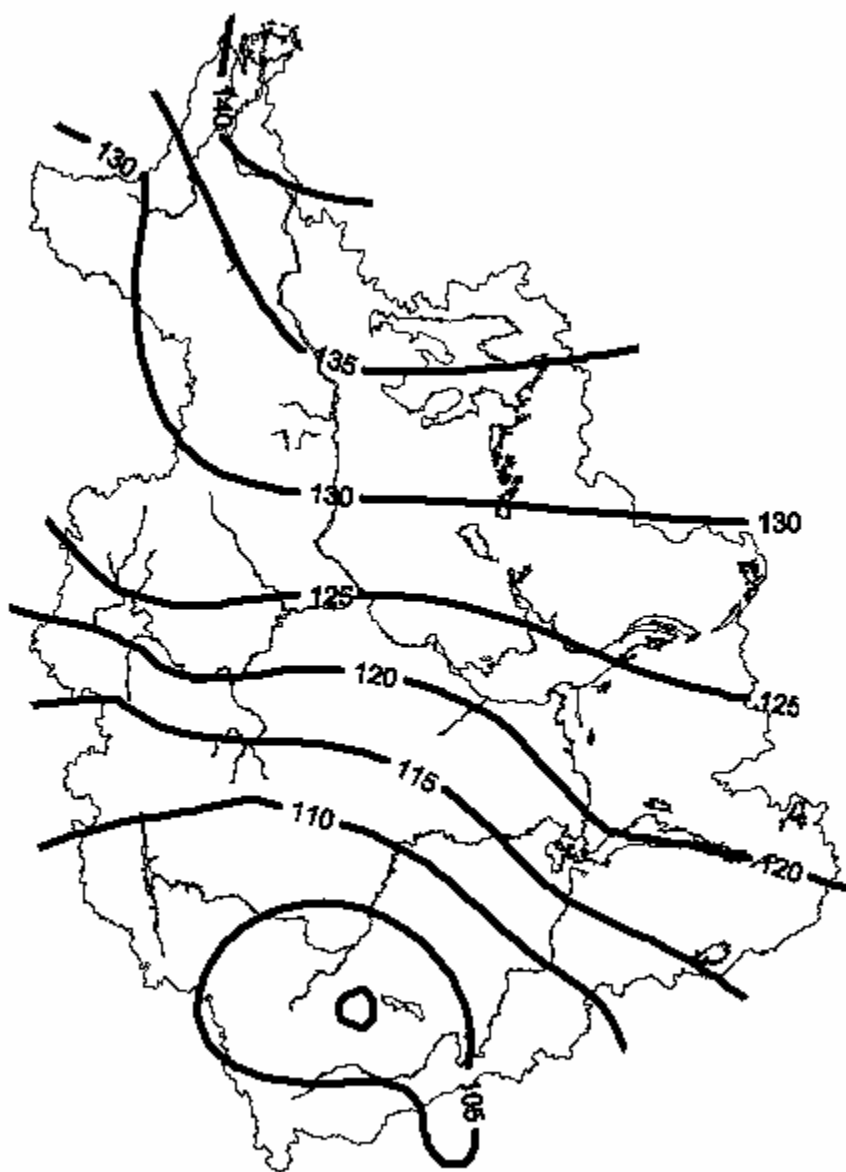


Figure 3b

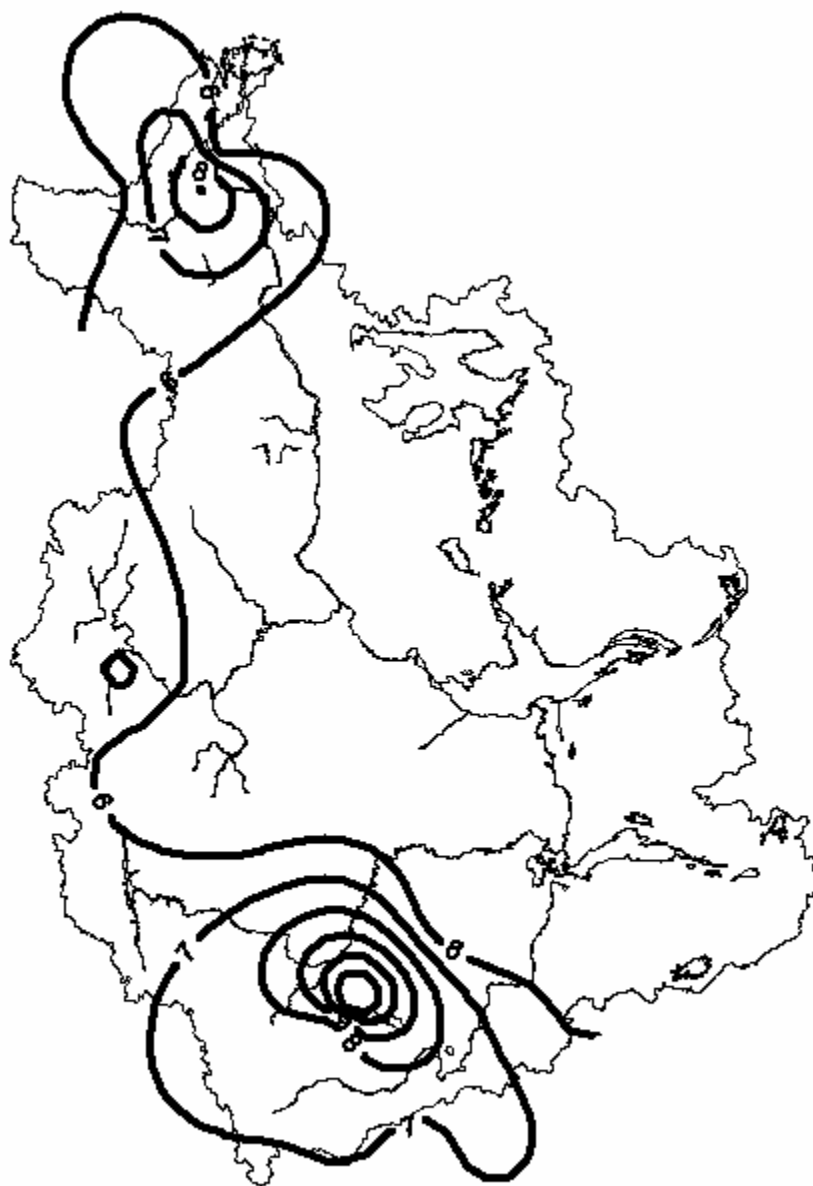


Figure 3c

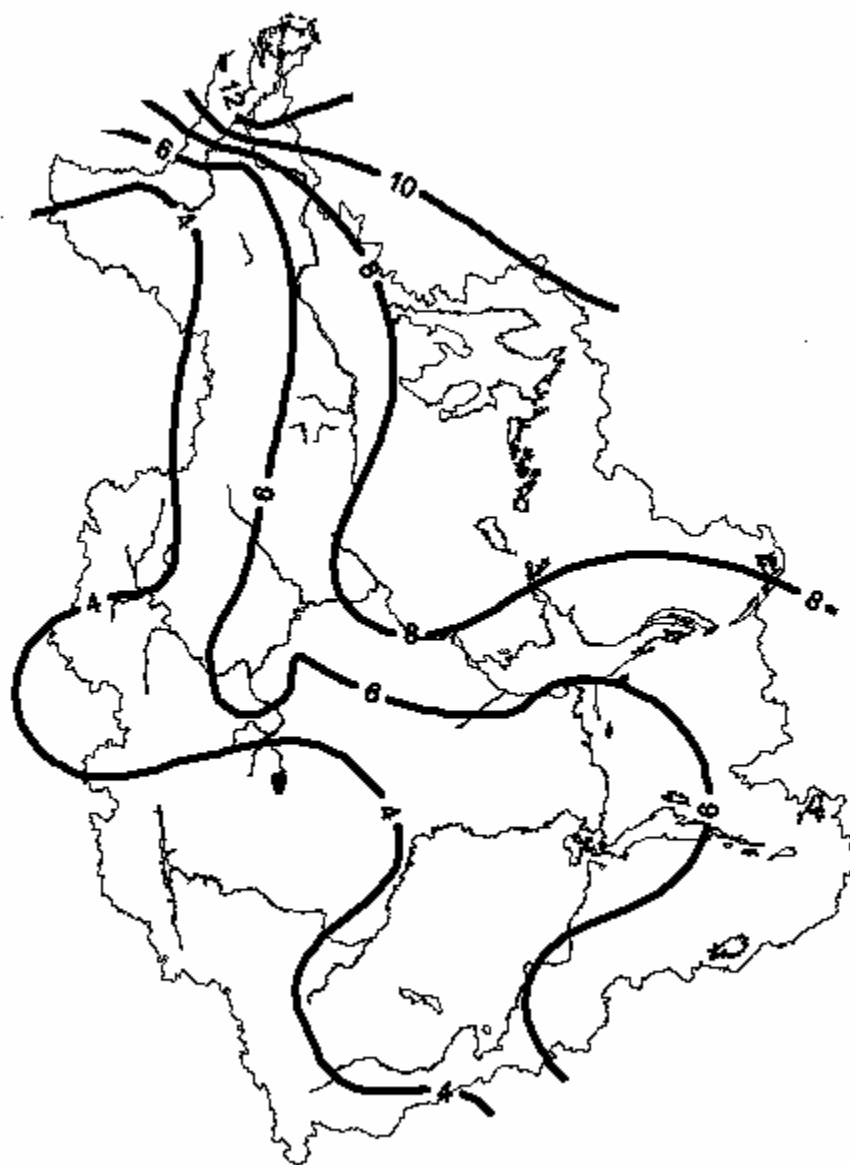


Figure 3d

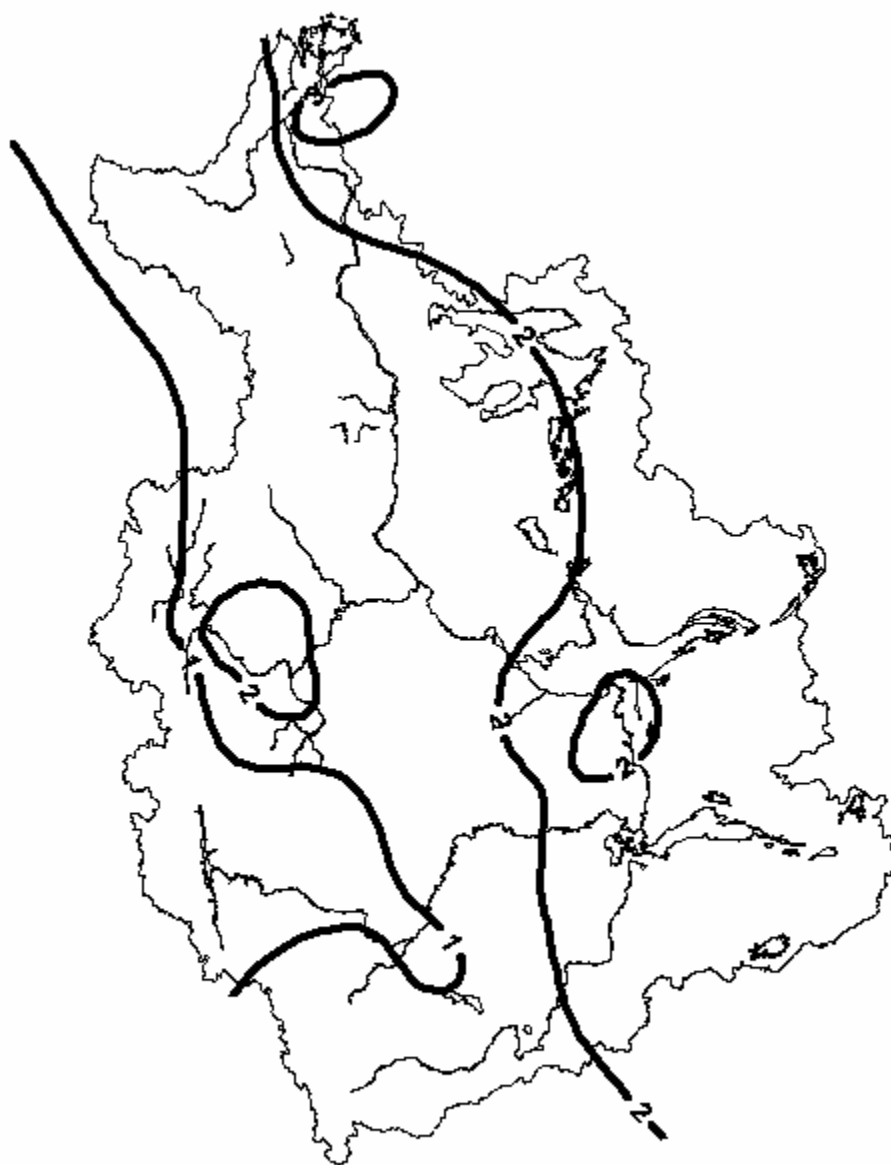


Figure 3e

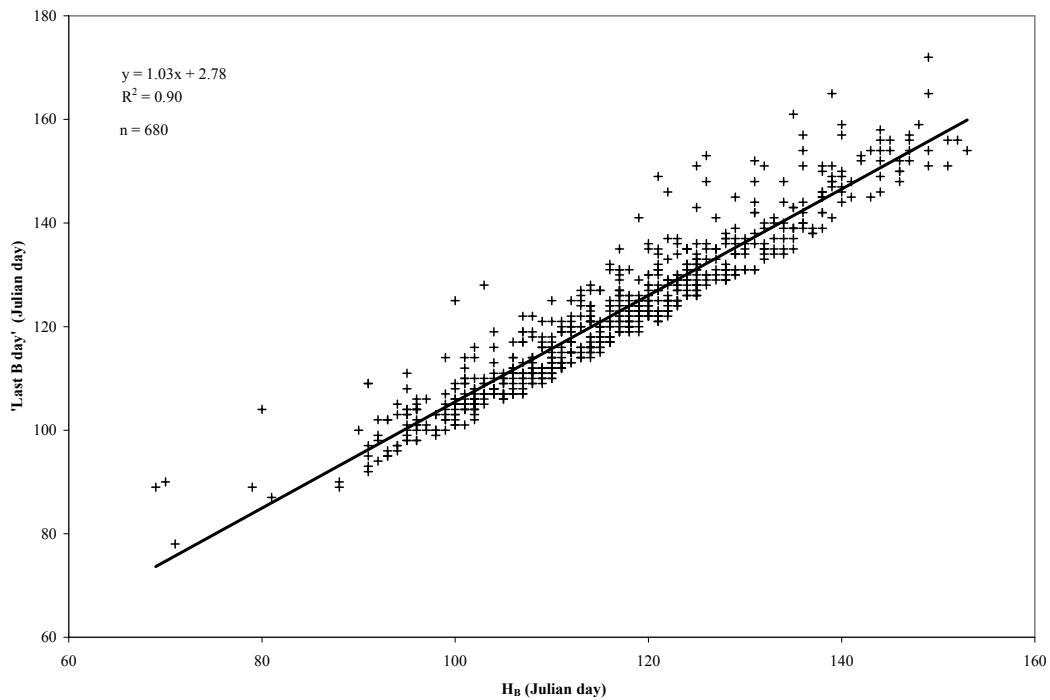


Figure 4

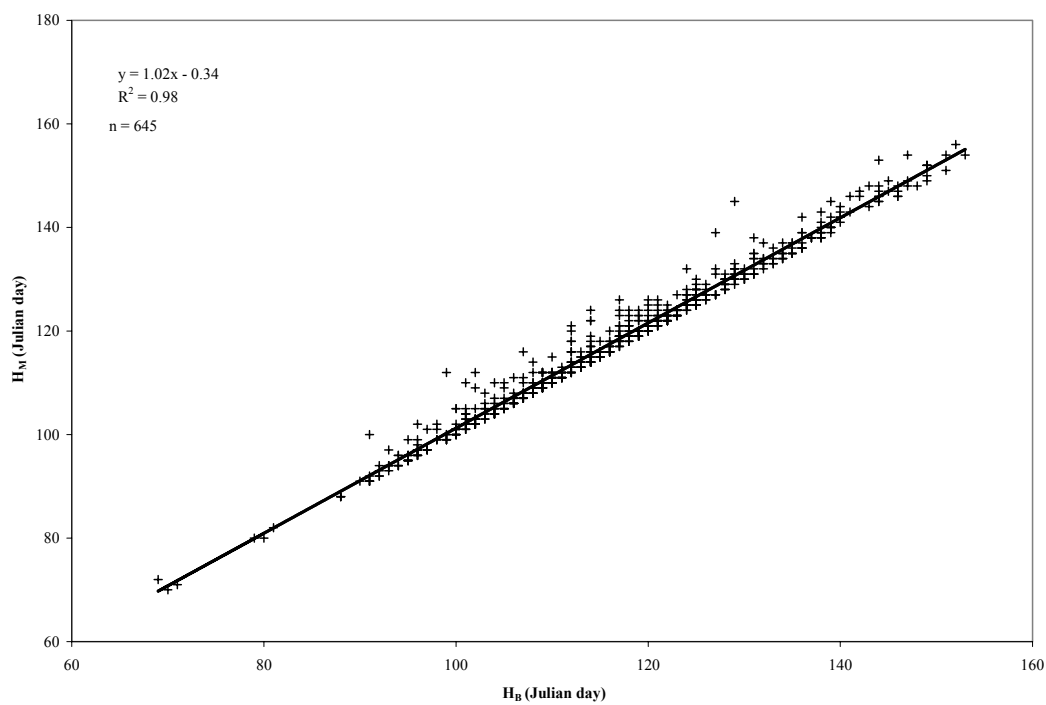
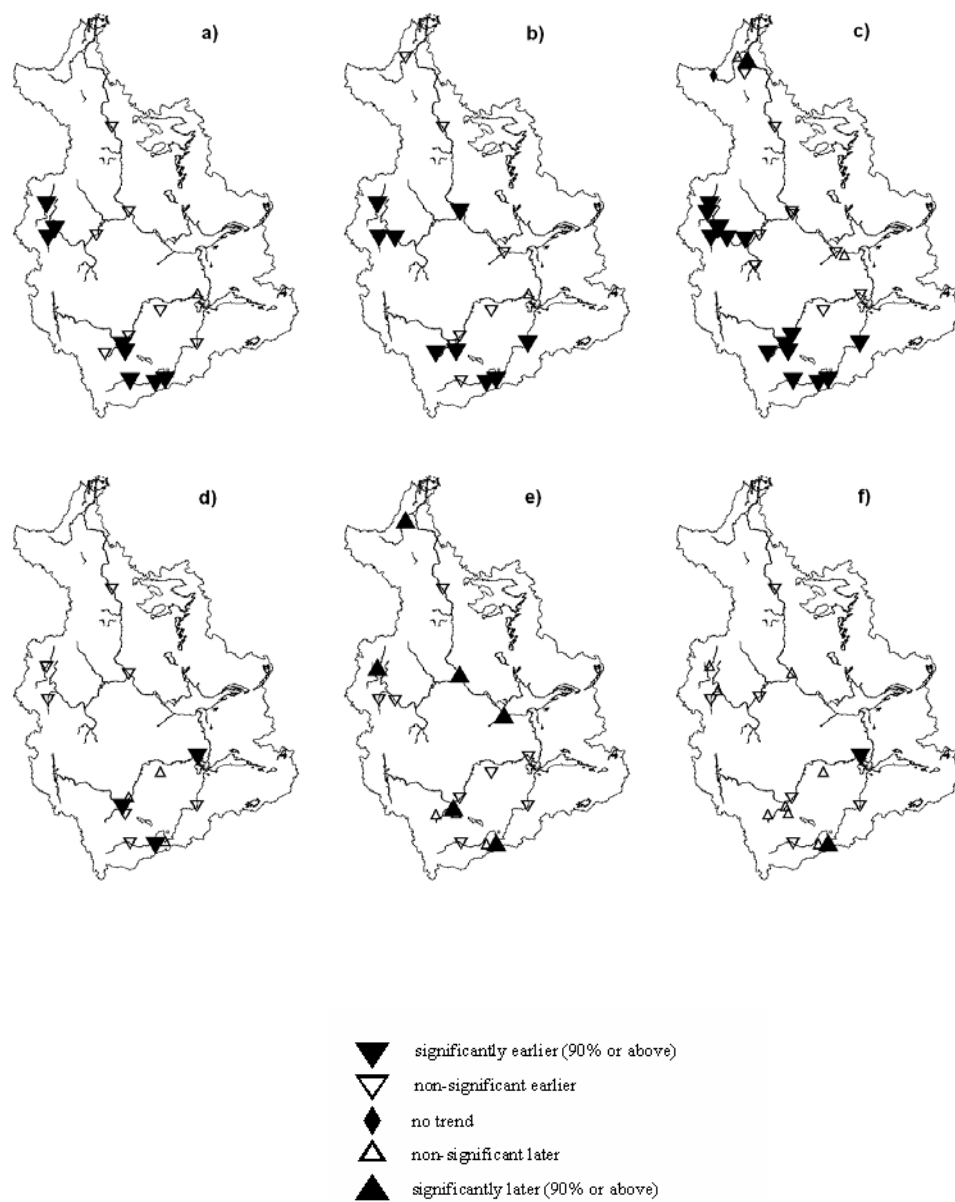


Figure 5

**Figure 6**

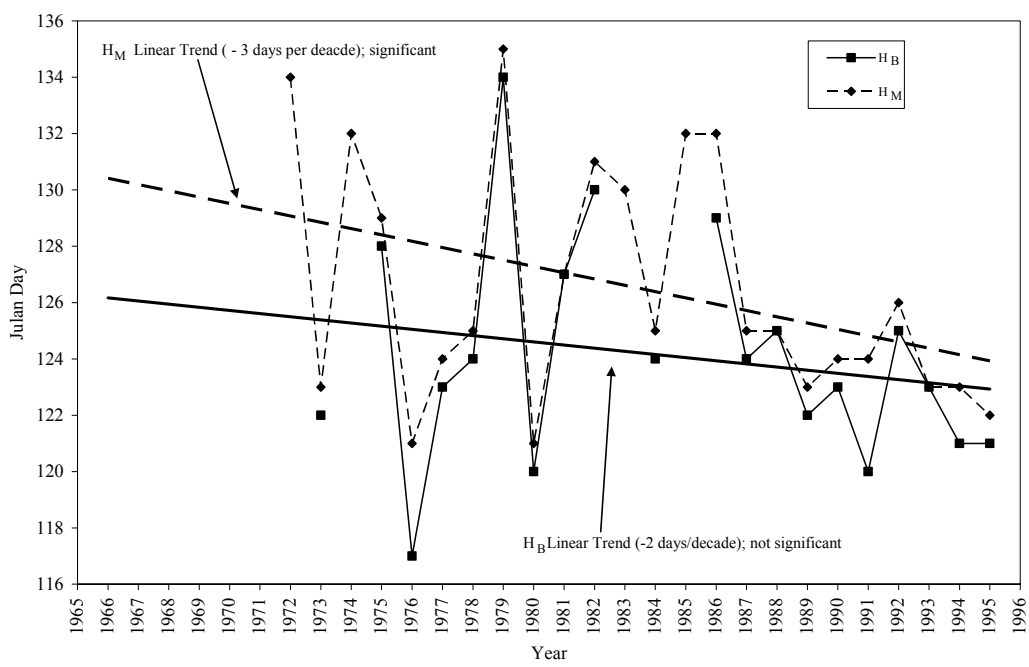


Figure 7

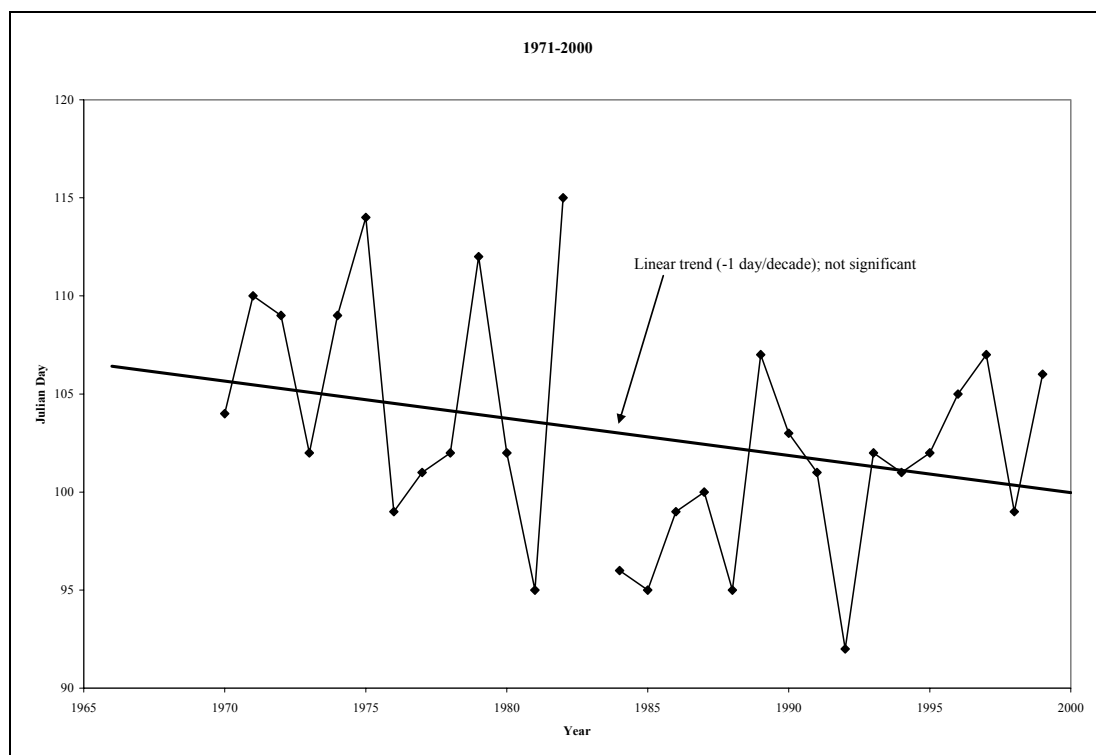
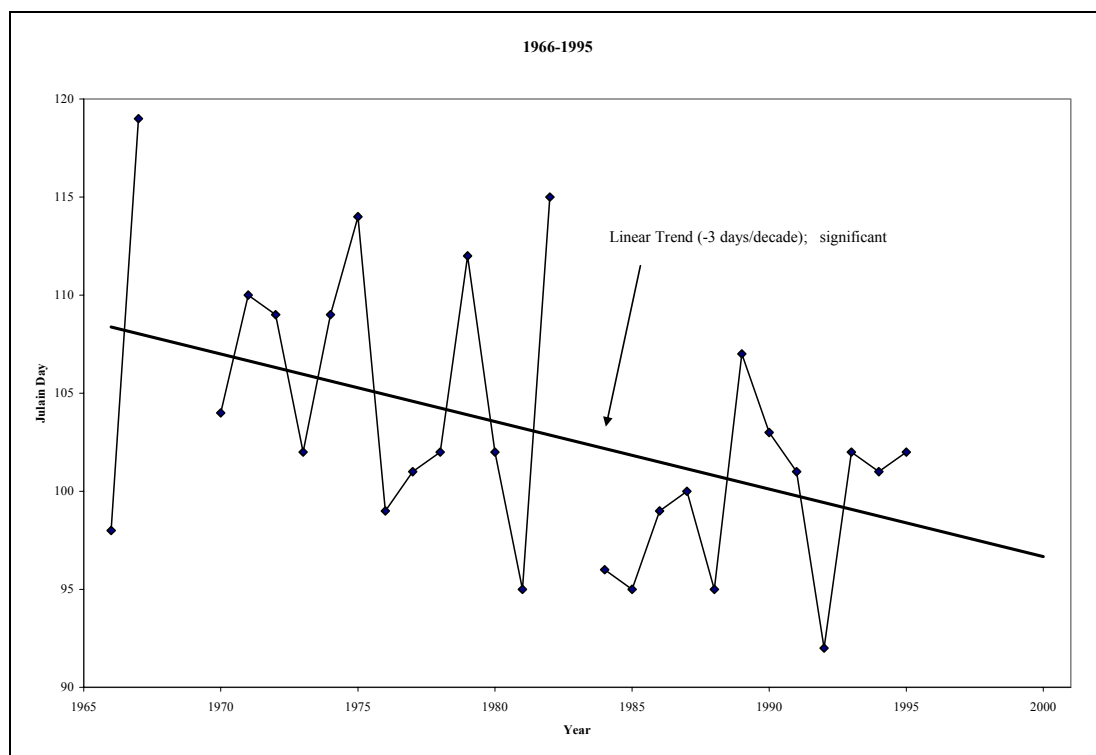


Figure 8

CHAPTER 4: CONCLUSION

To examine spatial and temporal variations of river-ice break-up in the Mackenzie River basin (MRB), Canada, several never-before assessed spring break-up event variables were extracted directly from Water Survey of Canada (WSC) hydrometric archives covering the 1913-2002 time period. The extracted variables included the timing of the initiation of break-up (H_B), and the timing and magnitude of the peak-water-levels occurring during the spring break-up season (H_M). The commonly assessed WSC ‘Last B date’ was also extracted to provide the timing of the end of the spring break-up period. Using these extracted variables, two journal-style manuscripts were written with Chapter 2 being focused on a quantification of ice break-up versus open water-levels and Chapter 3 focused on a temporal assessment of spring break-up in the MRB.

Results of Chapter 2 provide the 1st ever regional classification of river-ice break-up regimes. Return-period magnitudes at the 2, 2.33, 5, 10, 15, 20, 25 and 30 year return-periods for spring break-up (H_M) and open-water (H_O) were determined for 28 WSC hydrometric stations in the basin. In total 13(14) of the sites were identified as *spring break-up regime dominated* (R_B) (*open-water season regime dominated* (R_O)) with peak-annual events occurring during the respective season. At one location the dominance of high-water-levels was not clear, and was classified as *mixed break-up/open water regime* (R_M). Examination of the return period lines identified diverging, converging and parallel patterns, which were likely due to channel morphology. The commonly assessed 2.33-year mean annual open-water flood event was used as a baseline, and it was found that the magnitude of the 2.33-year spring break-up event at all R_B locations exceeds the

magnitude of the former. Thus, the 2.33-year event has limited applicability for flood studies on cold regions rivers. An assessment of the difference in water-levels between the 2 and 10-year ice and open-water events indicated that 70% of the stations in the basin experience greater water-level differences during the spring break-up period indicating the significance of ice on water-levels at the majority of sites within the basin.

A dimensionless stage versus discharge plot was used to compare mean spring break-up and open-water magnitudes at the sites. It was found that at R_B locations, when the break-up discharge is $\geq 1/4$ the open season discharge, water-levels can be expected to match and exceed those occurring during the open-water season. At R_O locations discharges $\sim 1/10$ of the open season flow result in water-levels reaching 50% of the open season events, while at the extreme end, when discharge during the spring break-up is equal to that occurring during open-water season, water-levels can be expected to increase by 60% over open water conditions. Finally, the spatial arrangement of the differing regimes were described using several physical, hydraulic and climatic characteristics. A map of the MRB was presented showing the dominant regimes in the basin.

In Chapter 3, spring break-up event timing variables including the initiation of break-up (H_B), peak water-levels during break-up (H_M) and 'Last B date', along with the time lags between events were used to describe the annual progression of ice break-up in the basin. It was found that the south to north break-up progression covers a period representative of $\sim 1/4$ of the year, while on average break-up lasts ~ 8 weeks. An anomalous zone of early spring break-up timing was found in the upper reaches of the Peace and Athabasca Rivers. The reasons for this are unclear. Time lags between events

were found to increase both in duration and variability moving from upstream to downstream. The reason is likely due to the occurrence of more mechanical type events on the downstream, R_B sites in the basin. Notably, for all sites in the basin, break-up duration was found to increase from south to north, and lasting, on average, from four days to four weeks depending on location. An assessment of the extracted variables (H_B and H_M) compared to the more commonly used 'Last B date' indicated that it is likely that previous studies indicating trends in 'Last B dates' are also applicable to the H_B and H_M event timing. A time series analysis was also performed and it was found that significantly earlier events are occurring over the 1966-1995 time period on regions of the upper Athabasca, Peace and Liard River systems. This regional shift towards earlier events, agrees with previous assessments of freshet timing for the MRB. Finally a comparison of trend results between the 1966-95 and 1971-2000 time period indicated the sensitivity of statistical test to shifting time periods.

Overall, the results of this research thesis provided several significant contributions to the field of cold-regions hydrology. The quantification of ice- versus open-water-levels, for the first time indicates the importance of river-ice on annual peak-water-level events at the cold regions watershed scale. The assessment of spring break-up event timing provides a quantification of the break-up using several never before assessed variables at the watershed scale.

The database of extracted variables developed for the thesis will be a valuable tool in future attempts to better understand the climatological controls of the ice break-up period. As temperature and precipitation data becomes more readily available to users in gridded formats, future research will be able to address how annual climatic conditions affect the

timing, and severity of the spring break-up period. Once the linkages are better understood, climate forecasts will enable researchers to predict changes to the spring break-up period at the watershed scale.

During the development and completion of this study, the reason for the sometimes slow development of advances in the field of cold-regions hydrology, specifically the spring break-up period, became evident to the author. The major reason is the lack of readily available hydrological information pertaining to this time of the year. Thus, if advances in understanding are to occur, an increased focus on the collection and dissemination of hydrometric data during the spring break-up period is required by all parties involved.

APPENDIX: LIST OF VARIABLES

CHAPTER 2:

H_M : maximum annual instantaneous/daily break-up water-level

H_O : maximum annual instantaneous/daily open water-level

Q_M : daily/instantaneous discharge corresponding to H_M event

Q_O : daily/instantaneous discharge corresponding to H_O event

H_M' : calculated magnitude of event at return period, where ' denotes 2, 2.33, 5, 10, 15, 20, 25, 30-year event

H_O' : calculated magnitude of event at return period, where ' denotes 2, 2.33, 5, 10, 15, 20, 25, 30-year event

H_M' Event: return period of event (H_M') which equals or exceeds the 2.33-year H_O' event

$\Delta H_{2.33}$: difference in water-level between the 2.33-year H_O' and H_M' Event

$\Delta H_M' 2$: difference in water-level between the 2 and 10-year H_M'

$\Delta H_O' 2$: difference in water-level between the 2 and 10-year H_O'

$\overline{Q_I}$: mean ice break-up discharge

$\overline{Q_O}$: mean open-water discharge

$\overline{H_I}$: mean ice break-up water-level

$\overline{H_O}$: mean open-water-level

CHAPTER 3:

H_B : timing of the initiation of break-up

H_M : timing of the peak water-level during break-up

'Last B date': last day when ice assumed to be affecting channel flow hydraulics

t_1 : break-up drive

t_2 : break-up wash

t_3 : break-up duration

$(\bar{\quad})$: mean value of break-up variables

(\pm) : standard deviation of break-up variables