# The River Ice Break-Up Season in Canada: Variations in Water Levels and Timing

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## 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. Notwithstanding the environmental implications, the direct physical action of river ice and associated flooding during break-up can cause extensive damage to hydroelectric and transportation infrastructure resulting in substantial financial costs. With respect to climate change, these effects are expected to be exacerbated in the future. Presented here is a Canada-wide analysis of the trend (Mann-Kendall) in break-up water levels as well as quantitative timing related variables representative of the river ice break-up season. The data were extracted from original water level records supplemented with recent digital data at 136 Water Survey of Canada hydrometric stations and analyzed for the 1969-2006 period. In general, trends in water levels observed at the initiation of break-up ($H_B$), as well as maximum water levels at break-up ($H_M$) show declines ranging from 0.1-0.5 m/decade and 0.1-1.2 m/decade respectively. Simultaneously, the timing of both events has advanced by 1.4-4.7 days/decade for the former and 1.2-5.6 days/decade for the latter. Similarly, the timing of 'last B date' (last day of ice effects) has advanced by 1.5-8.6 days/decade. Assessed also are river ice break-up phases including break-up *drive* ($t_1$), *wash* ($t_2$) and *duration* ($t_3$). With the exception of a few sites, the time (days) elapsed between break-up initiation and occurrence of peak water level ($t_1$), shows no trend. In contrast, the majority of sites show an increase in the time elapsed between peak water level occurrence and 'last B date' (break-up wash, $t_2$). Similar results are observed for the break-up *duration* ($t_3$), suggesting that river ice break-up is occurring over a prolonged period of time. Overall, the river ice break-up season has experienced reduced break-up water levels, occurs earlier in the season and over an extended period of time.

**Keywords**: River ice break-up, peak water levels, trend analysis

## INTRODUCTION

The annual regime of cold regions rivers are subject to numerous river ice processes dominated by the break-up of river ice in the spring. Identified as a dominant control of annual peak water levels on major northern river systems, break-up is one of the most important hydrologic events

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frequently causing extreme flooding (de Rham *et al.,* 2008a). The ecological, morphological and socio-economic implications can be significant. In this regard, spring break-up on northern rivers is known to create substantial ecological disturbance and destruction to riparian habitat (Cameron and Lambert, 1971; Gray and Prowse, 1995) and numerous assessments detailing the effects of river ice on the ecology and biology of rivers are available in the literature (e.g. Cunjak *et al.,* 1998; Prowse, 2001a; Prowse and Culp 2003). The break-up period is also an important geomorphic agent on river systems, capable of producing significant erosion, often altering channel characteristics directly and generating severe sediment fluxes (Prowse, 2001b). Socioeconomic implications primarily include extensive damage to hydroelectric and transportation infrastructure due to the direct physical interference of river ice, but also extreme high water levels and flooding (Beltaos 1995, 2000). Damage to infrastructure and development can be significantly greater when spring break-up conditions favor the development of ice jams. The most recent estimate of river ice related damage available in the literature cites costs of $250 million (USD) in North America (Prowse *et al.,* 2007). The fact that climate change is expected to intensify the effects of river ice during the break-up season is confirmed in a number of reports including the Intergovernmental Panel on Climate Change (IPCC, 2007) and the Arctic Climate Impacts Assessment (Wrona *et al.,* 2005; Prowse *et al.,* 2006).

Concurrent with pronounced warming trends across the country and the earlier timing of the 0° spring isotherm (Bonsal and Prowse, 2003) the strong relationship between air temperature and the timing of the spring break-up season in Canada is well established in the literature (eg. Prowse and Bonsal, 2004). Duguay *et al*. (2006) analyzed temporal and spatial patterns of lake ice break-up and freeze-up timing in Canada for the 1951-2000 period. Overall, results showed consistent trends of earlier break-up timing but were more pronounced in the western regions of the country. These results are consistent with findings by Lacroix *et al*. (2005) who assessed the timing of river ice break-up. Both studies also revealed a reasonably strong correlation between the timing of freshwater break-up and the 0° spring isotherm, providing further evidence of the association between air temperature and break-up timing. Most assessments of freshwater ice break-up rely on the readily retrievable 'B-date' qualifiers provided by the Water Survey of Canada (WSC) which are indicative of in-channel ice effects. To supplement the use of the 'B-date' qualifiers, the assessment of de Rham *et al*. (2008a) in the Mackenzie River Basin relied on event-based hydrometric variables directly derived from original (WSC) water level records. The authors observed an earlier occurrence of river ice break-up of 1 day/decade for the 1970-2002 period which corresponds to the findings of other spring freshet studies for the Mackenzie River Basin. Though regional variability is evident, Burn *et al*. (2004) and Aziz *et al*. (2005) identified earlier onset of the spring freshet using a suite of streamflow timing related hydrometric variables. Earlier peak spring streamflows were also observed by Burn (1994) in west-central Canada, Gagnon and Gough (2002) in the Hudson Bay region and in Nunavut by Spence (2002). In addition to spring freshet timing, the magnitude of peak spring streamflow is of concern in the context of climate change due to its far reaching implications. In this regard numerous studies reveal considerable regional differences and variability. In British Columbia, Cunderlik and Burn (2002) detected significant trends of increased peak spring discharges, while the comprehensive Canada-wide study by Zhang *et al*. (2001) found increases in mean monthly streamflows for March and April which were also occurring earlier in the season. The recent work by Cunderlik and Ouarda (2009) on the timing and magnitude of flood events in Canada show the significantly earlier occurrence of snowmelt flood events along the southern extent of the country and reduced magnitudes in peak spring flows in northern British Columbia, Alberta and Saskatchewan and southern Ontario for the 1974-2003 period.

Notwithstanding the environmental and socio-economic significance of changes to the timing and magnitude of peak spring flows, operational flood analyses still primarily rely on open water discharge recurrence intervals, neglecting the most important hydrologic effect of river ice, which is evident in elevated water levels (Figure 1).

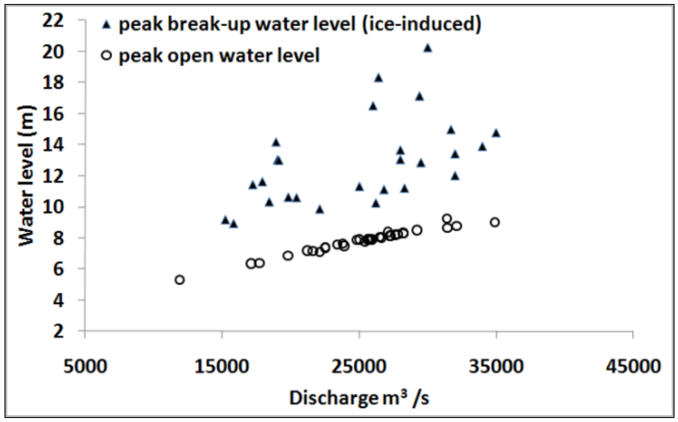


Figure 1. Stage discharge plot of annual ice-induced and open water peak events for the Mackenzie River at Arctic Red, 1972-2006.

During river ice break-up, peak water levels are attained due to in-channel ice effects (Gerard 1990) as opposed to peak open water levels which are generally a result of basin-scale landscape processes. Generally speaking, when roughness coefficients for the ice cover bottom and the channel bed are equal, the added hydraulic resistance of the ice cover produces a backwater effect and a 30% increase in mean water level for comparable open channel discharges (Gray and Prowse 1993). Break-up water levels are the direct result of two distinct types of break-up, defined as *dynamic* or *thermal*. Both types define the extremes of the river ice break-up continuum and reflect the balance of driving and resisting forces. The gravitational ice cover component and landscape processes responsible for increasing discharge (e.g. snowmelt) represent driving forces, while ice cover composition (strength and thickness) and bonding to the channel banks constitute resisting forces (Gray and Prowse 1993). Peak water levels during break-up define the *dynamic* type, in which case both forces are high (e.g. rapid snowmelt and a competent ice cover) as opposed to the *thermal* break-up, where the ice cover is thermally decayed, prone to fracture and presents little resistance to flow (Gray and Prowse, 1993). In the case of *dynamic* break-up and ice jam conditions, increases in ice cover roughness can be significantly greater and are frequently associated with extreme water levels. A number of studies have shown that ice-induced water levels can exceed those of comparable open channel discharges by 2-3 times (Beltaos 1982; Prowse 2005). Recognizing the role of ice hydraulics in conjunction with discharge as a flood producing mechanism in cold region climates is vital since nearly 60% of rivers in the Northern Hemisphere experience significant ice effects (Prowse, 2005). The effects of river ice as a control on peak break-up flood events were illustrated by de Rham *et al*. (2008a) for the Mackenzie River Basin. Using water level data extracted from original WSC records, the authors produced a river regime classification using a return period analysis of annual peak ice-induced and open water levels. It was found that annual peak break-up events for nearly half of the WSC hydrometric stations sampled occur due to ice effects. The river regime classification was expanded by von de Wall *et al.* (2009) to encompass 136 hydrometric stations across Canada, and results show that annual peak events in nearly one-third of rivers occur exclusively due to ice effects while a quarter of rivers are of the mixed regime type, where annual peak events can occur due to in-channel ice effects or under open water conditions. It follows that in addition to discharge, the hydraulic effects of river ice need to be addressed in flood analyses of snowmelt dominated cold regions basins. In this context, discharge data is an inadequate indicator of spring flood magnitude and the work presented here is the first Canada-wide assessment to use break-up water levels. This manuscript is part of a larger Canada-wide assessment of spatial and temporal patterns of the river ice break-up season based on more accurate physically-based water level and timing data directly extracted from original WSC water level records. This study addresses the lack of a Canada-wide assessment of the river ice break-up season, although at the basin-scale a number of such studies exist (e.g. Pavelsky and Smith, 2004; de Rham et al., 2008a,b). The significance of this assessment is evident in context of past as well as projected changes in climate, which are particularly pronounced in northern regions, where potential effects on river ice dynamics are anticipated to include changes in magnitude and frequency of break-up events (Anisimov *et al.,* 2007; Prowse *et al.,* 2006; Wrona *et al.,* 2005). Specifically, the work presented here addresses the following objective: using event-based, quantitative hydrometric variables representative of the river ice break-up season, the changes in the timing and magnitudes are assessed over the 1969-2006 period.

## DATA AND METHODOLOGY

### Data

The water level data used in this analysis originates from the Canada-wide hydrometric station network operated by the WSC. Although stream flow data are published in digital format, historic water level data are available as original pen chart records until 2000. Water level records were retrieved from regional WSC offices and supplemented with digital data from 2000 onwards. The selection of hydrometric stations is based on criteria identified by Prowse and Lacroix (2001) and only rivers representative of the mainstem channel were included in the analysis. Additional prerequisites require that rivers are representative of basin sizes in excess of 10 000 $km^2$ and drain into the Arctic Ocean. The former criterion assumes sufficient discharge to develop a free floating ice cover (Prowse and Lacroix, 2001). The work presented here focuses on the break-up of rivers in spring and the southern extent of the temperate ice zone developed by Prowse *et al.* (2002) was used to limit the influence of midwinter break-up events. Though a number of stations in British Columbia are located outside this zone, their inclusion was deemed valuable as they are representative of the Pacific influenced hydroclimatic regions. Using these criteria, 136 hydrometric stations with records encompassing the 1913-2006 period representative of an elevation range of 0 to 874 masl were included in this analysis.

### Methodology

The temporal component of the river ice break-up season was assessed using the timing (Julian day) of the following events: initiation of river ice break-up ($H_B$), peak water level during break-up ($H_M$) and 'last B date' (Figure 2). The initiation of break-up ($H_B$) can be observed on a typical stage hydrograph during the break-up of river ice as a distinct change in water level. As hydraulic conditions progress from an intact to a fractured ice cover set in sustained motion, water levels initially rise rapidly until fracture, and are followed by a decrease due to a reduced resistance to flow. Accordingly, the initiation of river ice break-up ($H_B$) is indicated by a distinct 'spike' on the break-up stage hydrograph preceding the maximum break-up water level ($H_M$) (Beltaos, 1990). The WSC 'last B date' designation identifies the last day during which ice conditions are observed to affect streamflow and water levels and has been used extensively in temporal analyses of the river ice season.

To enable a more accurate, physically quantifiable representation of the river ice break-up season, the timing of $H_B$, $H_M$ and 'last B date' is used. Following the guidelines by Beltaos (1990) the identification of these events on original pen chart records allows for the determination of the river ice break-up phases first identified by Deslaurier (1968) and Michel (1971). The break-up *drive* ($t_1$) as measured by the time elapsed from $H_B$ to the occurrence of $H_M$, represents the degradation and transport of river ice which will ultimately lead to the temporary arrest of the ice cover or an ice jam and hence maximum break-up water levels. According to Deslaurier (1968) the break-up *drive* is influenced by hydraulic factors (hydraulic slope), channel factors (direction of flow, cross-section) and cryologic factors (ice cover properties). Though the *drive* may be absent in *thermal* break-up events, its usefulness for the further study of the physical controls of break-up water levels is anticipated. The break-up *wash* ($t_2$) reflects the period of time required to clear residual ice from the channel by the spring flood wave, and combined with the break-up *drive* constitutes the break-up *duration* ($t_3$).

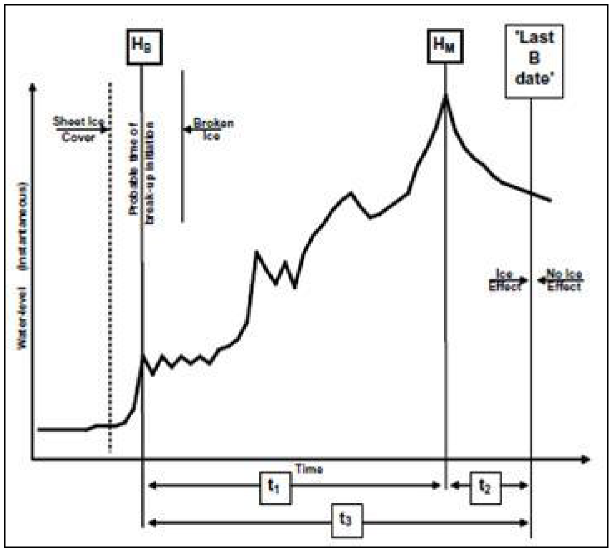


Figure 2. Water level recording chart illustrating a typical river ice break-up (adapted from Beltaos, 1990). Indicated are the timing and magnitude of the initiation of break-up ($H_B$) and peak water level during break-up ($H_M$). Also indicated are the timing of 'last B date' (last ice effects observed in channel), the break-up drive ($t_1$), break-up wash ($t_2$) and break-up duration ($t_3$).

Water levels and timing of HB and HM as well as the timing of 'last B date', and changes in t1, t2 and t3 in the time series of 136 hydrometric station records encompassing 1913 - 2006 were extracted and maximized for spatial and temporal coverage. The completeness of records met the criteria of >2/3 used by Duguay et al. (2006). The time series from 1969 - 2006 of each variable was assessed using the non-parametric Mann-Kendall test for trend at the 90% significance level (Mann, 1945; Kendall, 1975). The magnitudes of trends were determined using the Sen's slope estimate (Sen, 1968). This method is robust as it copes with missing values and low detection limits and has found wide use in hydrologic applications (eg. Smith, 2000; Zhang et al., 2001; Duguay et al., 2006; de Rham et al., 2008b). Though the Mann-Kendall test tends to exhibit an increased probability of detecting trends if serial correlation is present in the data, pre-whitening was not performed. While pre-whitening removes serial correlation, it may simultaneously reduce the ability of the Mann-Kendall test to detect trends, resulting in an increase (decrease) in the slope of trend in the presence of negative (positive) serial correlation (Yue and Wang, 2002). In addition, serial correlation was deemed minimal for annual break-up events. The period from 1969-2006 was determined to provide the maximum spatial and temporal use of data and are assessed at the 90% confidence level or greater. The Excel© template MAKESENS developed by Salmi et al. (2002) was used to perform the Mann-Kendall test and the Sen's slope estimate.

## RESULTS AND DISCUSSION

### Break-up water levels

The results of the Mann-Kendall analysis of break-up initiation and peak water levels are shown in Figure 3 and summarized in table 1 (shaded grey); only trends at the 90% significance level or greater are discussed. Over the period of observation from 1969-2006, water levels at the initiation of river ice break-up ($H_B$) show evidence of significant decline oriented northwest-southeast in central Canada and range from 0.1 to 0.5 m/decade. Similarly, the maximum break-up water levels ($H_M$) show declines of up to 1.2 m/decade throughout the Alberta/Saskatchewan region. Interestingly, isolated increases in break-up initiation ($H_B$) and maximum break-up water levels ($H_M$) of 0.9 and 1.1 m/decade are observed along the Alberta-Northwest Territory border. Though the majority of sites show reduced $H_B$ and $H_M$ magnitudes, they are not directly comparable, as they were assessed for trend independently.

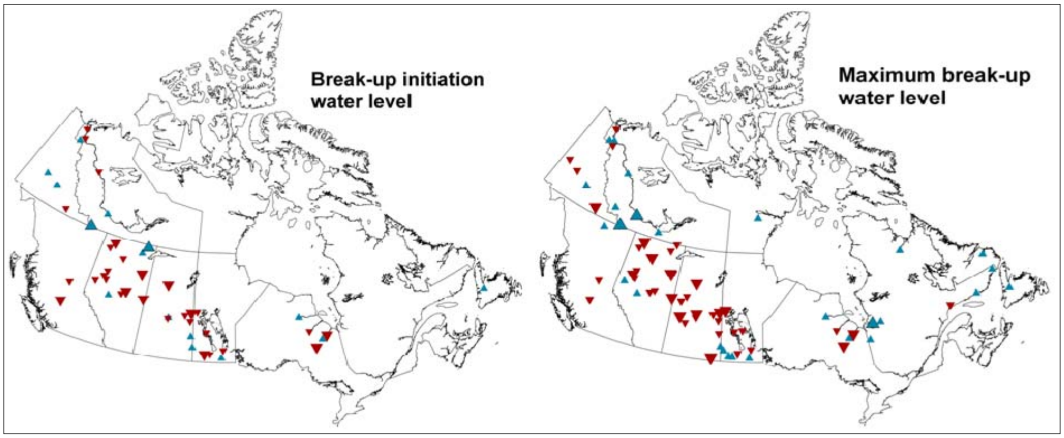


Figure 3. Trends in break-up water levels (metres/decade) for the period 1969-2006. Large red (blue) triangles indicate negative (positive) trends at the significance level of ≥ 90%. Small triangles represent non-significant trends.

**Break-up timing**

Trends in the timing of river ice break-up show an overwhelmingly earlier occurrence in the spring season. In general, ice break-up initiation ($H_B$) occurs earlier by 1.4 to 3.5 days/decade, while peak water level events ($H_M$) have advanced by 1.2 to 4.7 days/decade. While no significant trends towards later ice break-up are observed, the presence of sites with non-significant and no trend attest to the regional variability in the river ice break-up season. Results of the 'last B date' analysis correspond to those observed in break-up initiation and peak break-up timing; significantly earlier trends range from 1.5 to 8.6 days/decade (Figure 3). Although the periods of record differ, the trends of an earlier occurrence in all three river ice break-up variables observed here coincide with 'last B date' trends reported by Zhang *et al*. (2001) and Lacroix *et al*. (2005). Changes in the break-up *drive* ($t_1$), range from isolated increases of up to 1.3 days/decade in northeast Canada to decreases of up to 0.6 days/decade in central Canada (not included in Figure 3). For most part, no trends were detected. In contrast, the break-up *wash* ($t_2$) primarily shows increases in the Northeast and considerable variability of increasing/decreasing trends in central Canada. These results correspond closely to the changes in the timing of break-up *duration* ($t_3$). For most part, reduced break-up water levels and their earlier occurrence correspond to peak streamflow and timing trends previously observed by the aforementioned studies and others.

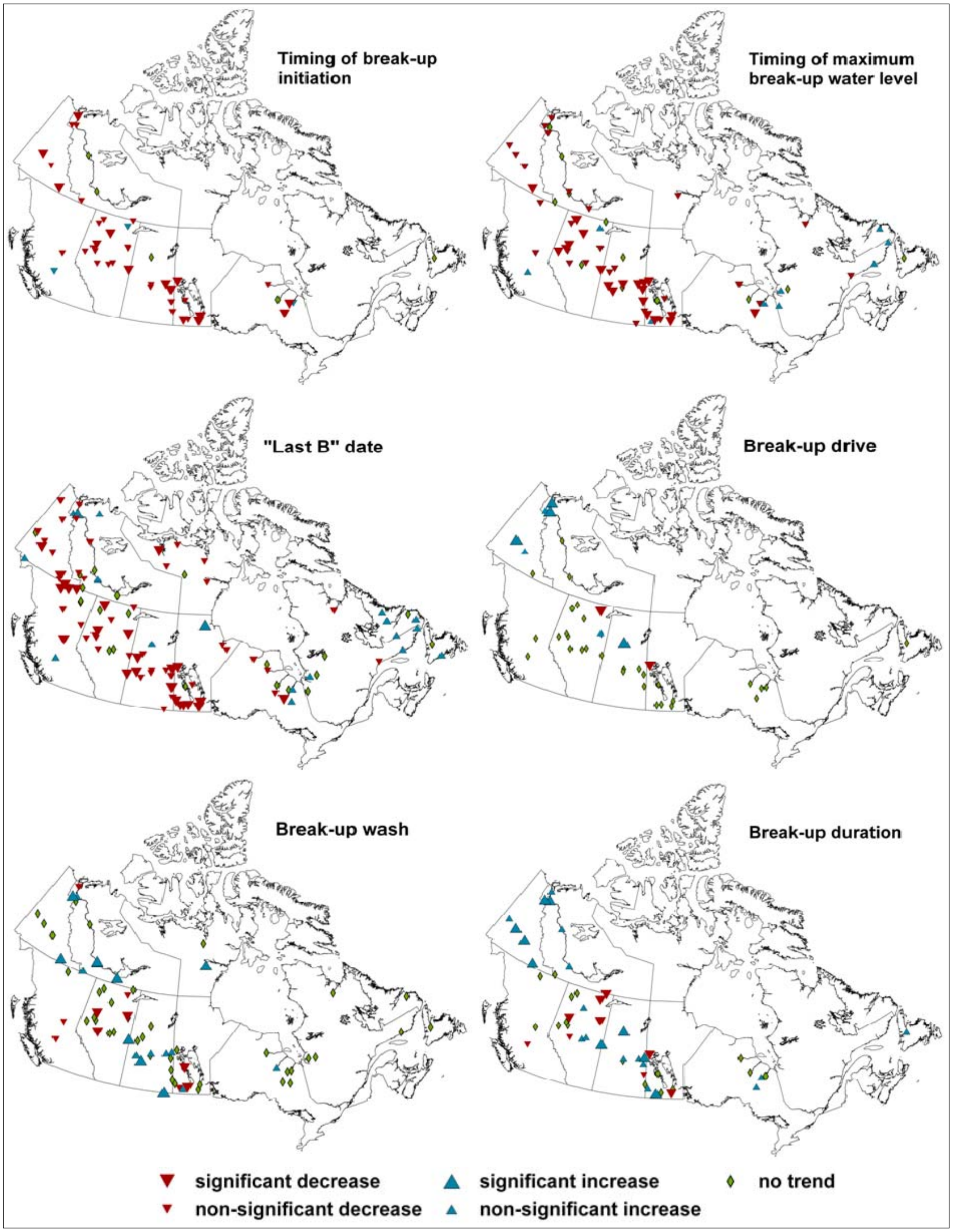


Figure 3 (continued). Results of the Mann-Kendall test of the break-up timing variables for the period 1969-2006.

**Table 1 Percentage of hydrometric stations indicating changes in trends of variables assessed. Significant trends are at the 90% significance level or greater. Magnitudes of trends are in days/decade for timing and in metres for water levels (shaded in grey).**

| | Percent of hydrometric stations | | | | | | |
|---|---|---|---|---|---|---|---|
| | No trend | Non-significant decrease | Significant decrease | Magnitude of change (-) | Non-significant increase | Significant increase | Magnitude of change (+) |
| Break-up initiation water level ($H_B$) | - | 44 | 22 | 0 - 0.5 | 29 | 4 | 0 - 0.9 |
| Break-up initiation timing | 11 | 51 | 31 | 0 - 4.7 | 7 | - | - |
| Maximum break-up water level ($H_M$) | - | 38 | 22 | 0 - 1.2 | 36 | 4 | 0 - 1.1 |
| Maximum break-up water level timing | 18 | 40 | 29 | 0 - 5.6 | 13 | - | - |
| 'Last B date' timing | 20 | 40 | 23 | 0 - 8.6 | 16 | 2 | 0 - 3.3 |
| Break-up drive ($T_1$) | 77 | - | 5 | 0 - 0.6 | 8 | 10 | 0 - 1.3 |
| Break-up wash ($T_2$) | 58 | 8 | 8 | 0 - 1.6 | 12 | 14 | 0 - 3.3 |
| Break-up duration ($T_3$) | 32 | 8 | 12 | 0 – 2.0 | 30 | 18 | 0 - 2.9 |

While no significant trends towards later ice break-up are observed, the presence of sites with non-significant and no trend attest to the regional variability in the river ice break-up season. Results of the 'last B date' analysis correspond to those observed in break-up initiation and peak break-up timing; significantly earlier trends range from 1.5 to 8.6 days/decade (Figure 3). Changes in the break-up *drive* ($t_1$), range from isolated increases of up to 1.3 days/decade in northeast Canada to decreases of up to 0.6 days/decade in central Canada (not included in Figure 3). For most part, no trends were detected. In contrast, the break-up *wash* ($t_2$) primarily shows increases in the Northeast and considerable variability of increasing/decreasing trends in central Canada. These results correspond closely to the changes in the timing of break-up *duration* ($t_3$).
For most part, the earlier occurrence of $H_B$ and $H_M$ correspond to the earlier onset of the spring freshet and streamflow timing trends previously observed by the aforementioned studies. Reduced magnitudes in break-up water levels however are not expected to show agreement with trends observed in peak streamflow studies. This is in particular the case for rivers that experience significant ice effects during break-up where ice induced peak water levels frequently occur at discharges below the maximum streamflow event (Figure 1).

## CONCLUSION

Using hydrometric variables extracted from original Water Survey of Canada (WSC) pen chart records, the work presented in this study is the first Canada-wide assessment of the river ice break-up season to use initiation ($H_B$) and peak break-up ($H_M$) water levels in conjunction with associated timing indicators. The majority of results indicate a reduction in initiation ($H_B$) and peak water levels ($H_M$) as well as an earlier occurrence of river ice break-up. The reduction in both, ($H_B$) and ($H_M$) magnitudes hint at a reduced occurrence of higher order break-up events.

Previous studies have shown reduced streamflow in autumn suggesting an increased likelihood of lower freeze-up stages. Since the freeze-up stage is likely a prominent control on break-up magnitudes (Beltaos, 2003), with lower freeze-up stages generating greater break-up water levels, the results observed here are counter-intuitive. Reduced break-up initiation ($H_B$) and peak water ($H_M$) levels suggest a greater frequency of *thermal* and fewer *dynamic* break-up events. Over the period of record, the break-up *drive* ($t_1$), *wash* ($t_2$) and break-up *duration* ($t_3$) show a relatively even distribution of significantly increasing and decreasing trends while at a number of locations no trends are observed. From a break-up event perspective, whether *thermal* or *dynamic*, it is difficult to conclude with certainty the underlying cause for the observed trends as they are only indicative of the rate of break-up. In this regard, both *thermal* and *dynamic* events may occur over a relatively short period of time, but in conjunction with reduced magnitudes, break-up events appear to have become more *thermal* in nature. In addition, the locations are not directly comparable due to the nature of the data. For example, if for some locations an insufficient number of peak break-up ($H_M$) events were available, the authors were only able to derive the break-up *duration* ($t_3$) but not the break-up *drive* ($t_1$) and *wash* ($t_2$). Hence, an analysis of the proportional increase/decrease of the break-up *drive* ($t_1$) and *wash* ($t_2$) and their effects on break-up duration ($t_3$) would prove useful to better understand the changes observed in the river ice break-up season. Furthermore, to gain insight into the underlying drivers of the observed trends, an assessment of large scale ocean atmosphere circulation patterns and their influence on the river ice break-up season would prove valuable.

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