

An Assessment of the River Ice Break-up Season in Canada

by

Simon Julius von de Wall
B.Sc., University of Victoria, 2007

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of the Requirements for the Degree of

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in the Department of Geography

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Abstract

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A return-period analysis of annual peak spring break-up and open-water levels for 136 Water Survey of Canada hydrometric stations was used to classify rivers across Canada and to assess the physical controls on peak break-up water-levels. According to the peak water-level river-regime classification and subsequent analysis, 32% of rivers were classified as spring break-up dominated, characterized by low elevations and slopes and large basin sizes while 45% were open-water dominated and associated with alpine environments of high elevations and channel slopes, and smaller basin sizes. The remaining 23% of rivers were classified as a mixed regime. A spatial and temporal analysis (1969-2006) of the river ice break-up season using hydrometric variables of timing and water levels, never before assessed at the northern Canada-wide scale, revealed significant declines in break-up water levels and significant trends towards earlier and prolonged break-up in western and central Canada. The spatial and temporal influence of air temperature on break-up timing was assessed using the spring 0°C isotherm, which revealed a significant positive relationship but no spatial patterns. In the case of major ocean/atmosphere oscillations, significant negative (positive) correlations indicate that break-up occurs earlier (later) during the positive phases of the Pacific North American Pattern (El Niño Southern Oscillation) over most of western Canada. Fewer significant positive correlations show that break-up occurs later during the positive phases of the Arctic Oscillation and North Atlantic Oscillation in eastern Canada.

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Dedication

*To my parents, with whom I would have loved
to share the completion of this work*

Preface

Throughout the research phase of this project, interim results of chapter 2 and 3 have been presented at several national and international scientific conferences and symposia. These include the *17th International Northern Research Basins Symposium and Workshop*, the *67th Annual Meeting of the Eastern Snow Conference*, the *6th and 7th ArcticNet Annual Scientific Meetings*, the *3rd Joint Congress of the Canadian Meteorological and Oceanographic Society and the Canadian Geophysical Union*, and the *63rd National Conference of the Canadian Water Resources Association*. Notably, chapter 2 originated from the published proceedings paper presented at the *17th International Northern Research Basins Symposium and Workshop*, while chapter 3 evolved from the proceedings and Wiesnet Award for best student paper presented at the *67th Annual Meeting of the Eastern Snow Conference*. For this reason, both content chapters are written in the form of two stand-alone, journal-style manuscripts intended for publication in leading hydrologic journals.

REFERENCES

- von de Wall S, de Rham LP, Prowse TD. 2009. Open water and ice-induced extreme water levels on Canadian rivers. In *Proceedings of the 17th International Northern Research Basins Symposium and Workshop*, Young KL, Quinton W (eds). Iqaluit-Pangnirtung-Kuuujuaq, Canada; 337-347.
- von de Wall S, de Rham LP, Prowse TD. 2009. Assessment of Spring Break-up Water Levels on Canadian Rivers. In *Conference Programme and Abstracts of the 6th ArcticNet Annual Scientific Meeting* Victoria, BC, Canada; 69.
- von de Wall S, de Rham LP, Prowse TD. 2010. The river ice break-up season in Canada: variations in water levels and timing. Presented at the *3rd Joint Congress of the Canadian Meteorological and Oceanographic Society and the Canadian Geophysical Union*, Ottawa, ON, Canada.
- von de Wall S, de Rham LP, Prowse TD. 2010. The river ice break-up season in Canada: variations in water levels and timing. Presented at the *67th Annual Meeting of the Eastern Snow Conference*, Hancock, MA, USA.
- von de Wall S, de Rham LP, Prowse TD. 2010. A national-scale assessment of spring break-up on Canadian rivers. Presented at the *63rd National Conference of the Canadian Water Resources Association*, Vancouver, BC, Canada.
- von de Wall S, de Rham LP, Prowse TD, Wrona FJ. 2010. A Canada-wide assessment of spring break-up water levels and relevant physical controls. In *Conference Programme and Abstracts of the 7th ArcticNet Annual Scientific Meeting* Ottawa, ON, Canada.

CHAPTER 1: INTRODUCTION

1. INTRODUCTION

As an integral component of the terrestrial cryosphere, river ice gives rise to a myriad of ecological, geomorphological and socio-economic effects on nearly 60% of rivers in the Northern Hemisphere (Prowse, 2005; Bennett and Prowse, 2010). Notably, these effects are confined primarily to the brief, but critical spring break-up period and are generated by the direct physical action of river ice and in particular, by the significantly elevated flood water levels (Beltaos, 2008). Notwithstanding the environmental implications, the socio-economic cost of river ice related damage associated with this period can be substantial and is estimated at \$250 million (USD) per year for North America alone (Prowse, 2007). For this reason, and in light of the anticipated increasing uncertainty due to a changing and more variable climate, further research needs to be undertaken to improve our current understanding of the complex river-ice dynamics during the spring break-up period.

2. RESEARCH UNKNOWNNS

Although the research of river ice hydrology has progressed significantly, flood-related studies have for the most part focused on the open-water period, while those assessing break-up flooding have mostly been limited to the site-specific scale. Consequently, Beltaos and Prowse (2001) recommended the need for large basin-scale assessments of rivers using ice versus open-water dominated water levels. In response, de Rham *et al.* (2008a) proposed a spring break-up, river-regime classification and quantified annual,

peak ice-induced and open-water levels for a suite of hydrometric stations in the Mackenzie River Basin. Until then, such a large-scale assessment had never been conducted, primarily because most hydrometric monitoring programs publish discharge rather than water level data, making the requisite data difficult to obtain. In addition, open-water flood studies commonly rely on stage-discharge-based return-period assessments, which are unreliable during spring break-up because in-channel ice effects generate peak water levels that frequently exceed those of the open-water period for comparable discharges. It follows that accurate assessments of flood-risk on cold-region rivers necessitate water-level data to account for river ice as a flood-producing mechanism. Although much of this is also applicable to mid-winter break-ups, which typically occur less frequently but are associated with conditions that generate very high water levels, this study is designed to focus exclusively on the spring break-up of river ice.

First and foremost, this work expands that of de Rham *et al.* (2008a) to enable a large-scale analysis of break-up flood regimes across the multiple hydro-climatic regions of Canada, while also addressing the recommendation of Beltaos and Prowse (2001) to examine the influence of invariable channel characteristics on break-up water levels. Deemed necessary because spring break-up water levels are not only controlled by climate but also by physical conditions (e.g., channel morphology and watershed characteristics), an assessment of this kind had never been conducted prior to this work. Instead, most large-scale analyses of break-up have generally relied on air temperature indices to assess the spatial and temporal aspects of river ice (e.g., Bonsal and Prowse,

2003; Bonsal *et al.*, 2006), while the most detailed studies of break-up conditions (e.g., physical controls of break-up) are almost exclusively site-specific (e.g., Petryk, 1990).

Consequently, these discontinuities in river ice research are addressed first, by providing a spring break-up, river-regime classification using annual, peak ice-induced and open-water levels, and second, by assessing the influence of invariable channel characteristics on break-up water levels.

A further contribution of the second component of this work stems from the use of novel event-based hydrometric variables of timing and water levels to assess the spatial and temporal trends of the river ice break-up season. Although similar studies of break-up timing have previously been conducted, this work is distinct in that these variables are more representative and descriptive of the entire river-ice break-up season. This is in contrast to the majority of large-scale studies that have relied primarily on the Water Survey of Canada (WSC) 'Last B date' qualifier to indicate the last day of ice conditions (e.g., time when flow in channel is affected by ice). Unfortunately however, this indicator is rarely confirmed with on-site observations.

More importantly, this work is highly relevant in that it examines the spatial and temporal changes in break-up water levels as part of a more comprehensive assessment. Studies of this kind are non-existent at this point in time because, as previously noted, large-scale studies have mostly focused on assessing changes in spring freshet flows rather than water levels, while those using water levels are limited to the site-specific scale. Collectively, this work will represent a significant contribution to the study of river ice hydrology.

3. DATA SOURCES

The primary data for this research originates from the Water Survey of Canada (WSC), the agency responsible for monitoring river discharge across Canada. Although the WSC's primary objective is to publish river flows, water level data are required to calculate discharges using local discharge-rating curves. While a number of methodologies are used to determine water levels, the majority of hydrometric stations utilize continuous and near-continuous recording systems including stilling well and pressure actuated systems, all of which conform to the standards set forth by the World Meteorological Organization (WMO) (Turgeon 1999). In contrast to discharge data published by the WSC, water-level data are retained as original pen-chart or digital recordings, and have only recently become readily available as daily values that are mostly limited to the open-water period. For this reason, and for the purpose of this research, event-based water level and timing data were extracted directly from original WSC hydrometric records. Data extraction for each hydrometric station was supported by WSC metadata including station description, hydrometric survey notes, gauge and benchmark history, and discharge and annual water-level tables.

To ensure that hydrometric stations are representative of rivers where break-up primarily occurs as a spring event, a focus was placed on northern-latitude sites. As a first-order guide, available sites were included north of the southern extent of a "temperate ice zone" defined by Prowse *et al.* (2002). Additional sites close to this line, representative of the high-elevation cold-regions climate of south-western Canada, and known to be characterized by spring break-up, were also included. All selected sites were required to have a minimum record length of ≥ 10 years and a minimum catchment

size of $\geq 10\,000\text{ km}^2$. Based on Prowse and Lacroix (2001), the latter requirement was used to try and eliminate sites with insufficient flow to develop a free floating ice cover. The final selection included 136 WSC hydrometric stations with records encompassing the 1913-2006 period and ranging in elevation from near sea level to 874 metres above sea level.

4. STUDY AREA

Since this work is a comprehensive assessment of spring river-ice break-up that evaluates the effects of climate as well as physical controls across all of Canada, every attempt was made to ensure that hydrometric stations are representative of the highly varied landscape and climate of the country. Unfortunately, the lack of data availability in remote regions, combined with the selection criteria noted above, resulted in limited representation in some of the north, north-eastern and eastern maritime parts of the country. Otherwise, the study area encompasses 8 of the 11 climatic regions of Canada, which include the dominant maritime influences of the Pacific and Atlantic Oceans as well as those dominated by the Arctic and Interior Continental environments. With respect to physical landscape characteristics, selected hydrometric stations are located in 5 of 6 physiographic regions across the country. Further details about the climatic and physiographic regions are provided in chapter 2 as they are integral to the analysis provided therein.

5. SPECIFIC OBJECTIVES

The overall research objectives of this work are addressed through two stand-alone journal-style manuscripts. In *verbatim*, the detailed components of objective 1, addressed in Chapter 2, are to:

- 1) *produce a peak water-level river-regime classification (WRC) of northern Canada based on a return-period analysis of annual peak, spring break-up and open-water levels,*
- 2) *compare the resulting spatial patterns to those for standard regional climatic and physiographic classifications, and*
- 3) *assess the relative importance of a number of physical characteristics that affect the identified river-regime classifications using multivariate and post hoc statistical methods.*

The specific components of objective 2, detailed in Chapter 3, are to:

- 1) *update the mean spatial and temporal patterns of river ice break-up using event-based break-up variables and assess the influence of the spring 0°C isotherm on river ice break-up in northern Canada,*
- 2) *perform trend analyses of the timing and water levels associated with the spring river-ice break-up season, and*
- 3) *examine the relationship between inter-annual climate variability, as implied by large-scale ocean/atmosphere oscillations, and the timing of the river ice break-up season.*

A complete summary and conclusions of this work are provided in Chapter 4, which also includes future research recommendations developed throughout the course of this research.

REFERENCES

- Bennett KE, Prowse TD. 2010. Northern Hemisphere geography of ice-covered rivers. *Hydrological Processes* **24**: 235-240.
- Beltaos S, Prowse TD. 2001. Climate impacts on extreme ice jam events in Canadian rivers. *Hydrological Sciences Journal* **46**: 157-181.
- Beltaos S. (ed). 2008. *River Ice Break-up*. Water Resources Publications, LLC, Highlands Ranch, CO, USA.
- Bonsal BR, Prowse TD. 2003. Trends and variability in spring and autumn 0 °C isotherm dates over Canada. *Climatic Change* **57**: 341-358.
- Bonsal BR, Prowse TD, Duguay CR, Lacroix MP. 2006. Impacts of large-scale teleconnections on freshwater-ice duration over Canada. *Journal of Hydrology* **330**: 340-353.
- de Rham LP, Prowse TD, Beltaos S, Lacroix M. 2008a. Assessment of annual high water events for the Mackenzie River basin, Canada. *Hydrological Processes* **22**: 3864-3880.
- Petryk S. 1990. Case studies concerned with ice jamming. In *Working Group on River Ice Jams: Field Studies and Research Needs*. NRHI Science Report No. 2. National Research Hydrology Institute, Environment Canada, Saskatoon, SK, 85-112.
- Prowse TD, Bonsal BR, Lacroix MP, Beltaos S. 2002. Trends in river-ice break-up and related temperature controls. In *Ice in the Environment: Proceedings of the 16th IAHR Conference on Sea Ice Processes*. Squire VA, Langhorne PJ (eds.), International Association of Hydraulic Engineering and Research, Dunedin, New Zealand, 64-71.
- Prowse TD. 2005. River-ice hydrology. In *Encyclopedia of Hydrological Sciences*. Anderson MG (ed.), John Wiley and Sons, West Sussex, England, 2657-2677.
- Prowse TD, Lacroix MP. 2002. Hydrologic Extremes on Arctic Flowing Rivers: Analysis and Recovery. Climate Change Action Fund (CCAF) Project S99-13-13.
- Prowse TD, Bonsal BR, Duguay CR, Hessen DO, Vuglinsky VS. 2007. River and Lake Ice. In *Global Outlook for Ice and Snow*. United Nations Environment Programme, DEW/0924/NA, available online: http://www.unep.org/geo/geo_ice/. (accessed 17 May 2009).
- Turgeon DL. 1999. The Water Survey of Canada: Hydrometric Technician Career Development Program. Environment Canada, Guelph Ontario. Available online at: <http://www.ec.gc.ca/rhc-wsc> (last accessed December 2011).

CHAPTER 2: OPEN-WATER AND ICE-INDUCED EXTREME WATER LEVELS ON CANADIAN RIVERS

ABSTRACT

Extreme water levels associated with the spring break-up period are some of the most significant hydrologic events on cold-regions rivers with important morphological, ecological and socio-economic implications. Numerous rivers experience their annual, peak water level due to in-channel ice processes, which frequently exceed open-water levels for comparable discharges. To this end, the physical controls of peak, spring break-up water levels have only been examined in disparate case studies and not quantified in a large-scale assessment. Previous studies of hydro-climatic controls on river ice have focused on phenologies rather than exploring the effects of hydro-climatic controls on peak, break-up water levels. Using a return-period analysis of annual peak, spring break-up and open-water levels, this paper presents a northern Canada-wide classification of river regimes, which is also compared to the spatial patterns of large-scale climatic and physiographic regions. Based on the results of this pattern analysis and previous research recommendations, the importance of major physical controls including elevation, channel slope, basin area and latitude were assessed using Canonical Correspondence Analysis. Across northern Canada, results show that the peak water-level regimes of 32% of rivers are classified as spring break-up dominated, 45% as open-water dominated and 23% as a mixed hybrid. Spatial patterns and statistical results indicate that annual peak water levels on rivers dominated by a cold continental climate and generally low relief, and more specifically on those also characterized by low elevations and slopes and large basin sizes, are generated predominantly by spring break-

up conditions. By contrast, rivers in more temperate or maritime climates, especially those associated with alpine environments of high elevations and channel slopes, and with smaller basin sizes tend to have their annual, peak water levels produced under open-water conditions. Somewhat surprisingly, latitude does not feature prominently as a control on the regime classification at this scale.

Keywords: Cold regions hydrology; river ice break-up; flood levels; return-period analysis; river regimes

1. INTRODUCTION

A large portion of the rivers in the Northern Hemisphere are affected seasonally by river ice (Bennett and Prowse, 2010). Of greatest importance is the spring break-up period that can produce a number of ecological effects (e.g., Cunjak *et al.*, 1998; Prowse, 2001a; Prowse and Culp, 2003), alter channel morphology, produce severe erosion, and greatly increase sediment fluxes (e.g., Prowse, 2001b; Ettema and Daly, 2004). This period is also responsible for a variety of socio-economic impacts, largely related to extreme high water levels and associated flooding (Beltaos, 2008). For example, a recent estimate of ice related damages by Prowse *et al.* (2007) cites a value of \$250 million (USD) per year for North America. Many of these effects are expected to be exacerbated under climate change (Wrona *et al.*, 2005; Anisimov *et al.*, 2007). Unfortunately, however, there are no broad regional assessments of river-ice baseline conditions from which future changes can be referenced.

During spring break-up, the most important hydrologic effect of river ice is manifested by elevated water levels. Although peak water levels during the open-water season are generally a result of basin-scale landscape processes, ice-induced peak water levels during the spring break-up period occur primarily due to in-channel ice effects (Gerard, 1990). For example, assuming equal bottom ice cover and channel roughness, the additional hydraulic resistance of an ice cover can produce a 30% increase in mean water level for comparable open-channel discharges (Gray and Prowse, 1993). Water levels can be substantially higher during spring break-up as a result of an increase in ice cover roughness and water level increases of 2-3 times for comparable open-channel discharges are not uncommon (Beltaos, 1982; Prowse, 2005).

Beltaos and Prowse (2001) emphasize that spring break-up water levels are not only controlled by climate, but also by physical conditions, such as channel morphology and watershed characteristics. In this regard, regional-scale studies of spring break-up have primarily relied on climate variables, such as air temperature, and focused only on simple ice phenologies (e.g., Bonsal and Prowse, 2003; Bonsal *et al.*, 2006). By contrast, more detailed evaluations of river-ice break-up conditions, such as peak water levels and the physical controls of break-up, have only been studied at the site-specific scale (e.g., Petryk, 1990), while regional-scale assessments are virtually non-existent.

Given the above, Beltaos and Prowse (2009) recommended that broad-scale assessments of the physical and climatic controls of river-ice break-up be undertaken. The first such regional assessment was conducted by de Rham *et al.* (2008a) for the Mackenzie River Basin, Canada. The authors analyzed return-periods of annual-peak ice-induced and open-channel water levels to produce a large basin-scale classification of rivers (i.e., ice versus open-channel dominated high water-level regimes), although only qualitative links were made to controlling physical variables. Expanding the focus to include a greater range of physiographic and climatic regimes, the broad goal of this research was to conduct a similar assessment of rivers over northern Canada, and to quantify statistically the importance of key physical controls that influence the ice versus open-channel regime classifications. Specifically, the objectives were to: (i) produce a northern Canada-wide peak water-level river-regime classification (WRC) based on a return-period analysis of annual peak, spring break-up and open-water levels; (ii) compare the resulting spatial patterns to those for standard regional climatic and physiographic classifications, and (iii) assess the relative importance of a number of

physical characteristics that affect the identified river-regime classifications using multivariate and *post hoc* statistical methods.

2. BACKGROUND

There are four distinct flow regimes that occur on ice-affected rivers: open-water, autumn freeze-up, mid-winter and spring break-up (Davar, 1979). For the three ice-affected periods, spring break-up typically produces the highest water levels because of spring snowmelt runoff and break-up dynamics, and is typically classified by two contrasting types, *dynamic* and *thermal* (Gray and Prowse, 1993). Both types represent the extremes of the break-up continuum, and reflect the balancing of opposing driving and resisting forces. The former represents factors such as increasing discharge and the gravitational ice cover component; the latter is controlled primarily by the strength and thickness of the ice cover and its attachments to the bed and banks. In general, a *dynamic* break-up produces the highest water levels due to both, high driving (e.g., large and rapid snowmelt) and resisting (mechanically competent ice cover) forces. By contrast, a *thermal* break-up, which produces only minor increases in water levels, occurs when the ice cover has been thermally decayed to a point when it presents little hydraulic resistance to flow and/or when there is only a small increase in spring flows. Spring break-up in any year can occur anywhere along this continuum of *dynamic* to *thermal* conditions, and will be reflected in the magnitude of the resulting water levels (Beltaos, 2003).

Beltaos and Prowse (2001) identified a number of physical (e.g., channel and basin characteristics) and climatic conditions that affect the magnitude of spring break-up water levels. Although controlling meteorological conditions can be highly variable (e.g., heat

fluxes that control the magnitude and intensity of spring snowmelt, or winter ice thickness and spring ablation), their "average" condition can be assumed to be reflected in the climatic regime of a region. The same is true for climatic/meteorological conditions controlling open-water levels (e.g., via rainfall magnitude and intensity). In contrast, physical controls of spring break-up water levels can be considered largely invariable, and include channel morphology (e.g., width, depth, slope and sinuosity; Kalinin, 2007) and run-off related watershed characteristics (e.g., basin elevation, slope, aspect and land cover). These controlling climatic and physical controls are broadly captured, although to varying degree, by the regional climatic and physiographic classifications employed below.

3. DATA SOURCES

3.1. Hydrometric Data

All analyses were conducted using data obtained from the Water Survey of Canada (WSC). While discharge data are readily available in digital format, water-level data that have only recently become available as a digital product are limited to daily values of short record length and typically only for the open-water period. For this reason, analyses of water levels during break-up, a period of rapid water-level fluctuations, required the extraction of information directly from the original pen-charts (~ pre mid 1990's) and later digital (~post mid 1990's) records, supported by examination of other metadata including hydrometric survey notes, station analysis and daily water level tables.

The focus of this work was on northern latitude sites in Canada to ensure that hydrometric stations are representative of rivers where spring break-up primarily occurs

as a spring event. As a first-order guide, available sites north of the southern extent of a "temperate ice zone" defined by Prowse *et al.* (2002) were included. Additional sites in the vicinity of this zone that are representative of the high-elevation cold-regions climate of south-western Canada, and known to be characterized by spring break-up, were also included. All selected sites were required to have a minimum record length of ≥ 10 years and a basin size of $\geq 10\,000$ km². The latter requirement, based on Prowse and Lacroix (2001), was designed to try and remove sites with insufficient flow to produce a free floating ice cover. The final selection resulted in 136 WSC hydrometric stations with records ranging from 1913 to 2006 with elevations from near sea level to 874 metres above sea level.

3.2. Physical Data

The selection of physical variables considered to be key factors affecting the river-regime classifications at the selected scale of this study are based on the recommendations in de Rham *et al.* (2008a), and the inter-comparison of initial WRC results to broad climatic and physiographic regional patterns (further detailed in section 4.2 below). The final selection of physical variables included: basin area (A), latitude (ϕ), elevation (E) and channel slope (S). Site-specific data for the first two were obtained from the WSC hydrometric station records, while those of the latter two were derived from the HYDRO 1k dataset, which is the hydrologically modified version of the 30 arc-second digital-elevation model GTOPO30 (USGS, 2009). Requisite S data were calculated from a 1km x 1km horizontal and 1m vertical resolution using ArcGIS 9.3TM (ESRI, 2008). Specifically, dimensionless ratio values of S were obtained as a quotient of the reach difference in elevation and reach length, the latter initially defined as 30

times the local river width. This definition is frequently used in fluvial geomorphology applications and allows for homogenous samples of S that are more representative of different sized rivers and minimizes small-scale variations (Simon and Castro, 2003). However, because of scale issues for narrow rivers, this width-length ratio precluded calculation of S for 40% of the selected sites. It was subsequently increased to 50, which then permitted derivation of S values for 126 of the 136 sites. Variables S and A were then log-transformed to limit their effect on central tendency and variances prior to analysis.

Although it was recognized that morphological characteristics of a river at a short-reach scale might influence the probability of particular ice effects, these site-specific morphological differences among hydrometric sites were assumed to be insignificant in affecting the results of the regional-scale regime classifications. This is primarily because the hydrometric station selection criteria used by WSC are designed to avoid open-water backwater conditions, i.e., selecting relatively straight sections that are sufficiently upstream of hydraulic obstructions (see Rantz, 1982 in Rees, 1999).

4. METHODOLOGY

4.1. Peak Water-Level River-Regime Classification

4.1.1. Northern Canada-wide

The background procedures used here to obtain the WRC are outlined in de Rham *et al.* (2008a) and Beltaos (1990). The classification is based on a comparison of the return-periods for annual maximum water levels during break-up (H_B) and the open-water period (H_O). The spring period examined for H_B was limited to those days denoted by WSC as being "ice affected" and labeled in the WSC records with a "B". H_B applies to

the peak water level occurring anywhere from break-up initiation to final ice clearance. Maximum levels are attained if an ice jam forms and, with sufficient ice supply, develops into an equilibrium state (e.g., see Beltaos *et al.*, 2008).

Because of the dynamic nature of river ice break-up, damage to water-level recording instrumentation is common and, hence, instantaneous peak water levels are often missed. Where possible, these missing values were replaced by mean-daily water levels, although these would typically be underestimates. H_O values were obtained from published instantaneous values or via conversion from a stage-discharge rating curve using records of instantaneous discharge. In the case where neither was available, values were derived from records of daily maximum discharge.

Since the WSC uses an arbitrary datum to reference water levels at hydrometric stations, such values do not reflect the true water depth. To permit comparison, all water level data were converted to nominal water depths (Y_B and Y_O) by referencing them to a 'zero stage at zero discharge' derived using the local rating curve (e.g., see de Rham *et al.*, 2008a). Return-periods (R) of Y_B and Y_O for each hydrometric station were then derived using the Weibull method, a cumulative frequency analysis that has found wide application in hydrology (Weibull, 1939; Singh, 1986; de Rham *et al.* 2008a).

Subsequently, R_B and R_O , were conventionally plotted with time (water level) on a logarithmic (arithmetic) scale. Equations were then derived for the 2, 5, 10, 15, 20, 25 and 30 year return-periods and subsequently used to define the WRC for each site. If $R_B/R_O < 1$ (>1) for all of the specified return-periods a site was classified as being open-water, R_O , (ice break-up, R_B) dominated. If the return-period ratios were mixed, it was classified as a mixed regime (R_M).

4.1.2. Synthetic Stage and Discharge

To further aid in the analysis of the WRC, mean ice-induced ($\overline{Q_B}$) and open-water discharge ($\overline{Q_O}$) and nominal water levels ($\overline{Y_B}$, $\overline{Y_O}$) for the 136 hydrometric sites were produced. The ratios of discharge ($\overline{Q_B} / \overline{Q_O}$) and water levels ($\overline{Y_B} / \overline{Y_O}$) were plotted as a 'synthetic stage and discharge curve' (e.g., de Rham *et al.*, 2008a) to allow the comparison of mean annual, peak water level and discharge for both types of events.

4.2. Classifications of Climate and Physiography

Two regional classifications of climate and physiography were compared to the above derived WRC data set. For broad-scale climatic comparison, the climatic regions originally defined by Hare and Thomas (1979) and later modified by Gullett *et al.* (1992) were used. These have been utilized in other applications such as the *Historical Canadian Climate Database* (Gullett *et al.*, 1992) and the *Climate Trends and Variations Bulletin* (Environment Canada, 2009). To assess whether regional combinations of physical characteristics are reflected in the WRC pattern, the major physiographic regions of Canada defined in Fulton (1989) were also employed. As earlier noted, the results obtained were also used to aid in the selection of specific physical variables for further analysis.

4.3. Assessment of Specific Physical Characteristics

4.3.1. Normality of Data

Prior to selecting the appropriate statistical methods for analysis, physical variables were evaluated for normality using the Shapiro-Wilk test (Shapiro and Wilk, 1965) at $\alpha = 0.05$. This test is robust to determine deviations from normality with sample sizes of 50 - 2000. Results indicated that the data do not conform to the assumptions of normality and, hence, the use of non-parametric statistical techniques was required.

4.3.2. Regime Classification

Although some physical parameters and their relevance to river ice break-up have been evaluated at the site specific-scale (e.g., Beltaos, 1997), others have only been alluded to in a qualitative manner (e.g., de Rham *et al.*, 2008a). Moreover, large-scale assessments of the combined effects of various physical characteristics have never been attempted. To perform a comprehensive quantitative assessment, canonical correspondence analysis (CCA) was used to investigate the relationship between invariable physical parameters and the WRC results using CANOCO (ter Braak and Šmilauer, 2002). CCA is an eigenvector ordination technique that allows the visualization and interpretation of large multivariate datasets, including nominal data (ter Braak, 1986; 1987), by producing canonical axes that are the result of the best linear combination of variables that maximize the explanation of variation in the dependent matrix.

Based on the results of the regional WRC analysis with physiography and climate, the physical variables E, S, A and ϕ (see section 3.2) were employed as the independent, explanatory variables and the WRC values, R_B , R_O and R_M , as the dependent variables. Relationships among variables are represented by an ordination diagram, where

quantitative variables are displayed as vectors with length proportional to their importance while direction is indicative of the extent of correlation with each canonical axis. Nominal data, such as the dependent variable WRC are represented as the weighted average or centroids (ter Braak and Šmilauer, 2002).

Subsequent to the CCA, the physical variables were assessed using the non-parametric Kruskal-Wallis (Kruskal and Wallis, 1952) test ($\alpha = 0.05$) to determine whether significant differences between the physical variables exist within the WRC. The results of this test indicate whether E, S, A and ϕ are different between the classifications of R_O , R_B and R_M .

5. RESULTS AND DISCUSSION

5.1. Peak Water-Level River Regime Classification

5.1.1. Northern Canada-wide

Figure 1 shows the spatial distribution of the WRC across Canada as well as example return-period plots for R_B , R_O and R_M . Evidently, the geographical extent of hydrometric stations is limited in some regions (e.g., parts of northern Manitoba and eastern Quebec) and, in the absence of additional defining characteristics (e.g., climate and physiography, detailed in section 5.2), no obvious patterns are observed in the distribution of the WRC. However, the return-period analysis of peak, ice-induced and open-water levels demonstrates the prevailing influence of ice during break-up at the larger scale. In particular, of the 136 stations, 32% are classified as R_B , 45% R_O and 23% R_M . The fact that approximately 1/3 of all rivers in Canada are completely dominated by ice-induced peak water levels is particularly notable, and illustrates the broad hydraulic effects of river ice across the country. In addition, a further 1/5 of sites, classified as R_M , highlight

that within the return-periods assessed, ice is a dominant control of water levels. The following explores further the significance of this.

5.1.2. Synthetic Stage and Discharge

The ‘*synthetic stage and discharge curve*’ for the 136 hydrometric sites, shown in Figure 2a, enables comparison of mean annual, peak water level and discharge for the two types of events. The one-to-one line in Figure 2a, included for reference, reflects conditions where mean peak break-up water levels and discharges are equal to those of peak open-water levels and discharges.

It is evident that break-up water levels of R_B rivers exceed substantially those of R_O rivers (e.g., $(\overline{Y_B} / \overline{Y_O}) > 1$). Shown in inset b) of Figure 2 are the box plots of the $(\overline{Y_B} / \overline{Y_O})$ ratios which increase from R_O (lowest) to R_B (highest), illustrating the increasing influence of river ice effects on water levels during break-up. A low ratio (e.g., a majority of R_O rivers) indicates that peak break-up water levels are low relative to those for the open-water period, while the opposite is true for a high ratio (i.e., a majority of R_B rivers).

While the R_B regime is characterized by break-up water levels greater than those of the open-water period, Figure 2a furthermore confirms that even R_O and R_M rivers have considerably elevated break-up water levels relative to their maximum open-water levels when a low $(\overline{Q_B} / \overline{Q_O})$ ratio is associated with a relatively high $(\overline{Y_B} / \overline{Y_O})$ ratio. In other words, low break-up discharges relative to the maximum open-water flows can still produce significantly elevated break-up water levels. For example, a number of R_O rivers (grey shaded rectangle) with mean break-up discharges of only 0.1 – 0.3 of the open-

water discharge can still produce nominal break-up water levels of 40% to 80% of that for open-water conditions. Similar effects are observed for R_M rivers, where for example the majority of R_M rivers have a $(\overline{Q_B} / \overline{Q_O})$ ratio of less than 0.6, yet attain nominal break-up water levels approximately equivalent to those observed under open-water conditions (e.g., $\overline{Y_B} / \overline{Y_O} = 1$; encircled in dashed grey). Hence, it is particularly noteworthy that R_O and R_M rivers, in addition to R_B rivers are also subject to substantial ice effects during break-up. A further observation of interest is that the proportion of R_O rivers decreases as the $(\overline{Q_B} / \overline{Q_O})$ increases and that no R_O rivers have a ratio greater than approximately 0.85. By comparison, R_B rivers are strictly limited to a $(\overline{Q_B} / \overline{Q_O})$ ratio of greater than 0.2. In other words, the difference between peak break-up and open-water flows is generally greater for the R_O regime.

The key point of the WRC is that it illustrates the important role of river ice with respect to spring flood studies which, more often than not, simply analyze discharge data to identify peak flow and flood events. Such an approach is only valid in more temperate regions where ice effects can largely be assumed negligible.

5.2. Regional Classifications of Climate and Physiography

5.2.1. Climate

Figure 3 shows the spatial distribution of the WRC results according to broad-scale climate zones (Gullet *et al.*, 1992) and the relative proportions in each. Overall, the river study sites are within 8 of 11 climatic regions found across all of Canada. As no sites are located in the *Pacific, Arctic Mountains & Fiords and Great Lakes/St Lawrence* climate regions, these are not included in this aspect of the results discussion. However, these

sites are included in the subsequent assessment of specific physical controls (see section 5.3).

Sites in the northern *Arctic Tundra* region are classified as 38% R_B , 38% R_O and 23% R_M (Figure 3). This region is dominated by year-round Arctic air masses with extreme cold temperatures and very little precipitation. Although one might expect that such a region might favour hydrologic systems where break-up water levels are dominated by river ice, almost 60% of sites are classified as R_O and R_M . Further evaluation suggests that, in spite of the catchment size criterion (see section 3.1), these rivers probably do not have sufficient discharge to develop a free floating ice cover, freeze to the river bed, and experience over-ice runoff during spring melt. As such, they are unlikely to experience a conventional spring break-up that would elevate water levels from enhanced ice-induced backwater. Unfortunately, insufficient hydrometric data were available to further divide these sites into a sub-classification of river regimes, but should be addressed in subsequent analyses. Such effects are not expected to have affected sites in other climatic regions.

For the two other, primarily high-latitude climatic regions, *Yukon/Northern BC Mountains* and *Mackenzie*, there exists a strong contrast in WRC proportions with 67% R_O for the former and 67% R_B for the latter. It is likely that large scale climate plays an influence as the more maritime climate of the Yukon/Northern BC Mountains to the continental climate of the Mackenzie region.

Further south, the *Northwest Forest, Prairie* and *Northeastern Forest* climate regions broadly encompass the boreal climate that is dominated by Arctic outflows during winter and spring - characterized by long, cold winters, short summers and generally little

precipitation (Hare and Thomas, 1979). Although such climatic conditions might again seem conducive to R_B conditions, this is not reflected in the WRC composition, which becomes increasingly variable and contains greater proportions of R_M sites. Specifically, the WRC of the *Northwest Forest* zone exhibits an equal representation (33%) of R_B , R_O and R_M sites. A similar pattern exists for the *Prairie* region with near equal proportions of the R_B (21%) and R_O (26%), although an increase in R_M (43%) is noticeable. The *Northeast Forest* climate zone features over one-half (52%) R_O , one-third (36%) R_B and fewer R_M (12%). These results highlight much greater variability in hydrologic conditions leading to peak annual water levels throughout this region.

While sites in the *South BC Mountain* region are limited ($n=3$), all were classified as R_O . As further discussed later, the prevalent Pacific Ocean influence with limited, intermittent Arctic outflows during the winter likely favours the R_O regime in this region as well as that for its similar dominance in the *Yukon/Northern BC Mountains* region noted above. In spite of the moderating maritime climate in the *Atlantic* climate region, the WRC results are more equally divided (29% R_B , 29% R_O , 43% R_M).

Although broad generalizations are apparent for some of the climatic regions (e.g., the contrast in the R_O and R_B regimes between coastal and cold-continental climatic zones), other factors that partially interact with climatic conditions (e.g., physiography) also affect the regional composition of the WRC.

5.2.2. *Physiography*

The regime classification and its proportions according to physiographic regions are shown in Figure 4. Overall, WRC study sites are located in 5 of 6 physiographic regions, the exception being the *Great Lakes & St. Lawrence Lowlands*.

Canada wide, a broad association between physiography and the WRC is evident. Generally speaking, R_O rivers are more common in regions characterized by diverse topography and high relief. This is particularly evident for the *Cordillera*, which exhibits a dominance of R_O rivers (71%, Figure 4). Similarly, although the *Canadian Shield* has a distribution of 41% R_B, 43% R_O and 16% R_M, and is characterized by low-lying plateaus with an elevation of less than 500 masl, rivers classified as R_O are mostly found in the eastern and south-eastern areas where the terrain becomes more variable and rugged with elevations of up to 1500 masl.

In contrast to the WRC results for high-relief areas, greater proportions of non-R_O regimes are more common in regions characterized by low elevation and relatively flat topography. Examples include the *Great Plains* with a nearly equal distribution of R_B (34%), R_O (38%) and R_M (28%), the north and central regions of the *Canadian Shield* (41% R_B, 43% R_O, 16% R_M) and the *Appalachian* (29% R_B, 29% R_O, 43% R_M). As noted, the observed change in WRC proportions for the *Cordilleran* (high R_O; few R_B) and *Great Plains* (nearly equal R_O and R_B) regions are linked to differences in relief and more specifically probably associated with differences in elevation and or channel slope that control river dynamics, particularly break-up, as explored further in section 5.3. These results expand upon those of de Rham *et al.* (2008a) for the Mackenzie River Basin.

5.2.3. *Combined influence of Climate and Physiography*

In spite of the pronounced variability of Canada's landscape and climate, the comparison of the WRC results with the macro-scale regional delineations of climatic and physiographic zones does reveal two basic relationships. In general, WRCs with a high proportion of R_B rivers are found in regions that are subject to the combined effects of low relief and a cold, dry Arctic climate (e.g., cold/arctic continental). The opposite was found for regions where mild, moist maritime conditions (e.g., temperate maritime) and the highly variable relief of alpine environments combine to produce greater proportions of R_O . R_M rivers, while distributed throughout, are evidence of more variable conditions, likely due to shorter term controls (e.g., inter-annual variability in hydro-climatic conditions) than the long-term conditions on which the broad climatic and physiographic regions are defined.

5.3. Assessment of Specific Physical Controls

5.3.1. *Canonical Correspondence Analysis and Kruskal-Wallis Test Results*

The above sections provided spatial patterns and some qualitative indications of WRC controls. A more rigorous quantitative multivariate analysis of physical controls is presented herein. The results are summarized in tabular format and by means of a CCA ordination plot (Figure 5). Box and whisker plots, representing the distribution of each physical variable (E, S, A and φ), according to the regime types (R_O , R_B and R_M) are discussed and shown in Figure 6.

Beginning with Figure 5, as indicated by the eigenvalues (λ), axis I ($\lambda = 0.234$) carries greater importance in explaining the variation observed in the river regime data than axis II ($\lambda = 0.004$). The strength of correlation between the WRC and the physical variables is

($r = 0.484$) for axis I and ($r = 0.063$) axis II. The variability that can be attributed to the underlying explanatory variables is 11.7% for axis I, and 11.9% for both axes combined.

The inter-set correlations indicate the relative importance of the explanatory variables to each canonical axis. According to the correlations shown in Figure 5, axis I is dominated by E (-), S (-) and A (+), while axis II is dominated by A (+) and S (+). Although the inter-set correlations for A and S of axis II are strong and moderate respectively, their relative importance is negligible as the cumulative variation accounted for by axis II is low. Against expectations, it is particularly noteworthy that ϕ contributes the least to either axis.

The interpretation of CCA results is complemented with the aid of an ordination diagram where each explanatory variable is plotted as a vector with magnitude and direction indicative of its correlation with its canonical axis. Visually, the results are interpreted using Figure 5 showing maximum separation of R_B , R_O and R_M along axis I that, as previously noted, is dominated by E, S and A. From right to left, axis I can be viewed as a gradient along which the magnitudes of the explanatory variables change; this change is reflected in the WRC. For instance, A and ϕ increase from left to right, while E and S increase from right to left. In general, it is evident that the proportion of R_B sites decreases from right to left, with R_O sites becoming more dominant towards the left of the diagram. Hence, the CCA ordination diagram indicates that R_B rivers show a greater association with lower E and S, but higher ϕ and greater A. In contrast, R_O rivers are predominantly influenced by greater E and S but smaller A and lower ϕ . However, as previously mentioned, the latter contributes little to axis I, suggesting that latitude is not a

dominant control of the WRC. This is furthermore supported by the spatial distribution shown in Figure 1, where it is evident that R_B rivers do not increase uniformly with ϕ . Although rivers classified as R_M are also oriented along axis I, these sites show no particular association with the physical variables, which suggests that the R_M regime is likely controlled by other variables not assessed here.

According to the results of the Kruskal-Wallis test, E, S and A are significantly different between R_B , R_O and R_M . Consistent with the CCA results, the standard box plots of E, S, A and ϕ with the WRC in figure 6, show that elevation and slope are lower and area are greater for R_B rivers while the opposite is true for R_O rivers. Comparing the difference in E of the WRC using the box plots in Figure 6a, more patterns are notable. Not only are R_B sites limited to a narrower range of E than R_O sites, but with the exception of a single outlier, no R_B sites occur at elevations greater than 470 masl. In contrast, R_M rivers generally have elevations greater than R_B rivers but less than R_O rivers, while only R_O rivers are found at the highest elevations. A similar pattern is observed about the effect of slope in the WRC where, again with the exception of few outliers, the S of R_B rivers is generally less than 0.0012 and also limited to a narrower range. In contrast, a significant proportion of rivers with greater S are overwhelmingly R_O while R_M rivers reflect more intermediate conditions (Figure 6b).

Variable A is significantly different within the WRC and the box plots of the (\log_{10}) transformed A in Figure 6c shows that R_B (R_O) rivers generally have larger (smaller) areas. Although R_B rivers generally occur at higher latitudes (Figure 6d), the difference between the R_B , R_O and R_M regimes is not significant. Based on the above findings,

further discussion of the various physical and climatic controls as they relate to the WRC is presented below.

5.3.2. R_O Regime

Characteristics of the R_O regime include higher elevation, alpine regions, typical of steeper channel slopes, and smaller basin sizes. The break-up events at these sites are probably less dynamic (see Gray and Prowse, 1993) because ice covers are generally weaker and offer little resistance to the spring break-up pulse. Elevation acts as a hydro-climatic control since the deeper snowpacks of alpine environments can limit seasonal ice cover growth, thickness and strength. Combined with steeper channel slopes, which are characteristic of greater flow velocities during the spring period, a more rapid break-up and subsequent flushing of ice in the channel is very probable (e.g., Ferrick and Mulherin, 1989; Beltaos, 1997). In addition, critical flow velocities (e.g., more turbulent flows due to greater channel slopes) can potentially limit ice cover growth over the course of the winter. Finally, smaller basin areas, typical of these sites, respond more rapidly to basin scale processes such as precipitation events, which consistently produce peak open-water levels greater than those observed during break-up.

5.3.3. R_B Regime

The R_B regime is characteristic of low elevation, low slope and large basin areas. In general these sites generate *dynamic* break-up events, with a tendency for mechanically strong ice covers and high resistance to the spring break-up pulse. As opposed to the R_O regime, rivers in these regions are likely to experience lower snowpack depth with limited thermal insulation and thicker ice covers, resulting in reduced ice clearance as

well as a greater potential for ice jam events at the time of break-up (e.g., Pavelsky and Smith, 2004; Beltaos, 1997, 2003). In addition to more competent ice covers, the lower slopes of R_B rivers would also contribute to reduced ice clearance due to lower flow velocities. Finally, larger basins generally have more protracted response times to watershed scale events (e.g., summer precipitation) and hence, do not produce significant flows and water levels during the open-water period.

5.3.4. R_M Regime

Based on the multivariate analysis completed for this study, the physical characteristics of R_M rivers are in between those of R_O and R_B . Clearly, physical controls alone do not adequately explain the occurrence of this regime. Peak break-up water levels at R_M sites can exceed peak open water levels in some years and vice versa (see R_M regime, Figure 1). For example, some R_M rivers are actually R_O for lower order break-up events (e.g., 5-10 year return-periods) while higher order events are R_B (e.g., 15-30 year return-periods). A viable interpretation is that the more frequent, lower order break-up events are the result of a particular combination of stable physical (invariable) and climatic (variable) conditions, while the higher order break-up events may be the result of ‘additional’ variability that is likely exerted by less frequent climatic extremes. However, the influence of climate, addressed here only from a limited, stable and long-term perspective, is most likely to leave a signature in the R_M sites.

6. CONCLUSION AND FUTURE RECOMMENDATIONS

Using the return-period analysis of peak break-up and open-water levels for 136 WSC hydrometric stations, this study represents the first northern Canada-wide assessment of

river ice, spring break-up regimes. Results show that 32% of rivers are ice dominated (R_B), 45% are open-water dominated (R_O) and 23% are mixed (R_M). A ‘*synthetic stage and discharge*’ plot highlighted that at all sites, regardless of classification, river-ice conditions during the spring break-up period cause in-channel ice effects and elevated water levels beyond those of the open-water season for comparable discharges.

Contrasting the spatial WRC distribution with regional climatic and physiographic classifications, revealed that R_O sites are generally found at high elevations and in maritime climates, while R_B sites are located at lower elevations and in cool continental climates.

A first multivariate analysis of physical controls of the regimes was completed using Canonical Correspondence Analysis. While slope, elevation and basin area were identified as contributing factors to the regime classification, latitude is not significantly correlated to the WRC. Overall, the R_B regime is primarily associated with rivers found in larger basins with, low elevation and low channel slopes. By contrast, small basin areas, with higher elevations and channel slopes tend to favour the R_O regime. The physical characteristics of the R_M regime are in between those of R_B and R_O rivers, and as such, hydro-climatic controls at an inter-annual time scale, such as ocean/atmosphere circulation patterns that are known to influence the climate of Canada, are likely the cause of the higher order peak water level events at these sites. Based on the findings of this manuscript, recommendations for future research are to:

- (1) Increase the spatial coverage of the WRC to include a greater range of physiographic and climatic combinations, particularly those in other circumpolar regions. For example, the WRC currently does not encompass sites found in a

cold continental climate that also features high elevations and channel slopes (e.g., Siberia).

- (2) Assess additional hydro-climatic controls of the WRC such as the occurrence of mid-winter break-ups and the freeze-up stage (the water level at which a complete ice cover develops). In general, the former event is prone to cause the *dynamic* type break-up with elevated water levels, while a greater (lower) stage at freeze-up in the preceding autumn can result in reduced (enhanced) break-up water levels (e.g., Beltaos, 2003). Unlike the invariable controls assessed here, these events are determined by the variable hydro-climatic conditions at the time of freeze-up and during winter. With the exception of site specific analyses (e.g., Beltaos *et al.*, 2003), these hydro-climatic controls have not been characterized at the Canada-wide scale.
- (3) Define an improved selection criterion to eliminate rivers that freeze to the channel bottom, as the basin-scale criterion of $\geq 10\,000\text{ km}^2$ used in this work was insufficient to allow for the development of a free floating ice cover.
- (4) Examine the influence of different modes of climate variability such as ocean/atmosphere circulation patterns on the WRC. In this regard, the R_M regime, where for example, the lower (higher) order return-period events are potentially controlled by physical (climatic) conditions, is particularly amenable for further study with a focus on the more short-term and variable climatic controls on river ice break-up.

REFERENCES

- Anisimov OA, Vaughan DG, Callaghan TV, Furgal C, Marchant H, Prowse TD, Hjalmar Viljalma H, Walsh JE. 2007. Polar regions (Arctic and Antarctica). In *Climate Change 2007: Impacts, Adaptation and Vulnerability*, Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Perry ML, Canziani OF, Palutikof JP, van der Linden PJ, Hanson CE (eds). Cambridge University Press: Cambridge; 653–685.
- Bennett KE, Prowse TD. 2010. Northern Hemisphere geography of ice-covered rivers. *Hydrological Processes* **24**: 235-240.
- Beltaos S. 1982. Notes on ice hydraulics. National Water Research Institute Report, Burlington, Canada. Background Material for lectures at Inland Waters Directorate Seminar *Hydraulics of ice covered rivers and ice jam analysis*, Quebec, Canada.
- Beltaos S. 1990. Guidelines for extraction of ice break-up data from hydrometric station records. In *Working Group on River Ice Jams: Field Studies and Research Needs*. NRHI Science Report No. 2, National Research Hydrology Institute, Environment Canada, Saskatoon, SK; 37-70.
- Beltaos S. 1997. Onset of river ice breakup. *Cold Regions Science and Technology* **25**: 183-196.
- Beltaos S. 2000. Advances in river ice hydrology. *Hydrological Processes* **14**: 1413-1625.
- Beltaos S. 2003. Threshold between mechanical and thermal breakup of river ice cover. *Cold Regions Science and Technology* **37**: 1-13.
- Beltaos S. (ed). 2008. *River Ice Break-up*. Water Resources Publications, LLC, Highlands Ranch, CO, USA.
- Beltaos S, Prowse TD. 2001. Climate impacts on extreme ice jam events in Canadian rivers. *Hydrological Sciences Journal* **46**: 157-181.
- Beltaos S, Prowse TD. 2009. River-ice hydrology in a shrinking cryosphere. *Hydrological Processes* **23**: 122-144.
- Beltaos S, Ismail S, Burrell BC. 2003. Midwinter breakup and jamming on the upper Saint John River: a case study. *Canadian Journal of Civil Engineering* **30**: 77-88.
- Bonsal BR, Prowse TD. 2003. Trends and variability in spring and autumn 0 °C isotherm dates over Canada. *Climatic Change* **57**: 341-358.

- Bonsal BR, Prowse TD, Duguay CR, Lacroix MP. 2006. Impacts of large-scale teleconnections on freshwater-ice duration over Canada. *Journal of Hydrology* **330**: 340-353.
- Cunjak RA, Prowse TD, Parrish DL. 1998. Atlantic salmon in winter; "the season of parr discontent". *Canadian Journal of Fisheries and Ocean Sciences* **55**: 161-180.
- Davar KS. 1979. Resistance to flow in ice covered rivers – General Introduction. Proc. *Canadian Hydrology Symposium, Vancouver, BC*; 32-51.
- de Rham LP, Prowse TD, Beltaos S, Lacroix M. 2008a. Assessment of annual high water events for the Mackenzie River basin, Canada. *Hydrological Processes* **22**: 3864-3880.
- de Rham LP, Prowse TD, Bonsal BR. 2008b. Temporal variations in river-ice break-up over the Mackenzie River Basin, Canada. *Journal of Hydrology* **349**: 441-454.
- Environment Canada. 2009. Climate Trends and Variations Bulletin. Available online at <http://www.ec.gc.ca/adsc-cmda/default.asp?lang=En&n=8C03D32A-1>. Accessed June, 2009.
- Ettema R, Daly SF. 2004. Sediment transport under ice. *ERDC/CRREL Report TR-04-20*, Cold Regions Research and Engineering Laboratory, US Army Engineer Research and Development Center, Hanover, NH. USA.
- ESRI, 2008. Environmental Systems Research Institute. ArcGIS – A Complete Integrated System, Environmental Systems Research Institute, Inc., Redlands, California (2008) <<http://esri.com/arcgis>>.
- Ferrick M, Mulherin ND. 1989. Framework for control of dynamic ice breakup by river regulation. US Army CRREL Rpt. 89-12, Hanover, NH.
- Fulton RJ. 1989. Foreword. In *Quaternary geology of Canada and Greenland*, Fulton RJ (ed), Geological survey of Canada, Ottawa: 1-11.
- Gerard R. 1990. Hydrology of floating ice. In *Northern Hydrology, Canadian Perspectives*, Prowse TD, Ommanney CSL (eds). NHRI Science Report No. 1, National Hydrology Research Institute, Environment Canada: Saskatoon; 103–134.
- Gray DM, Prowse TD. 1993. Snow and floating ice. In *Handbook of Hydrology*, Maidment D (ed.). McGraw-Hill: New York: 7.1-7.58.
- Gullett D, Vincent L. 1992. Development of an Historical Canadian Climate Database for Temperature and other Elements. *Climatological Bulletin* **26**: 125-131.

- Hare FK, Thomas MK. 1979. The Regional Climates of Canada. In *Climate Canada*. John Wiley and Sons, Toronto: 94-119.
- Kalinin VG. 2007. Study of Spatial distribution and occurrence frequency of ice jams in rivers of the Votkinsk reservoir catchment. *Russian Meteorology and Hydrology* **33**: 819-822.
- Kruskal WH, Wallis WA. 1952. Use of ranks in one-criterion variance analysis. *Journal of the American Statistical Association* **47** (260): 583-621.
- Pavelsky TM, Smith LC. 2004. Spatial and temporal patterns in Arctic river ice break-up observed with MODIS and AVHRR time series. *Remote Sensing of Environment* **93**: 328-338.
- Petryk S. 1990. Case studies concerned with ice jamming. In *Working Group on River Ice Jams: Field Studies and Research Needs*. NRHI Science Report No. 2. National Research Hydrology Institute, Environment Canada, Saskatoon, SK, 85-112.
- Prowse TD. 1990. Guidelines for river ice data collection programs. In *Working Group on River Ice Jams: Field Studies and Research Needs*. NRHI Science Report No. 2. National Research Hydrology Institute, Environment Canada, Saskatoon, SK, 1-36.
- Prowse TD. 2001a. River ice ecology: Part B) Biological aspects. *Journal of Cold Regions Engineering*, **15**: 17-33.
- Prowse TD. 2001b. River ice ecology: Part A) Hydrologic, geomorphic and water quality aspects. *Journal of Cold Regions Engineering* **15**: 1-16.
- Prowse TD. 2005. River-ice hydrology. In *Encyclopedia of Hydrological Sciences*. Anderson MG (ed.), John Wiley and Sons, West Sussex, England, 2657-2677.
- Prowse TD, Culp JM. 2003. Ice break-up: a neglected factor in river ecology. *Canadian Journal of Civil Engineering* **30**: 128-144.
- Prowse TD, Lacroix MP. 2001. Hydrologic Extremes on Arctic Flowing Rivers: Analysis and Recovery. Climate Change Action Fund (CCAF) Project S99-13-13.
- Prowse TD, Bonsal BR, Duguay CR, Hessen DO, Vuglinsky VS. 2007. River and Lake Ice. In *Global Outlook for Ice and Snow*. United Nations Environment Programme, DEW/0924/NA, available online: http://www.unep.org/geo/geo_ice/. (accessed 17 May 2009).
- Prowse TD, Bonsal BR, Lacroix MP, Beltaos S. 2002. Trends in river-ice break-up and related temperature controls. In *Ice in the Environment: Proceedings of the 16th IAHR Conference on Sea Ice Processes*. Squire VA, Langhorne PJ (eds.), International Association of Hydraulic Engineering and Research, Dunedin, New Zealand, 64-71.

- Rantz SE. 1982. Measurement and Computation of Streamflow: Volume 1. Measurement of Stage and Discharge, United States Geological Survey, Water Supply Paper 2175, Washington, D.C., 284.
- Rees RA. 1999. The Water Survey of Canada: Hydrometric Technician Career Development Program. Environment Canada, Guelph Ontario. Available online at: <http://www.ec.gc.ca/rhc-wsc> (last accessed June 2011).
- Shapiro SS, Wilk MB. 1965. An analysis of variance test for normality (complete samples). *Biometrika* **52**: (3-4) 591-611.
- Singh VP. 1986. On the Application of the Weibull Distribution in Hydrology. *Water Resources Management* **1** (1) 33-43.
- Simon A, Castro J. 2003. Measurement and Analysis of Alluvial Channel Form. In *Tools in Fluvial Geomorphology*. Kondolf GM and Piégay H (eds.), John Wiley and Sons, West Sussex, England, 291-322.
- ter Braak JF. 1986. Canonical Correspondence Analysis: A new eigenvector technique for multivariate direct gradient analysis. *Ecology* **67** (5): 1167-1179.
- ter Braak JF. 1987. The analysis of vegetation-environment relationships by canonical correspondence analysis. *Vegetatio* **69**: 69-77.
- ter Braak JF, Šmilauer P. 2002. CANOCO Reference Manual and CanoDraw for Windows User's Guide: Software for Canonical Community Ordination (version 4.5). Microcomputer Power, Ithaca, NY, USA; 500pp.
- United States Geological Survey (USGS). 2007. GTOPO30 documentation. Available online at: <http://edc.usgs.gov/products/elevation/gtopo30/README.html> (last accessed March 2009).
- Weibull W. 1939. A statistical theory of the strength of materials. *Ingeniors Vetenskaps Akademiens-Handlingar* 151.
- Wrona FJ, Prowse TD, Reist JD, Beamish R, Gibson JJ, Hobbie J, Jeppesen E, King J, Koeck G, Korhola A, Levesque L, Macdonald R, Power M, Skvortsov V, Vincent W. 2005. *Freshwater Ecosystems and Fisheries. Arctic Climate Impacts Assessment*. Cambridge University Press: Cambridge; Chapter 8, 353-452.

FIGURES AND TABLES

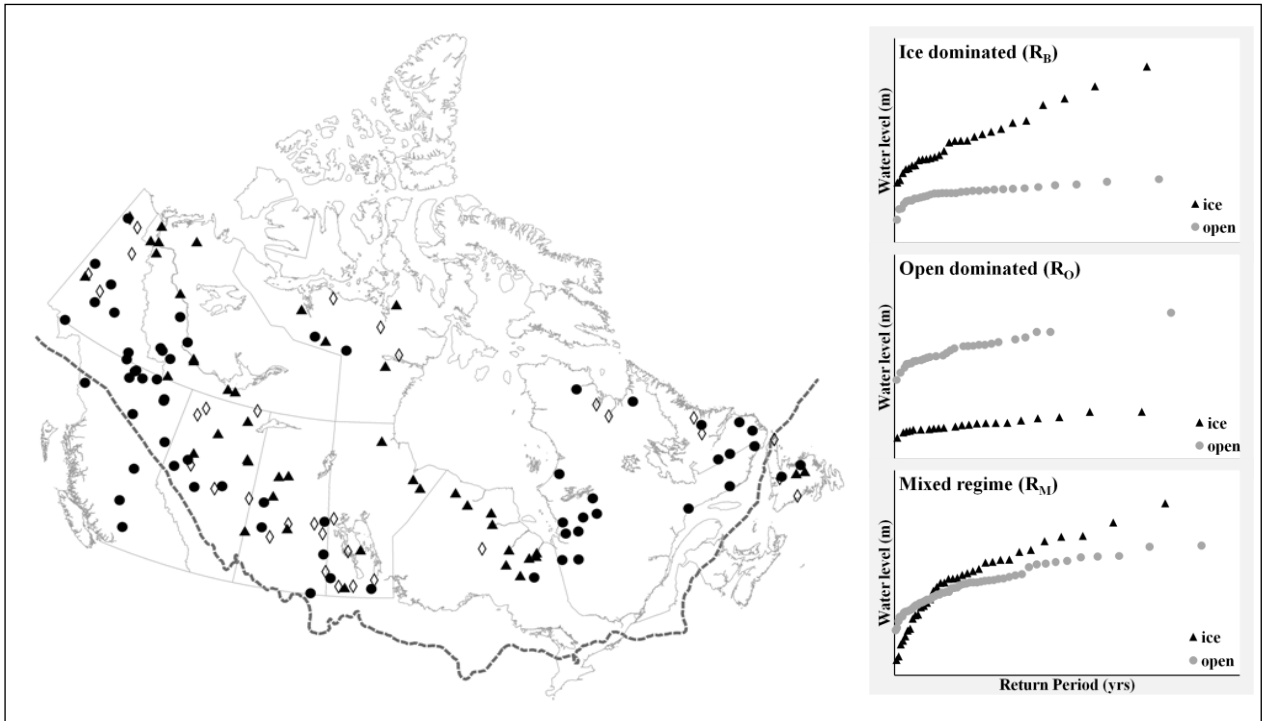


Figure 1. Distribution of hydrometric stations used to derive the WRC and the “temperate ice zone” (see section 3.1) which delineates the southern extent of the study area (dashed line). Also included are example return-period plots for the R_B , R_O and R_M regimes. Solid black triangles indicate ice break-up dominated rivers (R_B) and solid black circles are open-water dominated rivers (R_O); hollow diamonds represent the mixed regime (R_M).

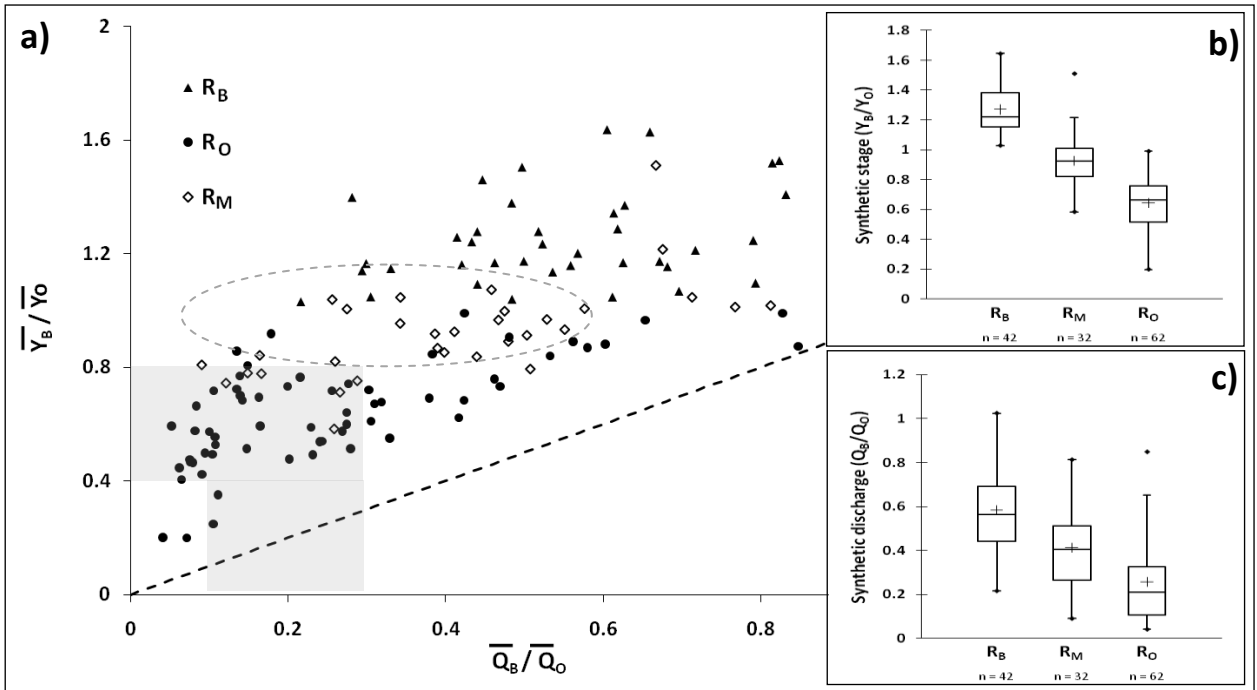


Figure 2. Mean dimensionless synthetic discharge ($\overline{Q_B} / \overline{Q_O}$) versus dimensionless stage ($\overline{Y_B} / \overline{Y_O}$) plot of the regime classification for the 136 WSC hydrometric stations used in this study. The shaded grey area shows that for R_O rivers, low break-up discharges ($\overline{Q_B}$) relative to the open maximum discharge ($\overline{Q_O}$) can still produce significantly elevated water levels during break-up. The dashed line represents one-to-one conditions where break-up water levels and discharges are nearly equal to those observed under peak open-water conditions. The dashed gray ellipsoid highlights R_M sites referred to in section 5.1. Insets b) and c) are standard box plots of synthetic stage and discharge that display the median, lower and upper quartiles (boxes), the mean (cross), minimum and maximum observations (end of whiskers) and outliers (black dots).

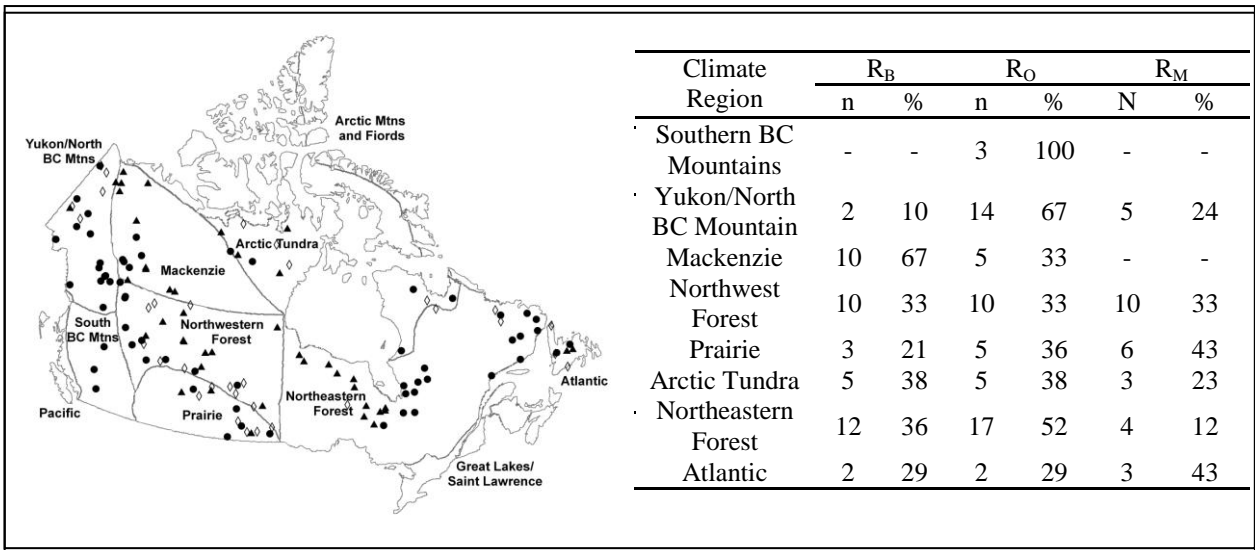


Figure 3. Spatial distribution of the WRC and the climatic regions of Canada. Also summarized are the proportions of regime types in each climate region. WRC symbols are the same as in Figure 1.

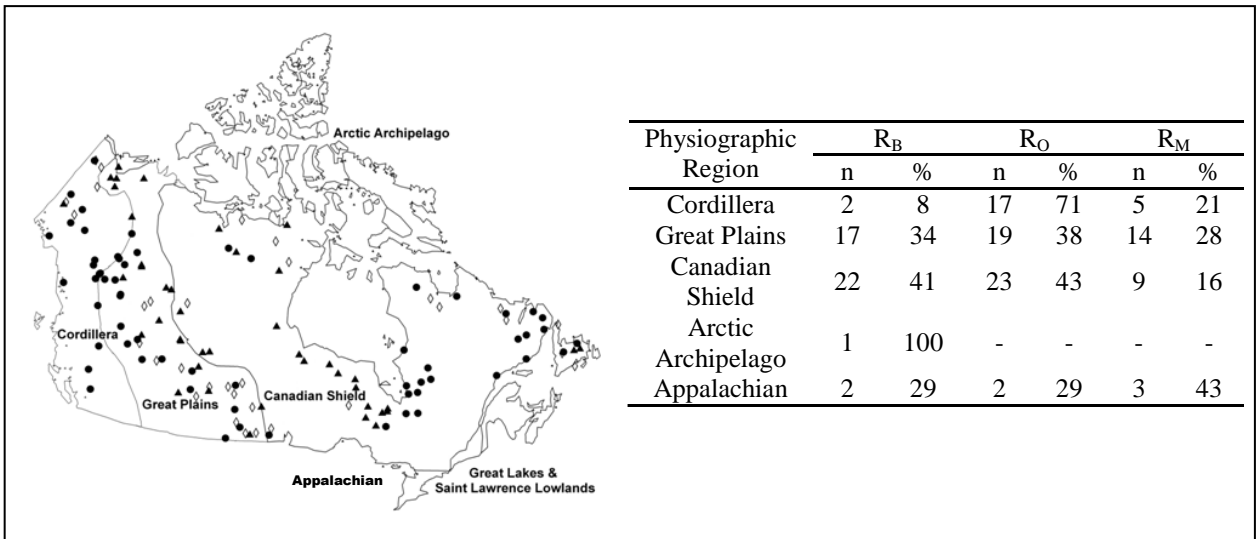


Figure 4. Spatial distribution of the WRC and the physiographic regions of Canada. Also summarized are the proportions of regime types in each physiographic region. WRC symbols are the same as in Figure 1.

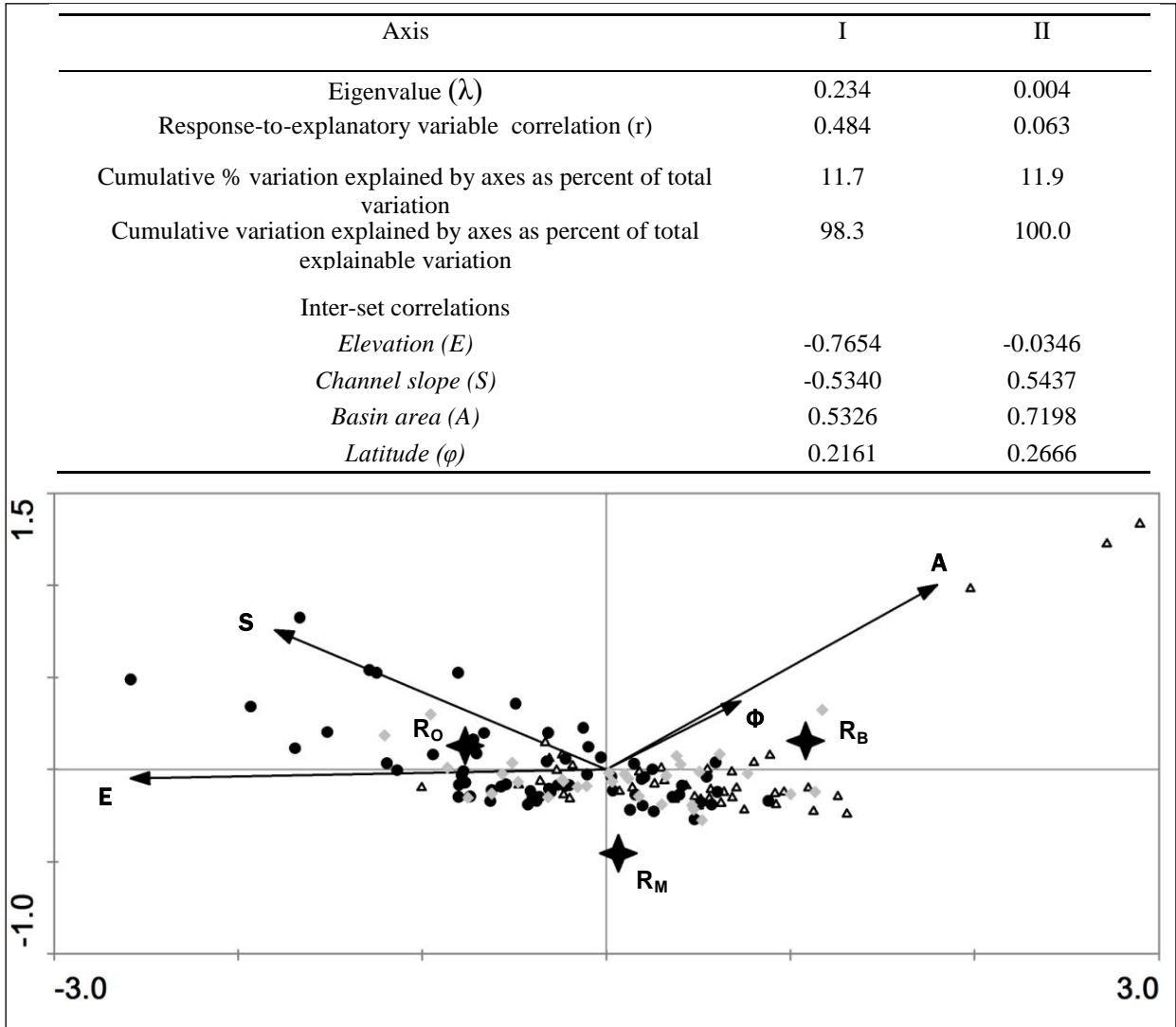


Figure 5. Summary of CCA results and ordination diagram showing canonical axis I (horizontal) and axis II (vertical). Physical explanatory variables (elevation-*E*, channel slope-*S*, basin area-*A* and latitude- ϕ) are represented as vectors and the dependent WRC variables are plotted according to their classification (R_B -hollow triangles, R_O -solid black circles, R_M -grey diamonds) as well as their centroids (black stars). For a detailed description, see section 5.3.1.

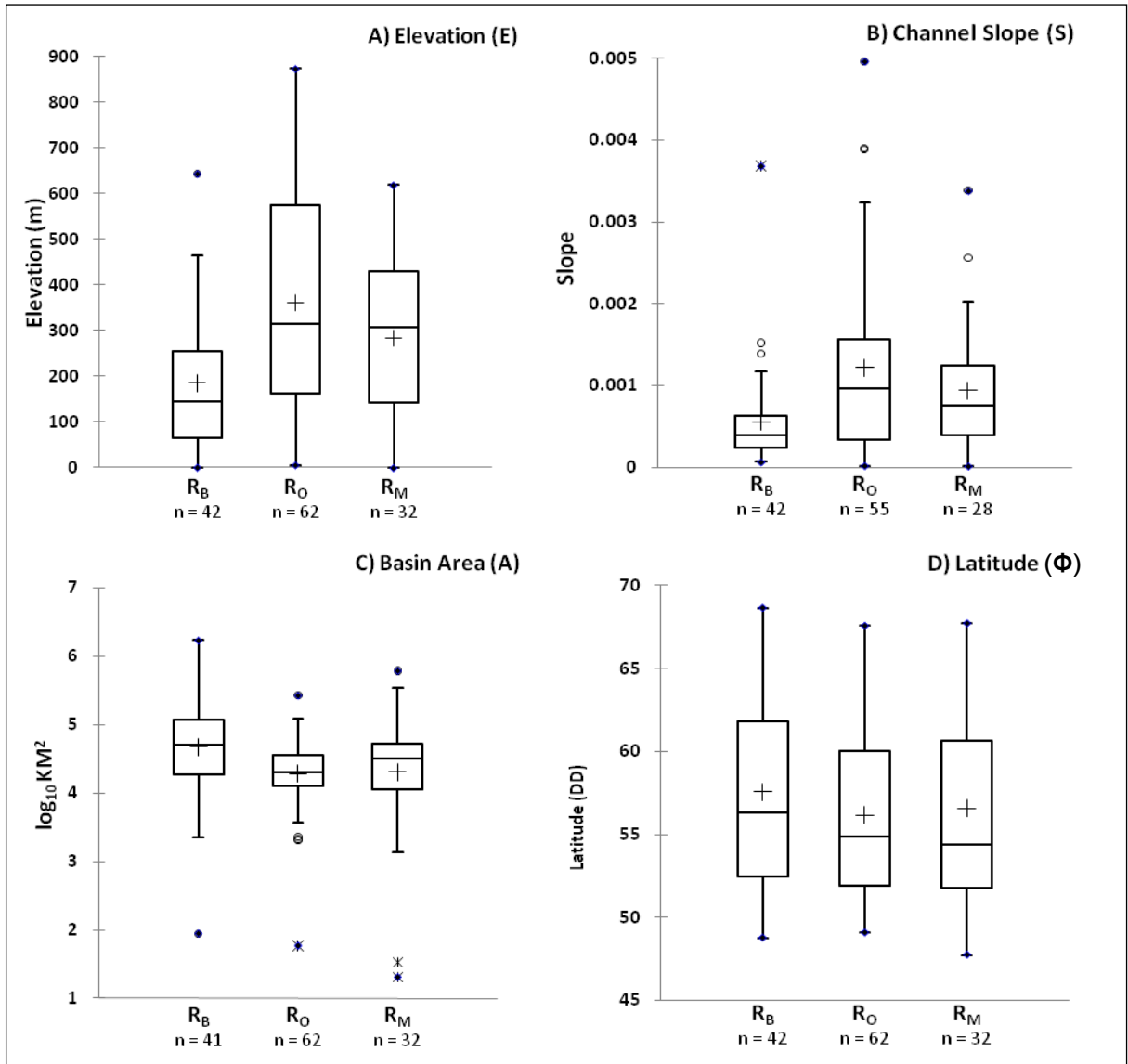


Figure 6. Standard box plot representation of physical variables. Displayed are: median and lower and upper quartiles (horizontal lines dissecting boxes), mean (cross), minimum and maximum observations (end of whiskers) and outliers (black dots). The differences between physical variables according to regime type, primarily R_O and R_B , are discussed in section 5.3.1.

CHAPTER 3: THE RIVER ICE BREAK-UP SEASON IN CANADA

ABSTRACT

The break-up of river ice is an important component of the annual regime of rivers in the Northern Hemisphere and has been identified as a dominant control of annual peak water levels. As a result, spring break-up can cause frequent and substantial changes to river environments and damage to hydroelectric and transportation infrastructure. Given the projected changes in climate, and the fact that the historical trends of cryospheric components, including river ice, mirror those of air temperature, these effects are expected to be exacerbated in the future. Based on an analysis of novel, event-based hydrometric variables representative of river ice break-up, a comprehensive spatial and temporal assessment of the break-up season of Canadian rivers is presented. Results of a trend analysis from 1969-2006 reveal that initiation and peak break-up water levels (H_B , H_M) have declined significantly, while the timing of break-up initiation (T_B), maximum break-up water level (T_M), and 'last B date' (B, a timing indicator used to specify when flow is no longer affected by ice) have been occurring significantly earlier in western and central Canada. In contrast, the break-up *drive* (Δt_1 , time between T_B and T_M) and the break-up wash (Δt_2 , time between T_M and B) show considerable variability, whereas for the most part, an increase in break-up *duration* (Δt_3) is evident. In addition, the spatial and temporal variability of break-up timing is assessed separately with the spring 0°C isotherm and dominant ocean/atmosphere oscillations. Results show that T_B , T_M and B are significantly and positively correlated to the spring 0°C isotherm, while correlations between these break-up timing indicators and major ocean/atmosphere oscillations are

predominantly significant for the Pacific North American Pattern (negative) and the El Niño Southern Oscillation (positive) over most of western Canada. In contrast, correlations between the Arctic and North Atlantic Oscillations with break-up timing are mostly non-significant over western Canada, while some significant positive correlations are found in eastern Canada. The results from this work provide a first order assessment of changes in break-up water levels over the period analyzed and shows that the temporal changes of event-based break-up timing variables are largely consistent with changes in the spring 0°C isotherm and large-scale climatic controls.

Keywords: River ice, break-up, teleconnections, spring 0°C isotherm, trends, variability, Canada

1. INTRODUCTION

The spring break-up of river ice is a critical period for river environments in the Northern Hemisphere. Since river ice is as a dominant control of annual, peak water levels on cold-region rivers (e.g., de Rham *et al.*, 2008a), break-up is responsible not only for ecological and morphological effects, but also has significant socio-economic implications (e.g., Prowse *et al.*, 2007a). In response to the extensive economic and environmental implications of river ice, and in light of the additional uncertainty due to climate change, a number of studies and reports have recommended that further spatial and temporal analyses of the climatic influences on river ice break-up water levels and timing be undertaken (e.g., Wrona *et al.*, 2005; Anisimov *et al.*, 2007; Beltaos and Prowse, 2001; 2009).

Although the growth and decay of freshwater ice is controlled by several physical and climatological factors at multiple spatial and temporal scales, an association between air temperature and break/freeze-up timing is well documented (e.g., Prowse and Beltaos, 2001). From a spatial perspective, the arrival of above-freezing temperatures in spring, as indicated by the spring 0°C isotherm, mirrors the timing of freshwater ice break-up (Bonsal and Prowse, 2003) and time series analyses of historical break-up observations have frequently been used as indicators of climate variability and change. According to a Canada-wide study by Duguay *et al.* (2006), lake ice break-up has been occurring significantly earlier from 1951-2000. These results are consistent with other analyses, such as Zhang *et al.* (2001) and Lacroix *et al.* (2005), who also noted pronounced trends towards earlier break-up of rivers in the western and south-western Canada. Additional evidence stems from other large-scale studies of freshwater ice phenologies (e.g., Prowse

et al., 2007b) which primarily reflect trends of warmer spring temperatures in the same regions of the country (e.g., Zhang *et al.*, 2000).

In Canada, a number of regional-scale studies (e.g., Jasek, 1998; Bonsal and Prowse, 2003; Shabbar, 2006) have also shown that air temperatures, in particular those during the cold seasons, are influenced by large-scale ocean/atmosphere oscillations (teleconnections). The most prominent of these to impact the western and central regions of Canada are the El Niño/Southern Oscillation (ENSO) (Rasmusson and Carpenter, 1982), the Pacific Decadal Oscillation (PDO) (Mantua *et al.*, 1997) and the Pacific North American Pattern (PNA) pattern (Wallace and Gutzler, 1981). Although the spatial extent of these oscillations is different, elevated cold-season temperatures during the El Niño and the positive PDO and PNA phases are most pronounced in the western and Pacific regions of North America (e.g., Bonsal *et al.*, 2001). By comparison, the North Atlantic Oscillation (NAO) (Hurrell and van Loon, 1997) and the Arctic Oscillation (AO) (Thompson and Wallace, 1998) cause colder spring and winter temperatures during their positive phases in the Arctic and Atlantic regions of Canada. Specific to their effects on freshwater ice, the most comprehensive work to date is that of Bonsal *et al.* (2006) who correlated seasonal index composites of the above noted oscillations to freshwater-ice break-up freeze-up timing across Canada.

Unfortunately, nearly all spatial and temporal assessments of freshwater ice have relied on surrogate indicators of river ice break-up timing, such as the Water Survey of Canada (WSC) 'last B date' (B) qualifier, with the primary purpose to only indicate that flow conditions could be affected by ice. This study differs from previous work in that it analyzes more reliable indicators of break-up timing that are directly extracted from WSC

pen-chart recordings in addition to the ‘last B date’ (e.g., de Rham *et al.*, 2008a, b). More specifically, event-based quantifiable hydrometric variables are used to assess the temporal changes in break-up timing and furthermore, to examine the influence of air temperature and ocean/atmosphere oscillations on these variables.

While the majority of large-scale river-ice studies are limited to analyses of break-up timing, those that have focused on break-up magnitudes are limited to the smaller, regional scale and have relied almost exclusively on assessments of spring freshet flows (e.g., Burn *et al.*, 2004; Burn *et al.*, 2008). Spring flood studies in particular, often use measures of discharge rather than actual peak break-up water-levels (e.g., Cunderlik and Ouarda, 2009), thereby ignoring the influence of river ice as a flood producing mechanism. In contrast, this work is significant in that it represents the first large-scale temporal assessment of break-up water levels across such a large cold-regions area as Canada.

Using a suite of hydrometric variables considered to best represent river-ice break-up timing and water level conditions, the specific objectives were to: (i) update the mean spatial and temporal patterns of river-ice break-up and, assess the influence of the spring 0°C isotherm on river-ice break-up across Canada; (ii) perform trend analyses of the timing and water levels associated with the spring river-ice break-up season, and (iii) examine the relationship between inter-annual climate variability associated with large-scale ocean/atmosphere oscillations and temporal characteristics of the river-ice break-up season.

2. DATA AND METHODOLOGY

To ensure the use of appropriate statistical methods for analysis, the hydrometric variables (timing and water levels), the spring 0°C isotherm values, and the monthly anomalies of ocean/atmosphere oscillation indices were evaluated for normality. Results of the Shapiro-Wilk test ($\alpha = 0.05$) revealed that the data do not comply with the assumptions of normality (Shapiro and Wilk, 1965), hence all statistical techniques used in this analysis are non-parametric.

2.1. Hydrometric data

The hydrometric data used in this study originate from the WSC archives. Unlike discharge, which is readily available in digital format, water level data are archived as original pen chart records prior to ~ mid 1990s and are only available in digital format since this time. As a result, relevant hydrometric variables were extracted directly from original records according to Beltaos (1990) and supported by additional metadata (e.g., hydrometric survey notes, station analysis, etc.). Initial site selection criteria follow those outlined in chapter 2 and hydrometric stations were included if records were ≥ 10 years, fed by a catchment $\geq 10\,000$ km² and primarily north of the southern boundary of the "temperate ice zone" (Prowse *et al.*, 2002). The latter two criteria were used to try and ensure that break-up occurs primarily as a spring event and that sufficient flow is produced to allow the development of a free floating ice cover. This requirement permits the identification of break-up events used in this study. However, criteria were slightly relaxed to increase regional coverage and 136 WSC hydrometric stations with records encompassing the 1913-2006 period (Figure 1) were chosen for analysis. Record lengths range from 13-96 years with a mean (median) length of 42 (38) years. As a result of the

loss of data due to frequent damage to hydrometric instrumentation during break-up, the time series records are of variable length and completeness. To obtain the most comprehensive spatial and temporal coverage, record selection was adjusted to meet analysis-specific requirements as set out in section 2.2. Unfortunately, complete regional coverage is limited primarily by lack of data for the northern and eastern regions of the country.

Note that some rivers identified as regulated by the WSC were also included. These are primarily located downstream of the WAC Bennett dam on the Peace River, a headwater tributary of the Mackenzie River in the Mackenzie River Basin (north-west Canada). However, these sites were included because they are located sufficiently downstream and regulation effects can be assumed negligible (e.g., de Rham *et al.*, 2008a). A number of rivers also identified as regulated by the WSC are located in the south-central provinces where the extent and subsequent effects of regulation are largely unclear. Further to this point, the inclusion of regulated sites was deemed useful to provide insight into the potential differences between spatial and temporal patterns that may be either due to climate variability or regulation.

The event-based variables chosen to assess the timing and magnitude of the river ice break-up season are similar to those of de Rham *et al.* (2008b) and include: the water level (H_B) and Julian day (T_B) at the initiation of river ice break-up, as well as the maximum break-up water level (H_M) and related Julian day (T_M). The commonly used ‘last B date’ (B; time when last ice effects are observed in the channel) was also assessed.

To assess the temporal changes in the length of the break-up season and to evaluate relationships to air temperature, the break-up *drive* (Δt_1), *wash* (Δt_2) and *duration* (Δt_3) (Deslaurier, 1968; Michel 1971) were used. These three phases are defined as:

$$\Delta t_1 = T_M - T_B \quad (1)$$

$$\Delta t_2 = B - T_M \quad (2)$$

$$\Delta t_3 = B - T_B \quad (3)$$

To establish mean baseline conditions of river ice break-up timing (T_B , T_M , B , Δt_1 , Δt_2 and Δt_3), summary statistics of central tendency were derived for all 136 WSC sites. Unfortunately, the exhaustive nature of summary statistics precludes a complete description of these variables in this work and results are limited to a discussion of the regional and temporal patterns of T_B and Δt_3 . These two timing indicators were chosen because they directly advance the river ice break-up timing assessment of Prowse and Onclin (1987). The spatial and temporal association between T_B and air temperature is then compared using the spring 0°C isotherm and is explored in further detail in section 3.3.

Time series of break-up initiation (H_B) and peak break-up water levels (H_M) as well as the timing of T_B , T_M , B , and changes in Δt_1 , Δt_2 and Δt_3 of 136 WSC hydrometric stations encompassing 1912-2006 were evaluated for temporal trend. Due to the variable length and completeness of records the 1969-2006 period was determined to provide the most comprehensive spatial and temporal coverage while meeting a 2/3 record completeness criteria (e.g., Duguay *et al.*, 2006; de Rham *et al.*, 2008a). Changes in the times series of hydrometric break-up variables were assessed with the non-parametric Mann-Kendall test for monotonic increasing/decreasing trends ($\alpha = 0.10$) (Mann, 1945; Kendall, 1975) and

the Sen's slope estimator (Sen, 1968) using the Excel[®] template MAKESENS developed by Salmi *et al.*, (2002). This method is robust as it copes well with missing values, has low detection limits and is frequently used in hydrologic applications (e.g., Duguay, *et al.*, 2006). The significance level of $\alpha = 0.10$ was deemed appropriate primarily due to the spatial focus of this analysis (e.g., Duguay *et al.*, 2006; de Rham *et al.*, 2008a).

2.2. Spring 0°C Isotherm

The spring 0°C isotherm data are the updated version (1900-2007) of those used by Bonsal and Prowse (2003), which were originally calculated using daily temperature values from the Adjusted and Homogenized Canadian Climate Database (AHCCD) (Vincent *et al.*, 2002). The spring 0° C isotherm is normally defined as the first date when mean daily temperature exceeds 0°C in the spring. However, because mean daily temperatures commonly fluctuate from above to below 0° C, the daily data are smoothed using a 31-day running mean and the 0°C isotherm is defined as the first day in spring when this running mean temperature crosses and remains above 0°C (e.g., Bonsal and Prowse, 2003).

The strength and significance of the relationship between the timing of break-up initiation (T_B) peak water level occurrence (T_M) and B and the spring 0°C isotherm were determined using spearman correlation ($\alpha=0.05$). Hydrometric timing variables from WSC stations were correlated with the 0°C isotherm values from those Meteorological Service of Canada (MSC) weather stations in closest proximity. Approximately 50% (86%) of WSC sites are located within 100km (200km) from the closest MSC weather station, and all are within 300km. Records of otherwise variable length encompassing the 1913-2006 period were included in the analysis only if they were more than 2/3

complete (e.g., Duguay *et al.*, 2006) and had a minimum overlap of 20 observations. The final selection resulted in the correlation of the spring 0°C isotherm with 65 records of T_B , 106 T_M and 134 B dates.

2.3. Ocean/atmosphere Circulation Indices

The teleconnection indices selected for analysis are those previously shown to most affect the Canadian climate and include the Southern Oscillation Index (SOI), Pacific North American Pattern (PNA), Arctic Oscillation (AO) and the North Atlantic Oscillation (NAO). All indices are available as monthly anomalies standardized to their period of record.

The SOI, a reliable indicator of El Niño/Southern Oscillation (ENSO) conditions, causes warmer (colder) temperatures by means of a stronger (weaker) Aleutian Low and more (less) frequent inflows of Pacific airmasses over western Canada during the cold season (Rasmusson and Carpenter, 1982; Bonsal *et al.*, 2001). SOI index values were obtained from <http://www.cdc.noaa.gov/Correlation/soi.data>.

The PNA primarily influences mid-tropospheric circulation over the North Pacific and North America during the cold season (Wallace and Gutzler, 1981). The positive PNA phase is associated with a northward shift in the jet stream producing above average temperatures over western North America, while a southward shift over the eastern regions permits more frequent southern advances of cold arctic air masses. The opposite effects are observed during the negative PNA phase. PNA data were obtained from http://www.jisao.washington.edu/data_sets/pna.

The AO is associated with a sea level pressure differential between the polar regions and the mid-latitudes (Thompson and Wallace, 1998). In the negative (positive) phase

the AO generates a southward (northward) advance in the jet stream resulting in more (less) frequent cold air surges into the mid-latitudes. AO index values are available at <http://www.cdc.noaa.gov/Correlation/ao.data>.

Although the NAO exhibits a high temporal correlation (e.g., phase synchronicity) with the AO, the regional extent of both oscillations is different in that the former is more pronounced in the Atlantic regions, while the latter primarily influences the climate in the Arctic regions of Canada. Since both oscillations produce comparable effects on temperature by means of similar mechanisms it has been suggested that the NAO is a regional manifestation of the AO. For the purpose of this analysis, both are treated as separate modes of variability. NAO data were obtained from <http://www.cgd.ucar.edu/~jhurrell/nao.stat.other.html>.

Since the timing of river ice break-up is affected by preceding climatic conditions, monthly oscillation indices were averaged into 1 month, 2 month and 3 month composites (prior to the mean break-up date at each WSC hydrometric station). Subsequently, each period was correlated to the timing of T_B , T_M and B using spearman correlation for records that met the completion criteria previously noted ($\alpha = 0.05$). The results are displayed as isopleths of correlation coefficient strength (spearman's rho) interpolated using Inverse Distance Weighting (IDW) (Shepherd, 1968) in ArcGIS 9.3TM (ESRI, 2008).

The results of the correlation analysis between the teleconnection indices and break-up timing variables are stratified according to the climatic regions originally defined by Hare and Thomas (1979) and later modified by Gullett *et al.* (1992). Also used in Chapter 2, these climatic regions have been used in applications such as the *Historical Canadian*

Climate Database (Gullett *et al.*, 1992) and the *Climate Trends and Variations Bulletin* (Environment Canada, 2009).

3. RESULTS AND DISCUSSION

3.1. Mean Timing of River Ice Break-up and Spring 0°C Isotherms

The mean timing of river ice break-up initiation (T_B) and the spring 0°C isotherm reveals a close correspondence in spatial patterns between both events (Figure 1). Notably, the influence of the Pacific Ocean on the climate of western Canada is reflected in the spring 0°C isotherm, where unlike the rest of the country, spring air temperatures do not increase uniformly with latitude. This is also reflected in the timing of T_B , where the distinct differences for comparable latitudes were previously noted by Prowse and Onclin (1987). For example, from Figure 1a it is evident that break-up initiation begins earliest in south-central British Columbia (mid to end of January) whereas those in Atlantic Canada and southern Manitoba break-up towards the middle to end of March. Generally speaking, initiation advances north-east for most of western Canada and occurs the latest in north-central Canada towards the end of June. Although variable across the country, the mean difference between T_B and the spring 0°C isotherm indicates that above 0°C temperatures precede break-up initiation on average by 11 days.

Canada-wide, the overall mean break-up *duration* is 5 days and ranges from 1 to 16 days (not shown). The longest durations are observed in the Northwest Territories and Atlantic regions, where mean break-ups occur over a period of 10-15 days. Break-ups of less than 10 days are highly variable and do not show any regional patterns (e.g., no relationship with latitude).

3.2. Trends in Break-up Timing and Water Levels

Figure 2 (a-f) shows the spatial patterns of trends in break-up timing variables while those for water levels are illustrated in Figure 3 (a-b). The number of sites with significant and non-significant trends are summarized in Table 1, which also provides Sen's slope estimates for the former.

3.2.1. Break-up Timing

The broad spatial patterns observed for T_B , T_M and B (Figure 2a-c) are generally consistent with those of previous temporal assessments that relied on more simple measures of timing less representative of break-up (e.g., Zhang *et al.*, 2001; Lacroix *et al.*, 2005; Duguay *et al.*, 2006). The earlier occurrence of break-up is most pronounced in the western parts of the country and the pattern of significantly decreasing trends is spatially largely consistent for regulated and non-regulated rivers. The number of predominantly decreasing trends is striking and the regional patterns of T_B and T_M are marked by an earlier occurrence in the season. This is indicated by the significantly decreasing trends and the decreasing magnitudes in timing (e.g., earlier break-up) of sites that tested non-significant. The overall mean Sen's slope estimates for both, T_B and T_M of sites with significant decreases are -2.7 days/decade.

Similarly, the timing of B has, with the exception of two significant increasing trends, occurred significantly earlier from 1969-2006 and is marked by a mean linear change of -3.1 days/decade. The regional pattern of sites with decreasing significant trends is consistent with those that tested non-significant in that decreasing Sen's slopes, indicative of earlier break-up timing, are most pronounced in the western regions. Although non-

significant increases in B occur across the country, they are concentrated mostly in Atlantic Canada.

Although considerable variability is evident in the intra-seasonal break-up timing variables (Figure 2d-f), the majority of significant trends are increasing and a few regional patterns are notable. Generally speaking, the durations of Δt_1 , Δt_2 and Δt_3 have become longer in the north-western region of the country, while near equal occurrences of both positive and negative changes in timing are observed in the Prairie regions. With the exception of some isolated regulated rivers characterized by a significantly shorter break-up *drive* duration (-0.3 to -0.6) in central Canada, Δt_1 is almost entirely dominated by increasing trends (0.6 to 1.3 days/decade). Similarly and as previously mentioned for the case of T_B and T_M , the regional patterns and trends of Δt_1 are also consistent for regulated and non-regulated rivers. By comparison, Δt_2 is much more variable and regional associations are not apparent (Figure 2e). Break-up *duration* (Δt_3) on the other hand has mostly increased significantly (0.6 to 2.9 days/decade) while significant decreasing trends are exclusively limited to rivers identified as regulated. The regional patterns towards a longer river ice break-up season are demonstrated by both, significant trends and those of no trend, where the latter is still indicative of increasing magnitudes (longer Δt_3). In general, trends towards earlier break-up (T_B , T_M and B) from 1969-2006 are most pronounced in western and central Canada and are generally accompanied by a prolonged duration of the break-up phases (Δt_1 , Δt_2 and Δt_3). While these temporal changes reflect those of warmer spring temperatures, it is of particular note that the dominant trends in T_B , T_M and B are largely consistent between rivers designated as regulated and non-regulated. In contrast to the more variable trends in Δt_1 and Δt_2 , those

of Δt_3 indicate prolonged (shorter) break-up *durations* in the case of non-regulated (regulated) rivers.

3.2.2. Break-up Water Levels

Break-up initiation water levels (H_B) and peak break-up water levels (H_M) have mostly decreased from 1969-2006 (Figure 3a-b), with significantly lower trends ranging from -0.1 to -0.5 m/decade in the western and central regions of the country (e.g., southwest BC, Alberta and Saskatchewan). Some spatial variability is evident as two sites with significant increases in H_B are found in northern British Columbia and Alberta (0.1 to 0.9 m/decade), one of which is designated as regulated by the WSC. Nonetheless, similar to break-up timing, significantly decreasing trends in water levels are generally consistent for regulated and natural rivers.

For the most part, patterns in H_M resemble those of H_B , in that isolated significant increasing trends, (0.3 to 1.1 m/decade) are found in northern British Columbia and Alberta as well as in Quebec. Spatially this pattern is supported by sites that show non-significant trend results but are nevertheless indicative of increases in H_M , which are also most distinct in eastern Canada. Again, the greatest proportion of significant decreasing trends is found throughout the Alberta and Saskatchewan (-0.10 to -1.1) region and, as previously mentioned, the lack of distinct differences between the trends of regulated and natural rivers is also evident in peak break-up water levels.

To substantiate the earlier occurrence of break-up in conjunction with reduced break-up water levels noted above, it is useful to consider river ice break-up in terms of the two contrasting types. Generally speaking, a break-up will be *dynamic* and marked by significantly elevated water levels when high discharge (e.g., early and rapid snowmelt)

encounters a mechanically competent ice cover (e.g., minimal thermal decay). By comparison, a *thermal* break-up is characterized by the opposite conditions (e.g., little discharge and a mechanically weak ice cover) and produces only minor increases in water levels (Gray and Prowse, 1993).

Although earlier break-up, associated with lower water levels suggest *thermal* break-up conditions, additional information is required to conclude that these results are due to earlier spring warming. In fact, while early warming is likely to be associated with the *dynamic* break-up and greater water levels (greater break-up discharges and limited thermal ice cover decay), it is in fact the rate of warming that would increase the discharge sufficiently for this type of break-up. For example, early and attenuated warming would be unlikely to produce discharges for the *dynamic* break-up. The influence of an additional control of break-up water levels is explored in the following sections.

3.3. Relationships with the Spring 0°C Isotherm

A broad spatial relationship existing between break-up timing and the occurrence of spring 0°C isotherms is suggested by the patterns evident in Figure 1. The strength of this relationship is enhanced by the data in Figure 4, which displays the frequency distributions of Spearman correlation coefficients between these isotherms and the timing of T_B , T_M and B. In the case of T_B , 59 out of 65 correlations are significant with a mean correlation of 0.70, which is slightly greater than those of T_M (0.68) and B (0.66), respectively. For T_M (B), 92 of 106 (116 of 134) correlations are significant. Although the relationship between the timing of break-up and the spring 0°C isotherm is strong, no regional patterns of such strength are evident. Considering the scale of this analysis, such

a pattern is unlikely to be markedly evident given some isolated factors that may influence the strength of the correlations (e.g., local physiography and the distance between WSC hydrometric and MSC weather stations).

Although the timing of spring break-up is affected by a number of hydro-climatic variables at multiple spatial and temporal scales, its strong correlation with the spring 0°C isotherm indicates that air temperature is a dominant control, and hence able to explain the observed spatial patterns between these two variables (Figure 1). This is also consistent with the fact that the majority of significantly earlier break-ups occur in the western regions of Canada where spring temperatures have increased the most (Zhang *et al.*, 2000).

The strong relationship between the spring 0°C isotherm and break-up timing, combined with trends of earlier break-up and reduced water levels, suggest a greater occurrence of *thermal* break-ups. However, these results are, as already discussed, insufficient to conclude that break-up has become more *thermal* in the western and southwestern regions. In contrast to break-up timing, which is primarily controlled by air temperature, other hydro-climatic factors such as the rate of spring snowmelt, resisting forces provided by the ice cover (strength, composition and attachment to channel banks) and, more importantly, the freeze-up stage can affect the type of break-up and the magnitude of break-up water levels (Beltaos, 2002). Governed by hydro-climatic conditions of the preceding autumn (e.g., precipitation and temperature), a higher (lower) freeze-up stage would be more likely to contribute to a *thermal (dynamic)* break-up as more (less) discharge is required to dislodge and break the ice cover. It follows that in order to substantiate reduced break-up water levels additional analysis of the freeze-up

stage and its effects on break-up water levels is required. Unfortunately, these data are currently unavailable for an assessment at the Canada-wide scale.

3.4. Influence of Ocean/atmosphere Circulation Indices

Spatial representations of the spearman correlations between T_B , T_M , B and the 2 month SOI and 3 month PNA and NAO indices are shown in Figure 5 while the percentages of significant correlations, stratified according to the climatic regions of Canada, are summarized in Table 2. These mean values of the monthly indices were chosen because they are spatially the most consistent.

3.4.1. Pacific Oscillation Indices

In general, the SOI index shows a significant ($\alpha=0.05$), strong and positive correlation to the break-up season over most of western Canada ($r = 0.4$ to 0.5). This is consistent with the work of Bonsal *et al.* (2006) and is furthermore evident in Figure 5a and Table 2, the latter of which shows that the proportions of significant correlations are for the most part higher in the western climatic regions. The opposite is observed in the eastern climatic regions of Canada where correlations are highly variable in that fewer correlations are significant and magnitudes are weakly positive and negative (e.g., $r = -0.2$ to -0.2). Also of note is that T_B and T_M are spatially more consistent with the SOI index than B, which indicates that the influence of the SOI on break-up timing is more accurately reflected in these timing variables than the often used, and more coarsely defined, 'last B date'.

The positive correlations indicate that by means of the more frequent advection of mild Pacific air masses, warmer temperatures during the negative SOI phase result in the

earlier break-up of river ice throughout western Canada. In contrast, colder temperatures due to fewer Pacific air mass intrusions produce later than normal river ice break-up (e.g., Lacroix *et al.*, 2005; Bonsal *et al.*, 2006).

Largely negatively correlated to the timing of river ice break-up, the spatial pattern of the PNA resembles that of SOI (Figure 4b). Greater proportions of strong, negative and significant correlations ($\alpha=0.05$) occur in the western climate regions ($r = -0.5$ to -0.4) which are also spatially consistent for T_B and T_M . In contrast, T_B is characterized by very weak negative correlations in eastern Canada, while stronger negative correlations ($r = -0.4$ to -0.3) are found in the case of T_M and B.

The positive (negative) PNA phase influences break-up timing through more (less) frequent mild airmass intrusions over western Canada, causing warmer (colder) air temperatures and earlier (later) break-ups.

Note that the Pacific Decadal Oscillation (PDO) (Mantua *et al.*, 1997), defined as a leading principle component of monthly sea surface temperature (SST) variability in the North Pacific, was also assessed (not shown). Results were consistent with the other Pacific-related oscillations in that the warm (cold) PDO phase corresponds to earlier (later) break-up timing in western Canada. This is also consistent with the results of Bonsal *et al.* (2006).

3.4.2. Atlantic Oscillation Indices

The percentages of significant correlations between the break-up timing and the AO and the NAO are summarized in Table 2, but due to the similarity of results, only the 3 month mean of the NAO is shown in Figure 5.

For both oscillations, the significant correlations are for the most part weak ($r = -0.2$ to 0.2), with the exception of a few positive r values of moderate strength ($r = 0.3$ to 0.4) in eastern Canada (e.g., Arctic Tundra, North-Eastern Forest and Atlantic climate regions). In these regions, the positive AO and NAO phases cause a greater influence of arctic air masses, colder spring temperatures and later river ice break-up while the opposite conditions apply during the negative phases.

In context of the stronger (weaker) relationships between break-up timing and the SOI and PNA (NAO, AO) in Western (Eastern) Canada, two key points stand out. First, it shows that, by means of above zero spring air temperatures preceding break-up, ocean/atmosphere oscillations influence break-up timing both spatially and temporally, and second, that these teleconnections account for some of the observed variability in break-up timing variables.

4. CONCLUSION AND FUTURE RECOMMENDATIONS

This work provides a unique northern Canada-wide assessment of river ice break-up timing and water levels utilizing event-based, quantitative hydrometric variables directly extracted from original Water Survey of Canada (WSC) pen chart records.

In general, from 1969-2006 findings show that the river ice break-up season has become longer in duration, occurred earlier in the year and is accompanied by reduced break-up water levels in the western parts of Canada. At the same time, the positive and significant correlation between break-up timing (T_B , T_M , B) and the spring 0°C isotherm, indicates that trends in air temperature are likely responsible for the observed changes while also providing further support to previous studies that have shown air temperature

to be a dominant control of freshwater ice break-up timing. Although the spatial patterns of these changes are largely consistent with trends of warmer spring temperatures, and even though lower break-up water levels are indicative of more *thermal* break-up conditions, further analysis of hydro-climatic controls is required. To conclude with certainty that break-up has indeed become more *thermal*, the effect of hydro-climatic controls on break-up water levels that quantify the relative driving and resisting forces, represented by discharge and the ice cover, need to be evaluated. This includes temperature indices that reflect the rate and intensity of springtime warming, the ice cover composition and its attachment to the channel bed and banks. Furthermore, the freeze-up stage, the water level at which a complete freeze over of rivers occurs in the preceding autumn, can affect break-up water levels (e.g., Beltaos, 2003). Generally speaking, lower freeze-up stages are more likely to produce greater break-up water levels since less discharge is required to dislodge and break the ice cover, while the opposite effect is observed in the case of higher freeze-up stages (Beltaos and Prowse 2009).

The influence of the inter-annual variability of temperature, as mediated by ocean/atmosphere circulation patterns, on the timing of river ice break-up was also examined. Although the strengths of correlations are weak to moderate, distinct spatial signatures are evident. The strongest effects on break-up are observed in most of western Canada, where the positive (negative) PNA phase generates earlier (later) break-ups in the season due to warmer (colder) than normal temperatures. Similarly, a significant and strong positive correlation with a similar spatial extent is found between ENSO, as measured by the Southern Oscillation Index (SOI). In other words, river ice break-up

generally occurs later in the season during a positive SOI year (i.e., La Niña) while it is delayed during negative (El Niño) phases.

Both, the Arctic and North Atlantic Oscillations show fewer significant, weak to moderately positive associations with the break-up season in the climatic regions of eastern Canada. Positive AO/NAO indices are indicative of more frequent arctic air mass intrusions which delay break-up to later than normal.

Overall, this study shows that the spatial and temporal variability of the river ice break-up season is largely dependent on the variability of spring air temperature. Accordingly, any changes in air temperatures via an increase in climate variability and change will also modify the break-up regimes of cold region rivers as well as their socio-economic effects. Based on these findings, future work should:

- (1) Increase the spatial and temporal coverage of the hydrometric station database such that the influence of air temperature on break-up dynamics can be assessed across all of Canada, as currently, the Atlantic and Northern regions are underrepresented.
- (2) Evaluate specific hydro-climatic controls of break-up water levels such as the rate of springtime warming and subsequent melt as well as components that contribute to the ice cover strength and, in particular, the freeze-up stage. This would aid in determining whether break-up has in fact become more *thermal* in response to warmer spring air temperatures in western Canada.

REFERENCES

- Anisimov OA, Vaughan DG, Callaghan TV, Furgal C, Marchant H, Prowse TD, Hjalmar Viljalmarsson H, Walsh JE. 2007. Polar regions (Arctic and Antarctica). In *Climate Change 2007: Impacts, Adaptation and Vulnerability*, Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Perry ML, Canziani OF, Palutikof JP, van der Linden PJ, Hanson CE (eds). Cambridge University Press: Cambridge; 653–685.
- Beltaos S. 1990. Guidelines for extraction of ice break-up data from hydrometric station records. In *Working Group on River Ice Jams: Field Studies and Research Needs*. NRHI Science Report No. 2, National Research Hydrology Institute, Environment Canada, Saskatoon, SK; 37-70.
- Beltaos S. 2003. Threshold between mechanical and thermal breakup of river ice cover. *Cold Regions Science and Technology* **37**: 1-13.
- Beltaos S, Prowse TD. 2001. Climate impacts on extreme ice jam events in Canadian rivers. *Hydrological Sciences Journal* **46**: 157-181.
- Beltaos S, Prowse TD. 2009. River-ice hydrology in a shrinking cryosphere. *Hydrological Processes* **23**: 122-144.
- Bonsal BR, Shabbar A, Higuchi K. 2001. Impacts of low frequency variability modes on Canadian winter temperature. *International Journal of Climatology* **21**: 95–108.
- Bonsal BR, Prowse TD. 2003. Trends and variability in spring and autumn 0 °C isotherm dates over Canada. *Climatic Change* **57**: 341-358.
- Bonsal BR, Prowse TD, Duguay CR, Lacroix MP. 2006. Impacts of large-scale teleconnections on freshwater-ice duration over Canada. *Journal of Hydrology* **330**: 340-353.
- Burn DH, Abdul Aziz OI, Pietroniro A. 2004. A comparison of trends in hydrological variables for two watersheds in the Mackenzie River Basin. *Canadian Water Resources Journal* **29**: 283–298.
- Burn DH. 2008. Climatic influences on streamflow timing in the headwaters of the Mackenzie River Basin. *Journal of Hydrology* **352**: 225-238.
- Cunderlik JM, Ouarda TBMJ. 2009. Trends in the timing and magnitude of floods in Canada. *Journal of Hydrology* **375**: 471-480.
- de Rham LP, Prowse TD, Beltaos S, Lacroix M. 2008a. Assessment of annual high water events for the Mackenzie River basin, Canada. *Hydrological Processes* **22**: 3864-3880.

- de Rham LP, Prowse TD, Bonsal BR. 2008b. Temporal variations in river-ice break-up over the Mackenzie River Basin, Canada. *Journal of Hydrology* **349**: 441-454.
- Deslauriers CE. 1968. Ice break up in rivers. In: *Proceedings of the Conference on Ice Pressures Against*. NRC Technical Memorandum No. 92, 217-229.
- Duguay CR, Prowse TD, Bonsal BR, Brown RD, Lacroix MP, Menard P. 2006. Recent trends in Canadian lake ice covers. *Hydrological Processes* **20**: 781-801.
- Environment Canada. 2009. Climate Trends and Variations Bulletin. Available online at <http://www.ec.gc.ca/adsc-cmda/default.asp?lang=En&n=8C03D32A-1>. Accessed June, 2009.
- ESRI, 2008. Environmental Systems Research Institute. ArcGIS – A Complete Integrated System, Environmental Systems Research Institute, Inc., Redlands, California (2008) <<http://esri.com/arcgis>>.
- Gullett D, Vincent L. 1992. Development of an Historical Canadian Climate Database for Temperature and other Elements. *Climatological Bulletin* **26**: 125-131.
- Gray DM, Prowse TD. 1993. Snow and floating ice. In *Handbook of Hydrology*, Maidment D (ed.). McGraw-Hill: New York: 7.1-7.58.
- Hare FK, Thomas MK. 1979. The Regional Climates of Canada. In *Climate Canada*. John Wiley and Sons, Toronto: 94-119.
- Hurrell JW, van Loon H. 1997. Decadal variations in climate associated with the North Atlantic Oscillation. *Climatic Change* **36**: 301-326.
- Jasek MJ. 1999. 1998 break-up and flood on the Yukon River at Dawson—Did El Niño and climate change play a role? In: Shen, H.T.(Ed.), *Ice in Surface Waters*. Balkema, Rotterdam, pp. 761-768.
- Kendall MG. 1975. *Rank Correlation Measures*. Charles Griffin, London, UK.
- Lacroix MP, Prowse TD, Bonsal BR, Duguay CR, Menard P. 2005. River ice trends in Canada. In: *Proceedings of the 13th Workshop on the Hydraulics of Ice Covered Rivers*, Hanover, NH, September 15-16.
- Leathers DJ, Yarnal B, Palecki MA. 1991. The Pacific/North American Teleconnection Pattern and United States Climate. Part I: Regional Temperature and Precipitation Associations. *Journal of Climate* **4**: 517 – 528.
- Mann HB. 1945. Non-parametric tests against trend. *Econometrica* **13**: 245-259.

- Mantua NJ, Hare SR, Zhang Y, Wallace JM, Francis RC. 1997. A Pacific interdecadal climate oscillation with impacts on salmon production. *Bulletin of the American Meteorological Society* **78**: 1069–1079.
- Michel B. 1971. Winter regime of rivers and lakes. Cold Regions Science and Engineering Monograph III-Bla, Cold Regions Research and Engineering Laboratory, U.S. Army, Hanover, New Hampshire.
- Notaro M, Wang WC, Gong W. 2006. Model and observational analysis of the Northeast US regional climate and its relationship to the PNA and NAO patterns during early winter. *Monthly Weather Review* **134**: 3479-3505
- Prowse TD, Onclin CR. 1987. Timing and duration of river ice break-up. In: Proceedings of the 44th Eastern Snow Conference. Fredericton, NB, pp. 192–196.
- Prowse TD, Bonsal BR, Duguay CR, Hessen DO, Vuglinsky VS. 2007a. River and Lake Ice. In *Global Outlook for Ice and Snow*. United Nations Environment Programme, DEW/0924/NA, available online: http://www.unep.org/geo/geo_ice/, 17 May 2009.
- Prowse TD, Bonsal BR, Duguay CR, Lacroix MP. 2007b. River-ice break-up/freeze-up: a review of climatic drivers, historical trends and future predictions. *Annals of Glaciology* 46: 443-450.
- Prowse TD, Bonsal BR, Lacroix MP, Beltaos S. 2002. Trends in river-ice break-up and related temperature controls. In *Ice in the Environment: Proceedings of the 16th IAHR Conference on Sea Ice Processes*. Squire VA, Langhorne PJ (eds.), International Association of Hydraulic Engineering and Research, Dunedin, New Zealand, 64-71.
- Prowse TD, Culp JM. 2003. Ice break-up: a neglected factor in river ecology. *Canadian Journal of Civil Engineering* **30**: 128-144.
- Rasmusson EM, Carpenter TH. 1982. Variations in tropical sea surface temperature and surface wind fields associated with the Southern Oscillation/El Niño. *Monthly Weather Review* **110**: 354–384.
- Rasmusson EM. 1984. El Niño. The ocean/atmosphere connection. *Oceanus* **27**: 5–12.
- Salmi T, Maä'tta A, Anttila P, Ruoho-Airola T, Amnell T. 2002. Detecting Trends of Annual Values of Atmospheric Pollutants by the Mann–Kendall Test and Sen's Slope Estimates – the Excel Template Application MAKESENS. Publications of Air Quality, No. 31. Finnish Meteorological Institute, Helsinki, Finland.
- Sen PK. 1968. Estimates of the regression coefficient based on Kendall's tau. *Journal of the American Statistical Association* **63**: 1379–1389.

- Shabbar A. 2006. The impact of El Niño-Southern Oscillation on the Canadian climate. *Advances in Geosciences* 6: 149-153.
- Shapiro SS, Wilk MB. 1965. An analysis of variance test for normality (complete samples). *Biometrika* 52: (3-4) 591-611.
- Shepard D. 1968. A two-dimensional interpolation function for irregularly-spaced data. *Proc. 23rd National Conference ACM, ACM*, 517-524.
- Thompson DW, Wallace JM. 1998. The Arctic Oscillation signature in the wintertime geopotential height and temperature fields. *Geophysical Research Letters* 25: 1297–1300.
- Vincent LA, Zhang X, Bonsal BR, Hogg WD. 2002. Homogenization of daily temperatures over Canada. *Journal of Climate* 15: 1322-1334.
- Wallace JM, Gutzler DS. 1981. Teleconnections in the geopotential height field during the Northern Hemisphere winter. *Monthly Weather Review* 109: 784–812.
- Wrona FJ, Prowse TD, Reist JD, Beamish R, Gibson JJ, Hobbie J, Jeppesen E, King J, Koeck G, Korhola A, Levesque L, Macdonald R, Power M, Skvortsov V, Vincent W. 2005. *Freshwater Ecosystems and Fisheries. Arctic Climate Impacts Assessment*. Cambridge University Press: Cambridge; Chapter 8, 353-452.
- Zhang X, Vincent LA, Hogg WD, Niitsoo A. 2000. Temperature and precipitation trends in Canada during the 20th century. *Atmosphere-Ocean* 38: (3) 395-429
- Zhang X, Harvey KD, Hogg WD, Yuzyk TR. 2001. Trends in Canadian streamflow. *Water Resources Research* 37 (4): 987-99.

FIGURES AND TABLES

Table 1. Summary of number of stations with significant and non-significant trends ($\alpha=0.1$) as shown in Figure 2. Changes in magnitude are only provided for significant trends. Units are days/decade for timing variables and metres/decade for water levels).

	n	Number of sites		Magnitude of significant trends					
		Significant increase/decrease	Non-significant increase/decrease	Significant increase			Significant decrease		
				Mean	Min	Max	Mean	Min	Max
H _B	44	2 / 10	12 / 20	0.5	0.1	0.9	-0.3	-0.1	-0.5
H _M	44	0 / 14	4 / 26	0.8	0.3	1.1	0.5	0.10	-1.2
T _B	67	3 / 15	23 / 26	-	-	-	-2.7	-1.4	-4.7
T _M	67	0 / 20	15 / 32	-	-	-	-2.7	-1.2	-5.6
B	104	2 / 24	23 / 55	2.6	2	3.3	-3.1	-1.5	-8.6
t ₁	40	6 / 3	19 / 12	0.9	0.6	1.3	-0.5	-0.3	-0.6
t ₂	65	10 / 7	28 / 20	1.5	0.5	3.3	-0.7	-0.1	-1.6
t ₃	49	9 / 6	21 / 13	1.5	0.6	2.9	-1.1	-0.6	-2

Table 2. Percentages of significant ($\alpha=0.05$) spearman correlation coefficients in Canada's climatic regions between timing of break-up initiation (T_B), peak-break-up water level (T_M), B and the mean 1 month, 2 month and 3 month SOI, PNA, AO and NAO indices. Note: the asterisk indicates a low sample size ($n = 2$) for the Southern BC Mountain climate region.

	Climate Region	SOI			PNA			AO			NAO		
		T_B	T_M	B	T_B	T_M	B	T_B	T_M	B	T_B	T_M	B
1 month mean	Southern BC Mountains*	50	50	100	0	50	100	0	0	0	0	0	0
	Yukon/North BC Mountain	17	14	10	33	28	15	16	0	10	33	43	20
	Mackenzie	25	0	7	50	50	23	0	16	7	0	0	0
	Northwest Forest	13	19	27	70	66	77	5	0	0	0	8	7
	Prairie	0	15	7	44	23	57	0	15	7	14	15	14
	Arctic Tundra	0	40	8	0	0	8	0	0	0	0	0	0
	Northeastern Forest	10	12	9	0	4	0	0	4	6	0	0	3
	Atlantic	0	0	14	0	16	0	20	34	14	0	0	14
2 month mean	Southern BC Mountains*	100	100	100	50	50	50	0	0	0	0	0	0
	Yukon/North BC Mountain	17	43	15	50	57	45	0	0	15	0	0	10
	Mackenzie	25	0	7	25	67	44	0	0	13	0	0	13
	Northwest Forest	17	23	23	56	61	67	0	0	3	0	0	0
	Prairie	22	23	21	55	46	71	0	0	0	0	0	0
	Arctic Tundra	0	0	0	0	20	15	0	20	8	0	0	8
	Northeastern Forest	10	4	0	0	8	18	0	21	22	20	8	16
	Atlantic	0	14	28	0	0	14	20	33	43	0	17	0
3 month mean	Southern BC Mountains*	100	100	100	50	50	50	0	0	0	0	0	0
	Yukon/North BC Mountain	33	57	15	33	57	37	0	0	0	0	0	5
	Mackenzie	25	0	7	25	50	25	0	0	13	0	0	13
	Northwest Forest	30	38	33	56	65	80	0	0	0	0	0	0
	Prairie	33	31	36	33	46	71	0	0	0	0	0	0
	Arctic Tundra	0	0	8	0	20	15	0	20	8	0	0	8
	Northeastern Forest	10	8	3	0	16	18	10	28	25	20	24	33
	Atlantic	0	0	14	0	0	0	0	33	29	40	33	43

(*) denotes small sample size

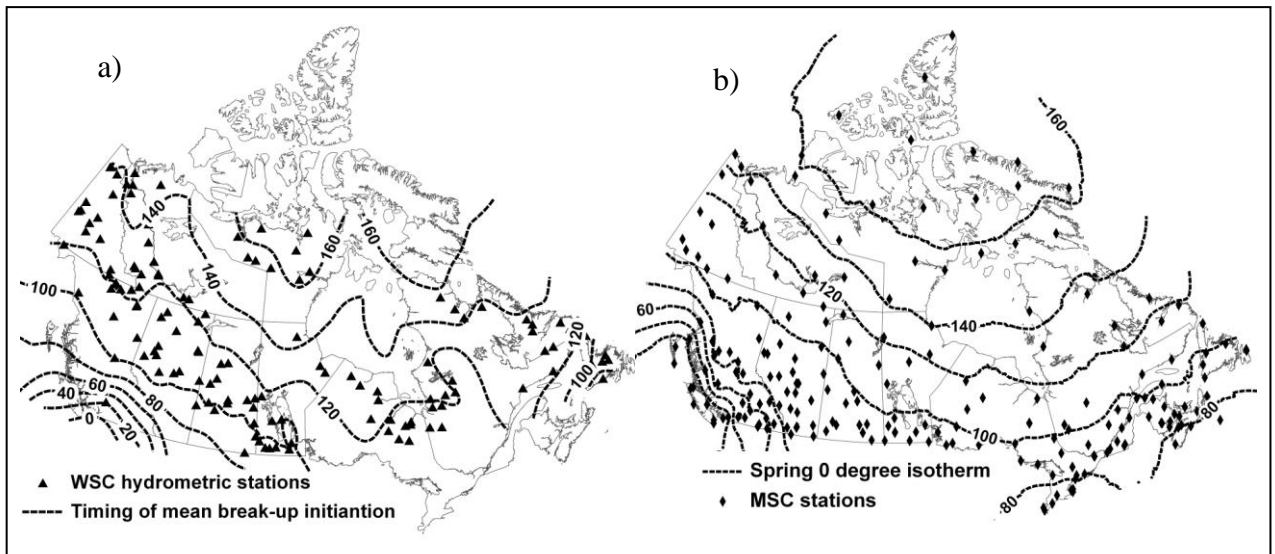


Figure 1. a) The locations of the 136 WSC hydrometric stations and isochrones of the Julian day of mean break-initiation (T_B) from 1913-2006 and b) The locations of the 210 MSC air temperature stations and average spring 0°C isotherm dates over the 1900-2007 period.

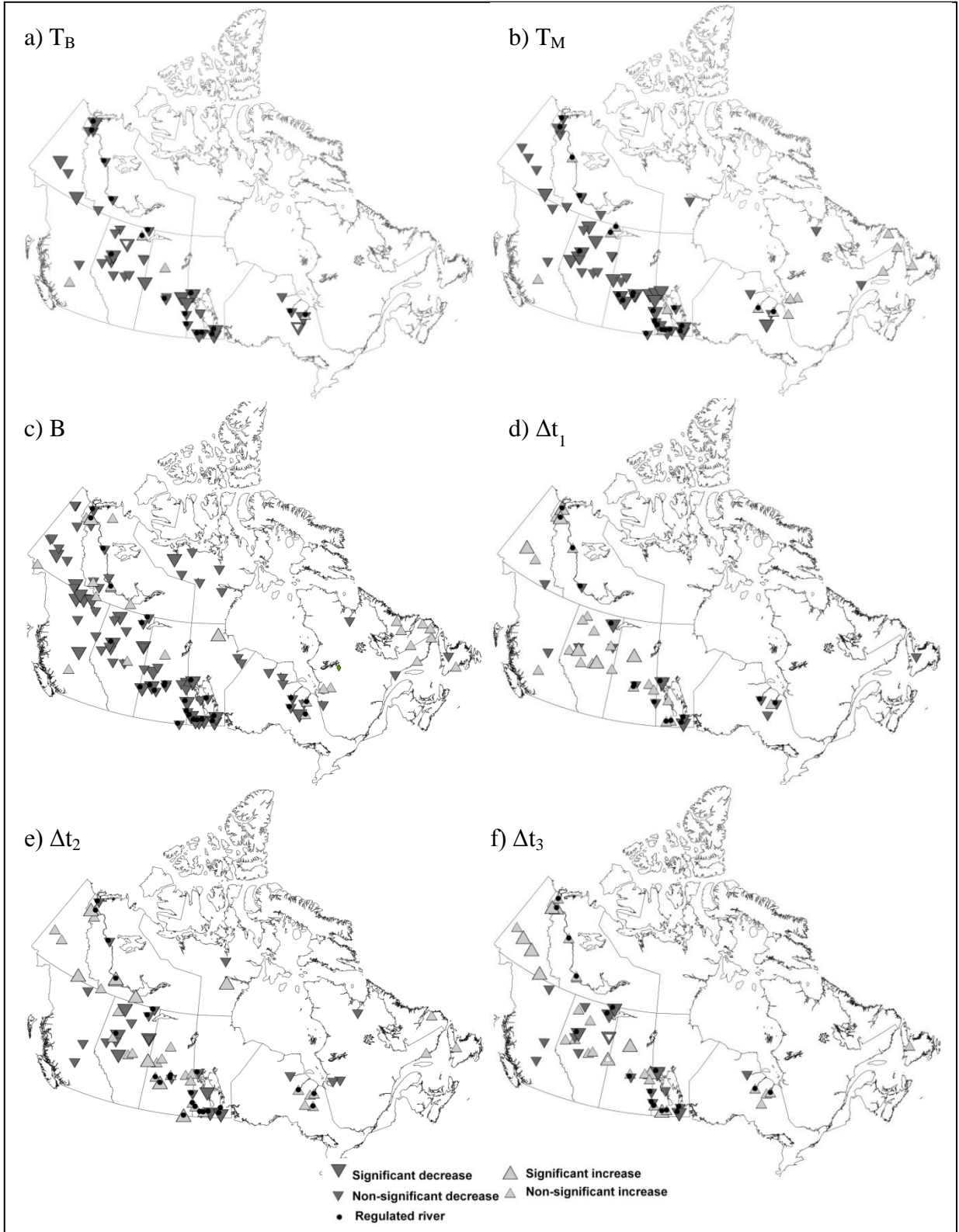


Figure 2. Results of the Mann-Kendall test ($\alpha=0.1$) for the 1969-2006 period. Trends in: a) T_B , b) T_M , c) B , d) Δt_1 , e) Δt_2 and f) Δt_3 . Regulated rivers are indicated with black dots; white triangles denote locations for which example time series are shown in Figure 4.

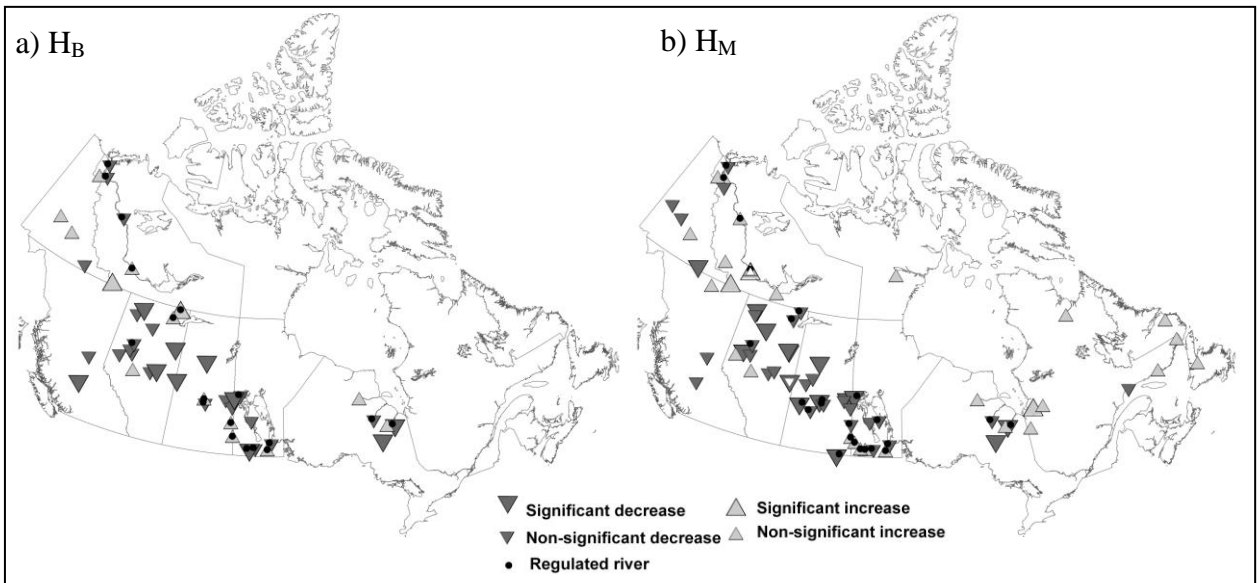


Figure 3. Results of the Mann-Kendall test ($\alpha=0.1$) of a) H_B and b) H_M for the 1969-2006 period. As in Figure 2, regulated rivers are indicated with black dots; white triangles denote locations for which example time series are shown in Figure 4.

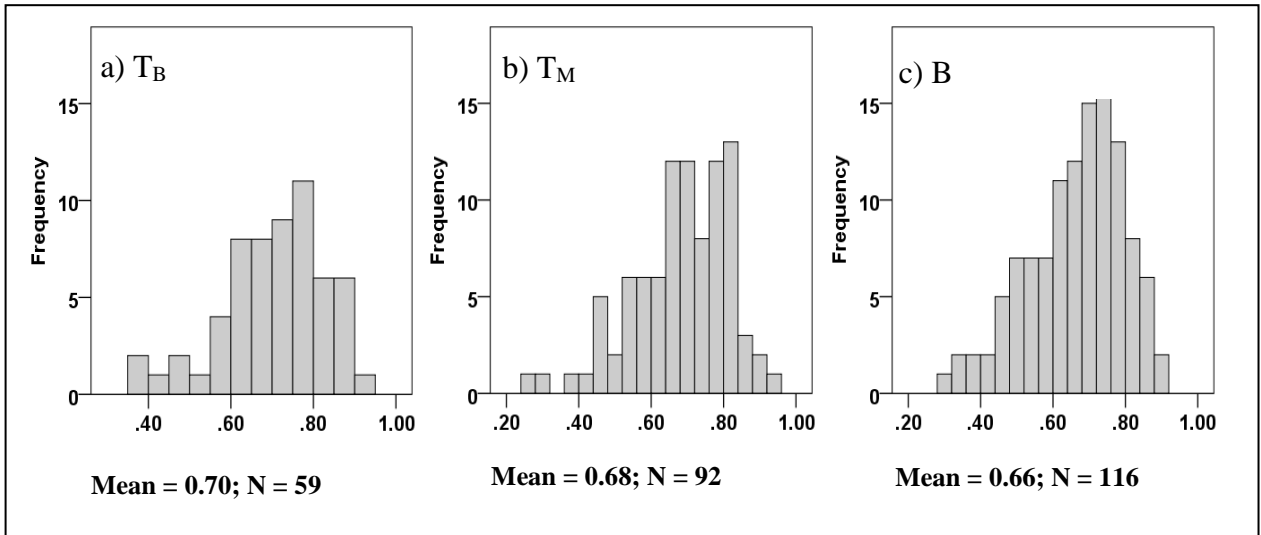


Figure 4. Histogram of spearman correlation coefficients between timing of break-up initiation (T_B), peak water level (T_M), 'last B date' (B) and the spring 0°C isotherm across Canada.

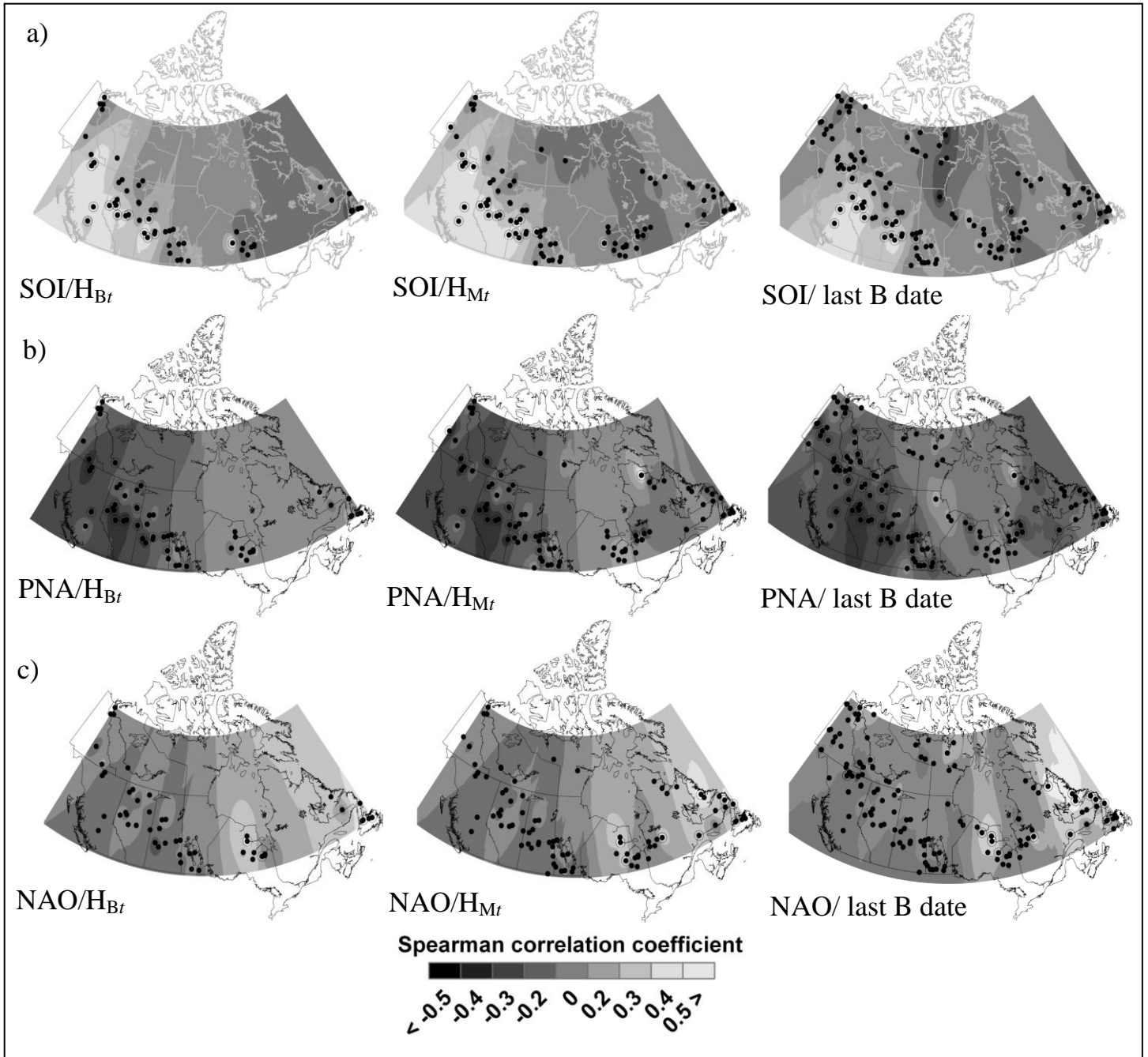


Figure 5. Isopleths of spearman correlation coefficients between the timing of break-up initiation (T_B), peak-break-up water level (T_M), ‘last B date’ (B) and the following indices: (a) the 3 month mean SOI, (b) 2 month mean PNA and (c) the 3 month mean NAO. Significant (non-significant) correlations ($\alpha=0.05$) are encircled (non-encircled) solid, black dots.

CHAPTER 4: CONCLUSION

An extensive database of hydrometric variables extracted directly from WSC archives for the 1913 – 2006 period was used to provide a comprehensive northern Canada-wide assessment of the river ice break-up season. Never before assessed at this scale, these variables include: the water level (H_B) and Julian day (T_B) at the initiation of river ice break-up as well as the peak water level (H_M) and Julian day of break-up (T_M). The ‘last B date’ indicator (B, time when last ice effects are observed in the channel) was also assessed as it designates the end of river ice break-up. The results were presented as two stand-alone manuscript-style chapters, with the focus of chapter 2 being an assessment of peak ice-induced and open water levels, followed by an analysis of the physical controls on peak break-up water levels across northern Canada. Provided in chapter 3 is a spatial and temporal assessment of river ice break-up timing and water levels that furthermore evaluates the influence of air temperature using the spring 0°C isotherm and large-scale teleconnections.

In chapter 2, a peak water-level river-regime classification (WRC), based on the return-period analysis of peak break-up and open-water levels for 136 WSC hydrometric stations, represents the first northern Canada-wide assessment of river ice, spring break-up regimes. The results indicate that 32% of rivers are ice dominated (R_B), 45% are open-water dominated (R_O) and 23% are mixed (R_M). At all sites, regardless of classification, the presence of in-channel ice effects was demonstrated by means of a ‘*synthetic stage and discharge*’ plot. In other words, for the vast majority of sites, river-ice conditions during the spring break-up period were such that ice-induced water levels exceed those of the open-water period for comparable discharges. A comparison of the

spatial WRC distribution with classifications of regional climate and physiography showed that R_O rivers generally occur at high elevations and in maritime climates, while R_B rivers are more common at lower elevations and in cool continental climates. These results were substantiated further with multivariate and *post hoc* statistical analysis of relevant physical controls. A Canonical Correspondence Analysis determined that slope, elevation and basin area are contributing factors to the regime classification, while latitude is not significantly correlated to the WRC. Overall, the R_B regime is primarily associated with rivers found in larger basins with low elevation and low channel slopes. This is in contrast to the R_O regime, which is mostly associated with smaller basin areas, higher elevations and greater channel slopes. The R_M regime exhibits more intermediate physical characteristics that are in between those of R_B and R_O rivers, and as such, it is likely that hydro-climatic controls at an inter-annual time scale (e.g., NAO, AO) are the cause of the higher order peak water level events at these sites.

Presented in Chapter 3 was a temporal analysis of river ice break-up using event-based variables of timing, and for the first time, break-up water levels. Never before analyzed at this scale, these variables enabled a comprehensive northern Canada-wide, spatial and temporal assessment of river ice break-up, followed by an investigation of the effects of air temperature by means of the spring 0°C isotherm and dominant large-scale ocean/atmosphere oscillations.

For the most part, trends from 1969-2006 indicate that the river ice break-up season has become longer in duration, occurs earlier in the year and is accompanied by reduced break-up water levels. With respect to timing, these trends are spatially and temporally largely consistent with the spring 0°C isotherm, suggesting that the observed changes are

likely due to warmer spring air temperatures. Also of note is the fact that, with the exception of break-up *duration*, observed trends of timing and water levels are consistent between regulated and non-regulated rivers.

Although the trends of reduced break-up water levels largely mirror those of timing, additional analysis of hydro-climatic controls of break-up water levels is necessary to conclude with certainty that changes in spring air temperatures are the sole cause of lower break-up water levels and indeed more *thermal* break-up events. This would include a quantification of the relative driving (e.g., melt and run-off intensity) and resisting forces (ice cover composition and attachment to channel bed and banks). An additional hydro-climatic control is the water level at which a complete freeze over of a river occurs in the preceding autumn, where for example a lower (greater) freeze-up stage will be more (less) likely to produce elevated water levels at break-up since less (more) discharge is required to dislodge and break the ice cover.

The inter-annual and regional variability of break-up timing in relation to spring air temperature was also assessed by means of dominant ocean/atmosphere circulation patterns. In western Canada, the positive (negative) PNA phase causes earlier (later) break-ups due to warmer (colder) than normal temperatures while the opposite correlation is observed for the SOI, where positive (negative) SOI years reflect colder (warmer) spring temperatures causing later (earlier) break-up.

Weak positive relationships between break-up timing and the AO and NAO are found in climatic regions of eastern Canada that reflect the influence of frequent arctic air mass intrusions (colder temperatures) and causing later than normal break-up during positive phases.

Overall, the results of this research thesis provide several valuable contributions to the field of cold-regions river hydrology. The peak water-level river-regime classification (WRC) illustrates, for the first time, the effects of river-ice on annual peak water-levels across Canada, while the subsequent analysis has shown that physical controls contribute to break-up magnitudes. In addition, the spatial and temporal assessment of spring break-up provides a first ever quantification of break-up using hydrometric timing variables previously not assessed at this scale, and more importantly break-up water levels. It is anticipated that these contributions will further aid the advances of river ice hydrology in the face of increasing climate variability and change.

Although separate recommendations for further research are derived from chapter 2 and 3, they are combined and summarized as a certain overlap between the proposed research needs exists. Based on this research, future assessments should:

- (1) Increase the spatial coverage of the hydrometric database to encompass those regions in Canada that are currently underrepresented (e.g., Atlantic and Northern Canada) and should include additional circumpolar, physiographic and climatic regions. This would allow an expansion of the WRC to assess the influences of other physiographic and climatic combinations, while also enabling further spatial and temporal analysis of the influence of spring air temperature on river ice break-up in those regions where data were limited for the purpose of this study.
- (2) For the purpose of the WRC proposed in chapter 2, define an improved selection criterion to eliminate rivers that freeze to the channel bottom, as the basin-scale criterion of $\geq 10\,000\text{ km}^2$ used in this work was insufficient to allow for the development of a free floating ice cover.

- (3) Assess the effects of additional variable hydro-climatic controls on peak break-up water levels. This should include the rate of springtime warming, measures of ice cover strength and composition, and furthermore, the freeze-up stage as well as the influence of mid-winter break-up events which, as noted above and in chapter 2, can influence break-up water levels. These controls are likely to influence the WRC while also enabling a much needed quantification of the mechanisms responsible for the reduced break-up water levels observed in chapter 3 of this work.
- (4) Examine the influence of different modes of climate variability on the WRC and break-up water levels in general. Although ocean/atmosphere circulation patterns have been shown to be responsible for some of the variability in river ice break-up timing, their influence on break-up water levels is less clear. Future work in this regard should focus on establishing a link between ocean/atmosphere oscillations and a temperature index that reflects the rate of warming prior to break-up. This would enable the quantification of the break-up discharge (e.g., driving force) and aid in determining whether break-up events have become more *thermal* in the past decades.

APPENDICES

Appendix A: Chapter 2 variables

H_O = maximum annual instantaneous/daily open water-level

H_B = maximum annual instantaneous/daily break-up water-level

Y_O = nominal water-level corresponding to H_O , referenced to channel bottom

Y_B = nominal water-level corresponding to H_B , referenced to channel bottom

Q_O = daily/instantaneous discharge corresponding to H_O event

Q_B = daily/instantaneous discharge corresponding to H_B event

$\overline{Y_O}$ = mean peak open water-level

$\overline{Y_B}$ = mean peak break-up water-level

$\overline{Q_O}$ = mean open water discharge

$\overline{Q_B}$ = mean spring break-up discharge

R_O = open water dominated regime, where $Y_B/Y_O < 1$ for the 2, 5, 10, 15, 20, 25 and 30 year return-periods

R_B = spring break-up dominated regime, where $Y_B/Y_O > 1$ for above specified return periods

R_M = mixed regime, where $Y_B/Y_O > 1$ for some but $Y_B/Y_O < 1$ for other return periods specified above

A = basin area

Φ = latitude (DD)

E = elevation, metres above sea level (masl)

S = channel slope, dimensionless ratio of difference in elevation and reach length

Appendix B: Chapter 3 variables

H_B = instantaneous water-level at river ice break-up initiation

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

T_B = Julian day corresponding to H_B

T_M = Julian day corresponding to H_M

B = 'last B date', time at which ice effects are no longer observed in the channel

Δt_1 = break-up drive

Δt_2 = break-up wash

Δt_3 = break-up duration