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Trends in Canadian streamflow

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Abstract. This study presents trends computed for the past 30–50 years for 11 hydroclimatic variables obtained from the recently created Canadian Reference Hydrometric Basin Network database. It was found that annual mean streamflow has generally decreased during the periods, with significant decreases detected in the southern part of the country. Monthly mean streamflow for most months also decreased, with the greatest decreases occurring in August and September. The exceptions are March and April, when significant increases in streamflow were observed. Significant increases were identified in lower percentiles of the daily streamflow frequency distribution over northern British Columbia and the Yukon Territory. In southern Canada, significant decreases were observed in all percentiles of the daily streamflow distribution. Breakup of river ice and the ensuing spring freshet occur significantly earlier, especially in British Columbia. There is also evidence to suggest earlier freeze-up of rivers, particularly in eastern Canada. The trends observed in hydroclimatic variables are entirely consistent with those identified in climatic variables in other Canadian studies.

1. Introduction

The detection and attribution of past trends, changes, and variability in climatic variables is essential for the understanding of potential future changes resulting from anthropogenic activities. This is especially true for high-latitude regions such as Canada where climatic change signals are projected to be stronger [*Nicholls et al.*, 1996] and where the impacts of climatic change may be more severe. Recent analyses [*Zhang et al.*, 2000a] of trends in Canadian climate revealed a generally wetter and warmer climate during the last half of the twentieth century. It was found that annual precipitation totals have changed by −10% to 35%, with the strongest increases occurring in the northern regions of the country. Significant decreasing trends in winter precipitation and in the proportion of spring precipitation falling as snow were identified in southeastern Canada. Annual mean temperature showed an increasing trend in southwestern Canada but exhibited a decreasing trend in the northeast. This pattern of changes in temperature is especially strong during winter and spring. Changes in the mean state of climate, such as annual precipitation totals and mean temperature, are associated with changes in both mean and extreme daily values. There was no evidence to suggest changes in the frequency of heavy precipitation events (daily rainfall/snowfall larger than a threshold value which is exceeded by an average of three events per year) across Canada [*Zhang et al.*, 2000b], but significant trends have been identified in extreme temperatures (daily temperatures larger than 95 or less than 5 percentiles). The increasing trend in spring temperature has also resulted in earlier starting dates of both frost-free period and growing season [*Bonsal et al.*, 2000] during the last half of the twentieth century. Such changes in both precipitation and temperature are likely to have impacted the hydrology of Canadian rivers, such as volume and timing of streamflow and river ice conditions.

The hydrologic regime of a stream under specific geomorphic conditions represents the integrated basin response to various climatic inputs, with precipitation and temperature being very important ones. The evolution of basin geomorphology is very slow compared with possible climatic changes caused by anthropogenic increases of greenhouse gases. Therefore the changes in the hydrologic regimes of pristine or stable, unregulated basins generally reflect changes in climatic conditions and thus can be used as indicators for the purpose of climate change detection. It is thus important to analyze trends in various hydrologic variables of river basins which are not subjected to human regulation. In addition to providing an understanding of the impacts of climatic change on society and ecosystems, such analyses may provide independent corroborative evidence to confirm and/or to verify the results of trend detection for climate variables.

Lins and Michaels [1994] revealed statistically significant increases over the period 1948–1988 in natural streamflow in autumn and winter over nearly all regions of the contiguous United States. The most significant increases were generally found from the Rocky Mountains eastward to the Atlantic Ocean. Along the west coast of the United States the increases in autumn and winter streamflow were associated with decreases in the proportion of streamflow during the period April–July to the annual totals [*Aguado et al.*, 1992]. Those findings were further confirmed by *Lettenmaier et al.* [1994], who analyzed trends in monthly precipitation, temperature, and streamflow for the continental United States and found strong increases in streamflow during the period November–April at almost half of the stations, with the largest magnitudes in the north central states. In an attempt to determine whether trends have occurred in U.S. streamflow over a range of discharge quantiles, *Lins and Slack* [1999] tested for trends in seven quantiles of daily mean streamflow, including annual minimum, the tenth, thirtieth, fiftieth, seventieth and ninetieth percentiles and annual maximum values. They found that trends were most prevalent in the annual minimum to median

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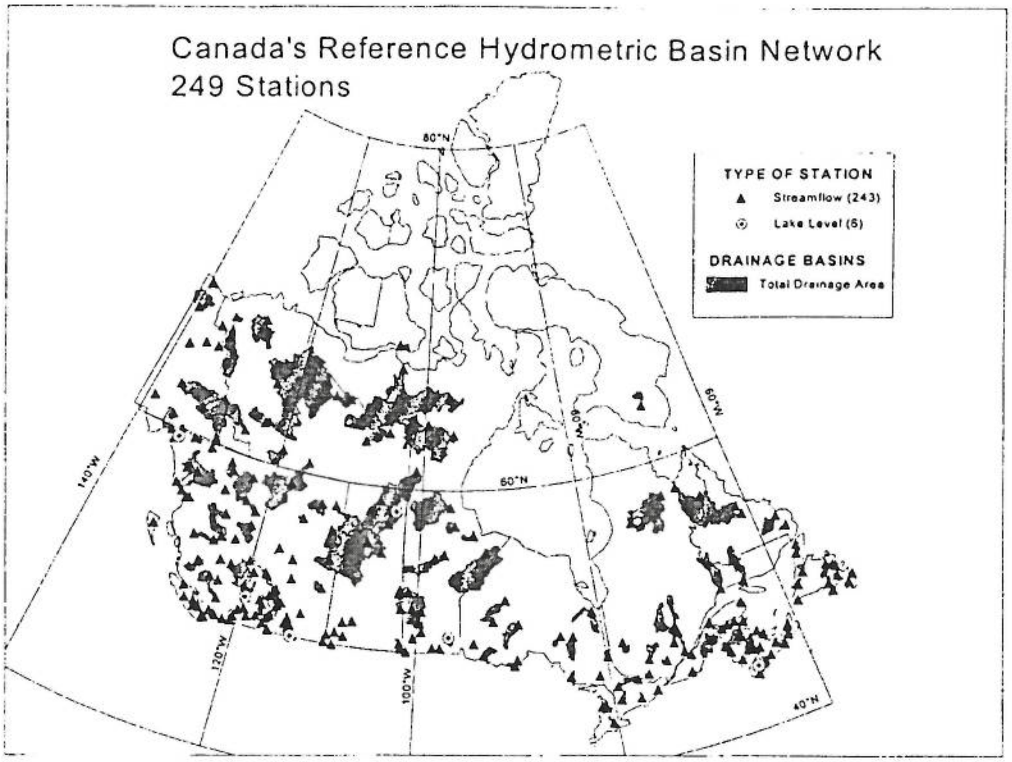

Figure 1. Locations and drainage basins of the Canadian Reference Hydrometric Basin Network (RHBN).

Mann-Kendall test is that the result is affected by serial correlation of the time series. Specifically, *Kulkarni and von Storch* [1995] found that if there is a positive serial correlation (persistence) in the time series, the test will suggest a significant trend in a time series which is actually random more often than specified by the significance level. To eliminate the effect of serial correlation, they and *von Storch and Navarra* [1995] suggest that the time series be "pre-whitened" before conducting the Mann-Kendall test. This study incorporates this suggestion, and the statistically significant trend for the time series $(y_1, y_2, \ldots, y_n)$ is identified using the following procedure: (1) Compute the lag-1 serial correlation c; (2) if $c < 0.1$, the Mann-Kendall test is applied to the time series; otherwise, (3) the Mann-Kendall test is applied to the "pre-whitened" time series $(y_2 - cy_1, y_3 - cy_2, \ldots, y_n - cy_{n-1})$.

The above test for trend against randomness was carried out separately for each basin to determine local significance. For a given variable the percentage of basins where significant trend is detected can be used as a measure of statistical significance of trend across the entire spatial domain, or field significance, of trend. The field significance of the trend was estimated by comparing the percentage of basins where significant trend was detected to the percentage of basins where significant trend would be expected to occur by chance, determined by Monte Carlo simulations as described by *Livezey and Chen* [1983].

3. Trends in Streamflow

3.1. Annual Mean Streamflow

The spatial distribution of trends in annual mean streamflow for the 30-, 40- and 50-year study periods are displayed in Figure 2. Basins located in southern Canada generally show

Table 1. Variables Analyzed

Variable	Definition
Annual mean streamflow	mean river discharge (m^3/s) for each year
Monthly mean streamflow	mean river discharge (m^3/s) for each month
Annual minimum daily mean streamflow	minimum daily mean discharge (m^3/s) for each year
Annual maximum daily mean streamflow	maximum daily mean discharge (m^3/s) for each year
Annual percentiles of daily mean streamflow	discharge (m^3/s) exceeding $X\%$ of daily streamflow in the year
Starting date of spring freshet (high-flow season)	date when the increase in daily streamflow across 4 days is greater than the average from January to July
Date of annual maximum daily mean streamflow	
Centroid of annual streamflow	date by which half of the annual total runoff has occurred
Date of river freeze-up	first date in the fall when, according to a flag in the archive, ice conditions alter the hydraulic characteristics of the channel and affect the computation of streamflow
Date of spring ice breakup	date in the spring when, according to a flag in the archive, channel hydraulics return to open water conditions
Duration of ice cover	number of days when channel hydraulics are affected by ice conditions

Table 2. Percentage of Basins Showing Significant (at the 10% Level) Positive (PI) and Negative (PD) Trends in Annual and Monthly Mean Streamflow[a]

	1967–1996			1957–1996			1947–1996		
	PI	PD	FS	PI	PD	FS	PI	PD	FS
Annual	4.0	11.3	Y	4.2	8.5		4.3	14.9	Y
January	10.2	7.6	Y	7.9	13.2	Y	2.1	12.8	
February	8.8	10.7	Y	5.3	7.9		0.0	8.5	
March	13.6	5.6	Y	20.7	4.6	Y	13.7	2.0	
April	29.4	2.8	Y	23.4	2.1	Y	29.1	5.5	Y
May	4.5	14.5	Y	6.5	12.0	Y	6.9	8.6	
June	2.2	11.1		2.1	21.1	Y	6.9	22.4	Y
July	2.2	9.5		5.2	12.4	Y	3.5	12.3	
August	1.1	13.3	Y	1.0	10.1		3.5	5.3	
September	1.1	12.0	Y	1.0	16.7	Y	5.3	10.5	
October	3.3	6.5		9.9	18.8	Y	19.3	12.3	Y
November	4.2	4.8		10.2	4.5		16.0	2.0	
December	4.4	11.3	Y	2.5	6.2		4.1	16.3	Y

[a]A Y for FS indicates the trends are field significant at the 5% level.

trend in spring streamflow in southwestern Canada during 1947–1996. The inconsistencies may be due to the different time periods used in each study and/or to the influence of different climate processes, such as shifting in the Pacific storm track or the North Pacific westerlies [*Chen et al.*, 1996].

3.3. Annual Minimum and Maximum Daily Mean Streamflow

The spatial distribution of trends in annual minimum and maximum daily mean streamflow for each of three study periods are plotted in Figure 4. Significant negative trends are observed across much of southern Canada for maximum daily streamflow but are not observed consistently for minimum streamflow. However, northern British Columbia and the Yukon show significant increases in minimum daily streamflow. Positive, and statistically significant at the 10% level, trends are also found in maximum daily streamflow in northern British Columbia. The changes in both of those extreme daily mean streamflow variables are also field significant as indicated in Table 3.

Some general circulation model simulations of climate under increasing atmospheric CO_2 conditions [e.g., *Kattenberg et al.*, 1996] have suggested that we can expect to see more extreme events due to an enhanced hydrologic cycle. This has not been consistently observed in the Canadian streamflow data but should not be considered too surprising because the effect of a given change in precipitation and temperature varies considerably between catchments, depending on climate regime

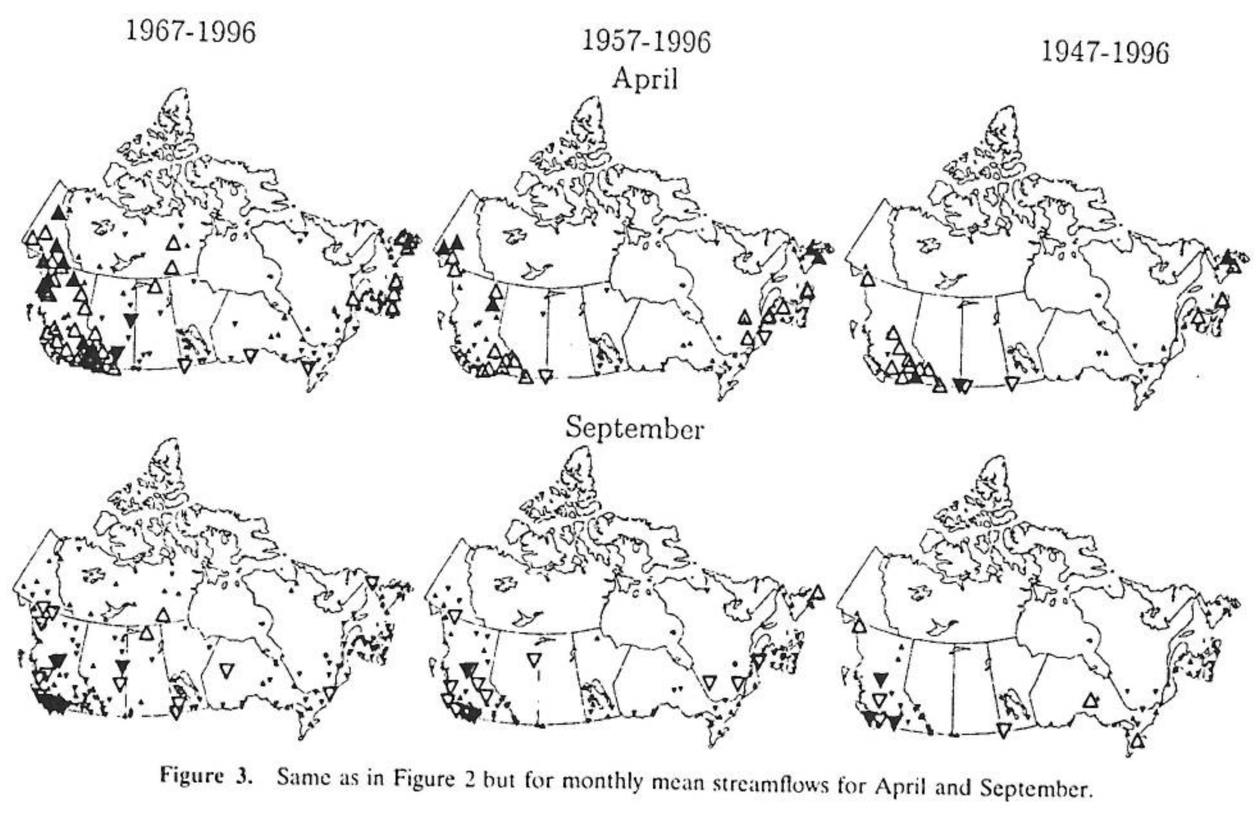

Figure 3. Same as in Figure 2 but for monthly mean streamflows for April and September.

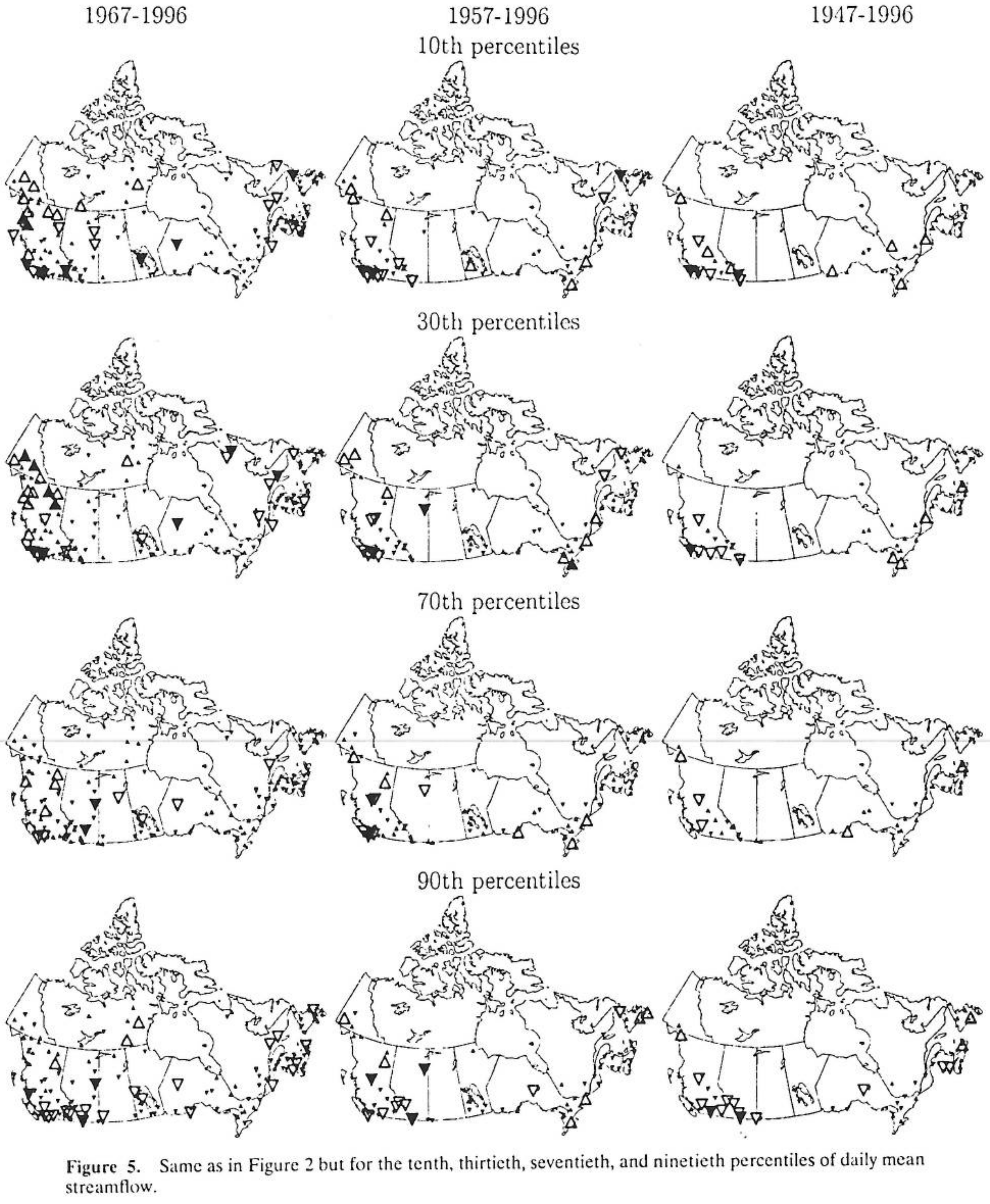

Figure 5. Same as in Figure 2 but for the tenth, thirtieth, seventieth, and ninetieth percentiles of daily mean streamflow.

and in southern British Columbia in particular. Positive trends prevail in northern British Columbia and the Yukon Territory. Nationally, the broad pattern is toward decreasing daily streamflow over the entire range of percentiles. This is consistent with the observed negative trends in annual mean streamflow.

A comparison of these results with those of *Lins and Slack* [1999] indicates consistency in the spatial distribution of trends. However, there are enough differences in trend characteristics across the range of percentiles of daily mean streamflow to suggest that regional climate plays an important role.

3.5. Comparison of Median and Mean Streamflow

Because of the large volumes associated with the higher moments of the daily streamflow distribution, trend in annual mean streamflow does not necessary reflect the trend in the

Table 4. Percentage of Basins Showing Significant (at the 10% Level) Trends in the Timing of Freshet Season[a]

Period of Record	Earlier Freshet	Later Freshet	FS
1967–1996	20.0	0.6	Y
1957–1996	31.5	1.4	Y
1947–1996	31.1	2.2	Y

[a]A Y for FS indicates the trends are field significant at the 10% level.

4.3. Centroid of Annual Streamflow

Centroids of annual streamflow were investigated to further explore the significance of an apparent shift in the hydrologic regime. The centroid is defined as the date by which half of the annual total runoff has occurred. A negative trend in the centroid indicates a shift in the annual streamflow distribution toward an earlier date. In this study the number of basins exhibiting negative trends (centroid occurs earlier) is twice the number of basins with positive trend (centroid occurs later). Basins with negative trends are generally located in British Columbia and Atlantic Canada. Basins in central Canada, including the prairies and Ontario tend to have positive trends. Basins with statistically significant negative trends are concentrated in British Columbia. However, there was no evidence to suggest that the trends were field significant at the 5% level.

4.4. River Ice Conditions

Trend test results for the dates of river freeze-up and subsequent ice breakup and the number of days of ice cover are summarized in Table 5. The spatial distribution of the trends is displayed in Figure 8. There is a strong pattern of trends over the last 50 years. The percentage of basins exhibiting significant negative trends for date of freeze-up ranges from a low of 21.4 at 30 years to a high of 50.0 at 50 years of record. The trends are field significant. This is strong evidence indicating that many Canadian streams are tending to freeze up earlier in the year.

There is also good evidence to suggest that river ice break-up is occurring earlier in most regions of Canada. The exception is Atlantic Canada, where break-up is occurring at a later date. The spatial patterns are field significant for all three study periods.

The duration of ice cover appears to be increasing in a majority of basins, with the strongest and most statistically significant trend in eastern Canada. Such changes are mainly the result of earlier freeze-up dates. In addition, delaying ice break-up in Atlantic Canada is also a factor in the significantly longer ice cover periods observed in that region.

These trends in the timing of river ice conditions are consistent with the observed changes in surface air temperature. The spatial pattern of trends for ice break-up reflect well the changes in spring temperature, including the warming in the southwest and the cooling in the northeast. The trend toward earlier river freeze-up is likely related to the trend, over the last 50 years, of decreasing November mean temperature across Canada, decreasing October mean temperature in central Canada, and decreasing December temperature in northeastern Canada. More than 80% of the river freeze-up occurred during these months.

The lengthening of ice cover periods is also directly linked to changes in temperature. The ice cover period has been significantly prolonged for more than a month over eastern Canada and in Atlantic Canada in particular, where decreasing temperatures have been observed in both spring and fall. In the west, especially in British Columbia, the earlier occurrence of the start of both freeze-up and break-up results in no significant change in the length of ice cover period.

The trends observed in this study for river ice breakup are consistent with the findings of *Skinner* [1992], who examined lake ice characteristics of 49 Canadian sites for periods of 18 to 49 years. Results differ for fall freeze-up trends, however, perhaps because of differences in time periods.

5. Conclusions and Discussion

Trends have been observed in various hydroclimatic variables measured in Canadian rivers and streams since 1947. Systematic analyses of 30-, 40- and 50-year study periods provide us with a general picture of how the hydrology of Canada has changed in recent history. The results of these analyses are summarized in Table 6.

A trend of decreasing annual mean streamflow was found across southern Canada. Trends significant at the 10% level are also field significant. Significant increases across Canada, particularly pronounced in British Columbia and the Yukon, were identified in monthly mean streamflow for March and April. However, decreases in monthly mean streamflow are observed in the late summer and autumn months. The upward and downward trends in spring and autumn actually shifted the annual hydrologic cycle toward an earlier spring high-flow season.

Across most of Canada a decreasing trend is evident throughout the entire daily streamflow distribution. This indicates that the decrease in annual mean streamflow is associated with decreases in both high and low daily flow regimes, although trends in the annual mean flow better represent those in the higher quantiles of daily flow. It also indicates that Canada is not experiencing more extreme hydrological events.

There have been significant changes in the timing of both streamflow and river ice buildup and breakup. Significant increases in streamflow were observed during March and April, probably due to earlier spring snowmelt. River freeze-up is

Table 5. Percentage of Basins Showing Significantly (at the 10% Level) Later (PD) and Earlier (PI) Freeze-up, Breakup, or Shorter Ice Cover Period[a]

	1967–1996			1957–1996			1947–1996		
Period of Record	PI	PD	FS	PI	PD	FS	PI	PD	FS
Freeze-up	1.6	21.4	Y	0.0	38.2	Y	0.0	50.0	Y
Breakup	3.2	15.1	Y	9.1	21.8	Y	5.0	30.0	Y
Days with ice cover	14.3	5.6	Y	20.0	3.6	Y	30.0	5.0	Y

[a]A Y for FS indicates the trends are field significant at the 10% level.

Table 6. Summary of Trends Detected

Variable	30-Year Trend? 1967–1996	40-Year Trend? 1957–1996	50-Year Trend? 1947–1996	Is Trend Field Significant?	Significantly Impacted Region(s)
Annual mean streamflow	decrease in southern Canada	decrease in southern Canada, except southern Ontario	decrease in southern Canada, except southern Ontario	no	southern British Columbia
Monthly mean streamflow	increase across Canada in March and April; decrease in summer and fall	increase across Canada in March and April; decrease in summer and fall	increase across Canada in March and April; decrease in summer and fall	yes, March and April, all study periods	southern British Columbia, Atlantic region
Annual minimum daily mean streamflow	decrease in southern Canada; increase in northern British Columbia and Yukon Territory	decrease in southern Canada; increase in northern British Columbia and Yukon Territory	decrease in southern Canada; increase in northern British Columbia and Yukon Territory	yes, for 40-year and 50-year trend	southern British Columbia
Annual maximum daily mean streamflow	decrease in southern Canada	decrease in southern Canada	decrease in southern Canada	yes, for 40-year and 50-year trend	southern British Columbia
Percentiles of daily mean streamflow	decrease in southern Canada; increase in northern British Columbia and Yukon Territory	decrease in southern Canada; increase in northern British Columbia and Yukon Territory	decrease in southwestern Canada	yes, below fortieth and above ninetieth percentile	southern British Columbia
Starting date of spring high-flow season	earlier across Canada	earlier across Canada	earlier across Canada	yes, for 40-year and 50-year trend	British Columbia
Date of annual maximum daily mean streamflow	earlier across Canada	earlier across Canada	earlier across Canada	no	extreme south
Centroid (date) of annual streamflow	earlier in British Columbia and Atlantic region; later in central Canada	earlier in British Columbia and Atlantic region; later in central Canada	earlier in British Columbia and Atlantic region; later in central Canada	no	British Columbia
Date of river freeze-up	earlier across Canada	earlier across Canada	earlier across Canada	yes, all study periods	Atlantic Canada
Date of spring ice breakup	earlier all regions except Atlantic	earlier all regions except Atlantic	earlier all regions except Atlantic	yes, for 40-year and 50-year trend	all regions
Duration of ice cover	generally longer, especially in Atlantic Canada	generally longer, especially in Atlantic Canada	longer, especially in eastern Canada	yes, for 30-year and 50-year trend	eastern Canada

and spatial coverage, especially in the north, was a problem. It is difficult to determine if the trends identified with the limited 30–50 years of data actually reflect the long-term tendency or interdecadal variation of hydroclimatic variables. The Northern Atlantic Oscillation, which exhibits strong decadal variability, has profound impacts on temperature in Atlantic Canada [*Shabbar et al.*, 1997]. The interdecadal variation of atmospheric-oceanic circulation over the North Pacific is known to impact climate over North America [e.g., *Chen et al.*, 1996] and the west coast in particular. The strongest changes in all hydroclimatic variables analyzed in this study were observed in British Columbia and the Yukon Territory. A more detailed analysis of this region, using a century-long precipitation and temperature data set [*Zhang et al.*, 2000a], proxy data for the region [*Luckman and Watson*, 1999; *Luckman et al.*, 1997], and additional hydroclimatic information, may shed additional light on the nature of causes of the trends.

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