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Detection of hydrologic trends and variability

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Abstract

This paper describes the development and application of a procedure that identifies trends in hydrologic variables. The procedure utilizes the Mann–Kendall non-parametric test to detect trends, a permutation approach to estimate the test distribution, and accounts for the correlation structure in the data in determining the significance level of the test results. The research investigates 18 hydrologic variables that reflect different parts of the hydrologic cycle. The hydrologic variables are analyzed for a network of 248 Canadian catchments that are considered to reflect natural conditions. A selection of catchments identified to have trends in hydrologic variables is studied further to investigate the presence of trends in meteorological variables and the relationship between the hydrologic and the meteorological response to climatic change. It is concluded that a greater number of trends are observed than are expected to occur by chance. There are differences in the geographic location of significant trends in the hydrologic variables investigated implying that impacts are not spatially uniform.

Keywords: Trend detection; Variability; Climate change; Streamflow

1. Introduction

The potential impacts of climatic change and variability have received a great deal of attention from researchers in a variety of fields. Reviews of related work include Gleick (1989) and the Intergovernmental Panel on Climate Change (IPCC, 1996). From these and other works, a range of potential impacts on the hydrologic regime for various geographic areas has been hypothesized.

A comprehensive review of the potential impacts of climatic change is provided in IPCC (1996). The report indicates that climatic change is likely to increase runoff in higher latitude regions because of increased precipitation. Changes in flood frequencies are expected in some locations, particularly in northern latitudes and in catchments experiencing snowmelt-flooding events. The frequency and severity of drought events could increase as a result of changes in both precipitation and evapotranspiration. Changes in the hydrologic regime that do occur are not expected to be equally distributed throughout the year. For example, increased temperatures in the winter are expected to lead to earlier snowmelt events and a shift in runoff from the spring to late winter with a corresponding decrease in runoff in the summer period.

Gan and Kwong (1992) investigated the presence of a relationship between climatic warming and the northward migration of permafrost by analyzing the monthly maximum, minimum and mean temperature data from nine stations in northern Canada. Burn

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(1994a) identified a trend in the timing of the peak snowmelt runoff event for catchments in west central Canada with more recent events occurring earlier in the year. Lins and Michaels (1994) identified increases in the fall and winter streamflow in the United States, possibly associated with increased cloudiness and decreased evaporation. Increases in winter and spring streamflow for much of the United States were found by Lettenmaier et al. (1994). Westmacott and Burn (1997) found decreases in streamflow for the Canadian Prairies that could be related to changes in the temperature. Yulianti and Burn (1997) investigated the impact of temperature change on low streamflow conditions for 77 rivers in the Canadian Prairies and found that low flows have a decreasing tendency. Lins and Slack (1999) evaluated 395 stations in the conterminous United States for the presence of trends in selected quantiles of discharge. They found that upward trends were prevalent in the annual minimum to medium flow quantiles while less prevalent in the annual maximum flow quantiles leading them to conclude that the conterminous United States is getting wetter but less extreme. Douglas et al. (2000) examined trends in flood and low flows in the United States and found evidence for upward trends in low flows. They also demonstrated the importance of properly considering the effects of cross-correlation in the data. Whitfield and Cannon (2000) compared hydrologic and meteorological data for Canada from two different decades and found the more recent decade to be generally warmer with the occurrence of both increases and decreases in precipitation and streamflow. Mortsch et al. (2000) considered climatic change impacts on the Great Lakes region under the scenario of a doubling of atmospheric CO_2. The modelling results point to a reduction in water levels on the Great Lakes and generally reduced water availability throughout the basin that could lead to water management concerns. Zhang et al. (2001) calculated trends for 11 hydrometric variables for Canadian catchments and found generally decreasing trends in flow volumes.

This paper represents an initial stage in research designed to identify some of the hydrologic impacts of climatic change for catchments in Canada. The emphasis in the research reported herein is on the quantification of trends in hydrologic variables and the investigation of the relationship between trends in hydrologic variables and trends in meteorological variables. The spatial distribution of catchments exhibiting trends and not exhibiting trends is also investigated. Future work will examine the issue of trend attribution and thus attempt to establish a linkage between climate change and observed hydrologic trends. Section 2 of this paper describes the hydrologic variables that are examined in this work. This is followed by a presentation of the trend detection techniques that are used. The methodology outlined is then applied to a collection of catchments in Canada. The paper ends with a summary of the results and conclusions.

2. Methodology

When attempting to detect trends in a natural series one must be cognizant of the inherent variability of hydrologic time series (Burn, 1994b). Askew (1987) indicates that there is a difficulty associated with differentiating between natural variability and trends. This argues for the development of a rigorous procedure for detecting trends. The systematic approach that was adopted herein to determine the significance of the detected trends can be summarized in the steps outlined below:

1. The first step was to choose the variables to be studied. Streamflow variables were used, as they tend to reflect an integrated response of the catchment area as a whole.
2. The second step was to choose the stations to be investigated. The primary factor on which the choice was based was the record length. Further criteria were applied as part of the process of defining the Reference Hydrometric Basin Network (RHBN) (Harvey et al., 1999), from which all stations analyzed were drawn.
3. The third step was to check for the presence of trends in the data. This was done using the Mann–Kendall non-parametric test.
4. The fourth step was to determine the significance of the detected trends. This was accomplished utilizing a permutation procedure. It was also necessary to define a global, or field, significance level, reflecting the correlation structure that exists in the data set.

The steps outlined above are described in the sections that follow.

2.1. Selection of hydrologic variables

Hydrologic variables are important indicators of climatic change. These variables tend to reflect climatic change and can help in understanding the relationships between hydrology and climate. Numerous studies have suggested different variables for detecting climatic change. Pilon et al. (1991) suggested streamflow variables, while Anderson et al. (1992) considered mean, low and high flow regimes for climate change investigation. Burn and Soulis (1992) suggested studying a large number of hydrologic variables since climatic change is expected to affect various variables in different ways.

Streamflow variables are advocated herein because of the spatially integrated hydrologic response that they provide. The procedure adopted is to select a collection of variables encompassing the important components of the hydrologic regime. In addition to hydrologic variables reflecting low flow, average flow, and high flow regimes, the timing and duration of hydrologic events were also included.

2.2. Selection of stations

The selection of stations is one of the more important steps in climatic change research. This work takes advantage of the research undertaken to identify the RHBN, which represents an appropriate collection of hydrometric gauging stations for climatic change investigations (Harvey et al., 1999). Stations were selected from the RHBN with a minimum record length of 25 years to ensure statistical validity of the trend results.

2.3. Trend detection test

The time series of all the hydrologic variables were analyzed using the Mann–Kendall non-parametric test for trend. Mann (1945) originally used this test and Kendall (1975) subsequently derived the test statistic distribution. This test was found to be an excellent tool for trend detection by other researchers in similar applications (Hirsch et al., 1982; Gan, 1992). The Mann–Kendall test statistic is given by

$$S = \sum_{i=1}^{n-1} \sum_{j=i-1}^{n} \mathrm{Sgn}(X_j - X_i) \tag{1}$$

where X_i and X_j are the sequential data values, n is the data set record length, and

$$\mathrm{Sgn}(\theta) = \begin{cases} +1 & \theta > 0 \\ 0 \quad \text{if} & \theta = 0 \\ -1 & \theta < 0 \end{cases} \tag{2}$$

The Mann–Kendall test has two parameters that are of importance to trend detection. These parameters are the significance level that indicates the trend's strength, and the slope magnitude estimate that indicates the direction as well as the magnitude of the trend.

The distribution of the test statistic is generated in this work by a permutation approach (Robson et al., 1998). The Mann–Kendall statistic, S, is calculated for each of a large number of different random orderings (permutations) of the data set. The test statistic for the original data set is then compared to the distribution of the test statistic obtained from the permutated data sets and a significance level is estimated from this distribution. The rationale behind this approach is that under the null hypothesis of no trend in the data, each ordering of the data set is equally likely. Therefore, the null distribution of the test statistic can be estimated from the permutation approach. This approach can be applied with any statistical test for trend.

The non-parametric robust estimate of the magnitude of the slope, β, determined by Hirsch et al. (1982), is given by

$$\beta = \mathrm{Median}\left[\frac{(X_j - X_i)}{(j - i)}\right] \quad \text{for all } i < j \tag{3}$$

2.4. Significance of trend results

The results of the trend tests can be used to determine whether or not the observed collection of time series for a hydrologic variable exhibits a number of trends that is greater than the number that is expected to occur by chance. However, to do this, it is necessary to consider the correlation structure of the data. Of concern is both the serial correlation of the data series and the cross-correlation between the hydrologic variables at different locations. These issues are each addressed in the sections below.

2.4.1. Serial correlation

The presence of serial correlation can complicate the identification of trends in that a positive serial correlation can increase the expected number of false positive outcomes for the Mann–Kendall test (von Storch and Navarra, 1995). Several approaches have been suggested for removing the serial correlation from a data set prior to applying a trend test. The two most common approaches are to pre-whiten the series or to 'prune' the data set to form a subset of observations that are sufficiently separated temporally to reduce the serial correlation.

The pre-whitening approach is adopted herein and involves calculating the serial correlation and removing the correlation if the calculated serial correlation is significant at the 5% level. The pre-whitening is accomplished through

$$yp_t = y_{t+1} - ry_t \tag{4}$$

where yp_t is the pre-whitened series value for time interval t, y_t the original time series value for time interval t, and r is the estimated serial correlation coefficient.

2.4.2. Cross-correlation

Lettenmaier et al. (1994) note that the effect of cross-correlation in the data is to increase the expected number of trends under the hypothesis of no trend in the data. Livezey and Chen (1983) indicate the need to consider the field significance in ascertaining the overall significance of the outcomes from a set of statistical tests. Field significance allows the determination of the percentage of tests that are expected to show a trend, at a given local (nominal) significance level, purely by chance. Douglas et al. (2000) adopted an approach for determining the field significance that involves calculating a regional value for the Mann–Kendall statistic.

A bootstrap, or resampling, approach was used herein to determine the critical value for the percentage of stations expected to show a trend by chance. The bootstrap approach involves the following steps:

1. A year is randomly selected from a specified range of years. The specified range is either the entire period of record for which data are available or a defined period of record for which analysis is to be conducted (e.g. 1960–1997).
2. The data value for each station that has a data value for the selected year is entered in the data set being assembled (i.e. is added to the resampled data set).
3. Steps 1 and 2 are repeated until the resampled data set has the required (target) number of station-years of data. The target number of station-years of data is set equal to the number of stations-years in the initial data set.
4. The Mann–Kendall test is applied to the data from each station in the resampled data set and the percentage of results that are significant at the α_1% level is determined. α_1 is referred to as the local significance level.
5. Steps 1–4 are repeated a total of NS times resulting in a distribution for the percentage of results that are significant at the α_1% level. From this distribution, the value that is exceeded α_f% of the time is selected as the critical value, p_{crit}. α_f is referred to as the field, or global, significance level. Results obtained with a percentage of stations showing a significant trend larger than p_{crit} will be considered significant at the α_f% level. In this work, NS was set to 600.

Any temporal structure (i.e. a trend or pattern) that exists in the original data set will not be reproduced in the resampled data sets because of the nature of the resampling process, which selects the years to be included at random. However, the cross-correlations in the original data sets are preserved through including all data values for a given year in the resampled data set. This allows the impact of cross-correlation to be determined in establishing the critical value for the percentage of stations exhibiting a trend.

3. Application of the methodology

3.1. The Reference Hydrometric Basin Network

The study to detect trends in hydrological variables was performed on stations from the RHBN, a data collection network of natural rivers in Canada identified by Environment Canada for climatic change research. Fig. 1 shows the location of each hydrometric station

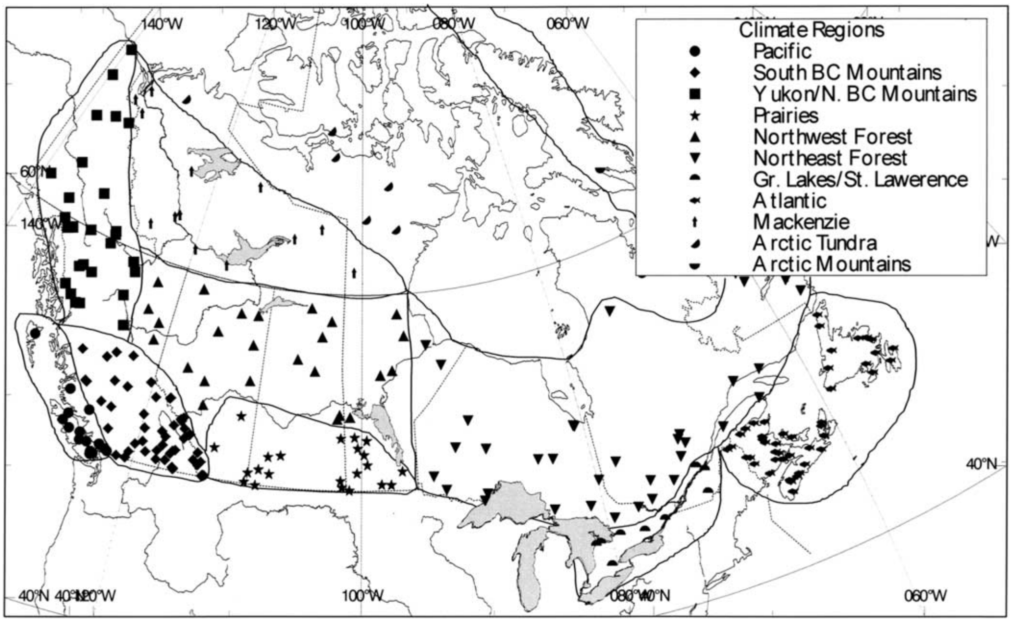

Fig. 1. Location of hydrometric stations in the Reference Hydrometric Basin Network and the associated climatic regions.

in the RHBN and indicates the climatic region for each station. The climatic regions are as defined by Gullet (1992). The criteria according to which stations were selected for the RHBN are (Harvey et al., 1999):

1. *Degree of basin development*. Stations that were included in the network were those that reflect catchments that are pristine or have stable land-use conditions. As a guideline, a catchment that has less than 10% of its surface area modified from natural conditions was considered to represent pristine conditions.
2. *Absence of significant regulations or diversions*. A catchment was considered natural if there was no control structure upstream of the gauging station while it was considered regulated if there was an upstream control structure.
3. *Record length*. A station must have a minimum record length of 20 years to be included in the RHBN. This record length was chosen to make sure that under-represented climatic or geographic areas, which are characterized by minimal data availability, were included in the network. This work selected from the RHBN only those stations with a record length of at least 25 years.
4. *Longevity*. This criterion was based on the judgment of the regional staff. A station was excluded from the network if it is currently active but was expected not to have future data collection activities.
5. *Data accuracy*. Data accuracy was assessed qualitatively by local experts based on knowledge of the hydraulic condition of the stations to ensure that only stations with good quality data were included in the network.

The RHBN is made up of 255 hydrometric stations, seven of which are lake level sites, 37 are seasonal streamflow stations, and 211 are continuous streamflow stations. All stations have at least 20 years of record, with an average record length of 38 years. The longest record length is 86 years while 60% of the stations have 30 or more years of record. Basin sizes range from 3.9 to 145 000 km^2 with a mean size of 1100 km^2, 10% of the basins have a drainage area greater than 20 000 km^2, and 10% have a drainage area less than 100 km^2.

3.2. Selection of hydrologic variables

A total of 18 hydrologic variables were selected for this research. These variables include the annual mean

Table 1
Trend test results for the 1950–1997 period (Note: Bold figures indicate significant results)

Variable	Number of stations	Number of decreasing trends	Number of increasing trends	Percent significant trends
Annual mean flow	48	7	5	**0.250**
Annual maximum daily flow	59	18	9	**0.458**
Date of maximum daily flow	59	10	0	0.169
Date of start of ice conditions	22	8	1	**0.409**
Date of end of ice conditions	22	9	1	**0.455**
Number of ice days	22	4	3	**0.318**
January mean flow	50	7	5	**0.240**
February mean flow	51	5	3	0.157
March mean flow	55	1	20	**0.382**
April mean flow	58	3	16	**0.328**
May mean flow	61	6	5	0.180
June mean flow	61	15	2	**0.279**
July mean flow	61	12	6	**0.295**
August mean flow	62	5	3	0.129
September mean flow	62	8	4	0.194
October mean flow	61	9	11	**0.328**
November mean flow	50	1	8	0.180
December mean flow	53	9	3	**0.226**

flow, the annual maximum daily flow, and the monthly mean flow for each month. Variables related to the timing of hydrological events that were investigated include the date of occurrence of the annual maximum daily flow, the date when ice conditions start, and the date when ice conditions end. A variable reflecting the duration of hydrologic events that was studied was the number of days with ice conditions. This collection of variables was analyzed in order to gain a broad understanding of the hydrologic response to climatic change.

3.3. Study period

The trend detection procedure was performed on five study periods. These periods started in 1940, 1950, 1960, and 1970 and ended in 1997. In addition, a final study period corresponding to all of the available records at each station, subsequently referred to as the 'All Records' case, was considered. The different fixed study periods selected represent a trade-off between the temporal and spatial coverage afforded by the selected data set. Earlier starting points result in a longer period of record at each station, but since fewer stations have data for the early parts of the record, the total number of stations included in the data set is reduced. It should be noted that for a station to be included in a given study period, there could be no more than five years during the study period for which the station did not have data. Selecting a common period of record in this way facilitates investigation of variable climatic conditions during the (common) prescribed period. The investigation of all available data through the All Records study period allows for an optimal spatial coverage, although the periods of record reflected at each station will potentially differ, making interpretation of the results more difficult.

Results obtained from the trend tests were analyzed using a local significance level of 10% and a field (global) significance level of 10%. Other combinations of local and global significance level could also be investigated, although the results were not found to be overly sensitive to the significance level selected.

4. Results

This section presents summary tables of the Mann–Kendall test results at the 10% local and global significance levels. Maps showing the trend detection results for the hydrologic variables at the 10% significance level are presented as well as a summary of the

Table 2
Trend test results for the 1960–1997 period (Note: Bold figures indicate significant results)

Variable	Number of stations	Number of decreasing trends	Number of increasing trends	Percent significant trends
Annual mean flow	86	6	5	0.128
Annual maximum daily flow	104	14	4	0.173
Date of maximum daily flow	104	22	3	**0.240**
Date of start of ice conditions	73	14	2	**0.219**
Date of end of ice conditions	73	20	4	**0.329**
Number of ice days	73	7	16	**0.315**
January mean flow	92	4	10	0.152
February mean flow	90	5	10	0.167
March mean flow	102	2	28	**0.294**
April mean flow	106	2	31	**0.311**
May mean flow	107	14	14	**0.262**
June mean flow	111	23	3	**0.234**
July mean flow	113	10	7	0.150
August mean flow	114	17	3	0.175
September mean flow	115	15	1	0.139
October mean flow	114	19	11	**0.263**
November mean flow	101	3	9	0.119
December mean flow	92	3	6	0.098

trends for each climatic region. Finally, the relationships between hydrologic variables and precipitation and temperature variables are explored for a selection of locations.

4.1. Mann–Kendall test results

Table 1 presents the trend results for the 1950–1997 study period for the 18 variables. The trend results for the 1960–1997 study period are presented in Table 2. Apparent from Tables 1 and 2 is the decrease in the density of the network as the length of the study period is increased. The density of stations for the study period that begins in 1940 is quite low and results in a very uneven spatial distribution of gauging stations across the country. For the earliest time period, the network contains almost exclusively southern catchments and comparatively few catchments from the Prairie Provinces. For the latest study period, beginning in 1970, the spatial coverage is very good but the available record length is quite short implying that the power of the Mann–Kendall test will be poor. For these reasons, the focus in this work will be on the analysis of results from 1950–1997 and 1960–1997 periods as well as the All Records case.

Table 3
Fraction of variables with significant trends

Study period	Fraction of variables with trends
1940–1997	0.39
1950–1997	0.67
1960–1997	0.50
1970–1997	0.33
All records	0.94

Tables 1 and 2 indicate that there are differences in the results for the individual hydrologic variables and that there are differences in the results for the different study periods selected. Table 3 summarizes, for each study period, the fraction of hydrologic variables determined to have a number of trends that is field significant at the 10% level. The All Records case results in the greatest number of significant trends with all variables, except for the November flow, resulting in a number of trends that is field significant. The fraction of variables with significant trends is less for the shorter study periods. The lower fraction of significant results for the 1960–1997 and the 1970–1997 study periods is possibly a result of the shorter data records in these data sets resulting in reduced power for the Mann–Kendall test.

Several hydrologic variables were noted to have particularly strong trend results. The date that ice

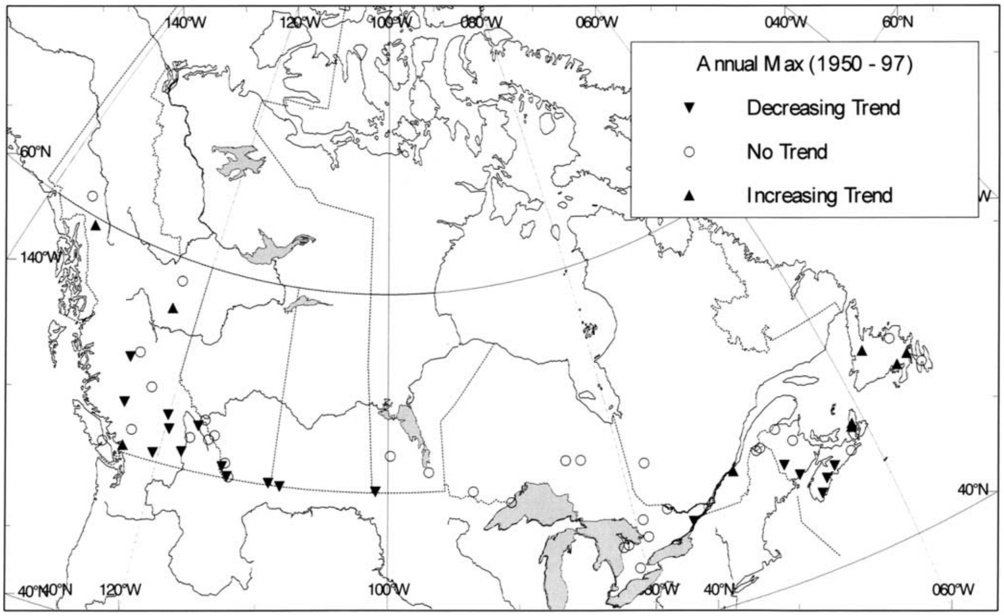

Fig. 2. Trend results for the annual maximum daily flow for the 1950–1997 study period.

conditions end is noted to have a decreasing trend implying that ice conditions are ending earlier in more recent years, probably as a result of earlier onset of spring melt conditions. From the monthly flow variables, March, April, June, and October were observed to have strong trend results while a general lack of trends was noted for February, August, September, and November. March and April both display an increasing trend indicative of an earlier onset of spring snowmelt. Flows in June display a decreasing trend while flows in October display both increasing and decreasing trends.

The results for many of the variables discussed above include both increasing and decreasing trends. To examine the spatial consistency of the observed trends, maps were created displaying the locations of catchments with decreasing and increasing trends for each of the variables. These results are discussed below.

4.2. Spatial distribution of trend results

Maps were created showing the results of the trend tests for each variable and for three study periods (i.e. 1950–1997, 1960–1997, and All Records). Figs. 2–5 show selected maps. Each map shows the location of gauging stations with trends that are significant at the 10% level and the location of gauging stations with no significant trend at the 10% level. The former stations are divided into stations with a decreasing trend and stations with an increasing trend. The focus will be on results for the 1960–1997 study period since this period provides a good spatial coverage and contains a reasonable record length. Although the record length is longer for the 1950–1997 study period, the spatial coverage is quite poor. While the All Records case provides good spatial coverage the different record lengths at the stations included in the analysis makes it more difficult to interpret the results.

Fig. 2 shows the results for the annual maximum daily flow for the 1950–1997 study period. As can be seen from Table 1, the number of trends for this variable far exceeds the critical level for establishing field significance. The conclusion is that there are considerably more trends than would be expected to occur by chance. Fig. 2 reveals definite spatial patterns in the location of stations that exhibit a significant trend. Decreasing trends occur in the western part of the country in the South British Columbia Mountains and Prairies climatic regions. Increasing trends are noted in the northwest part of the study area. There is a collection of decreasing trends in the west portion

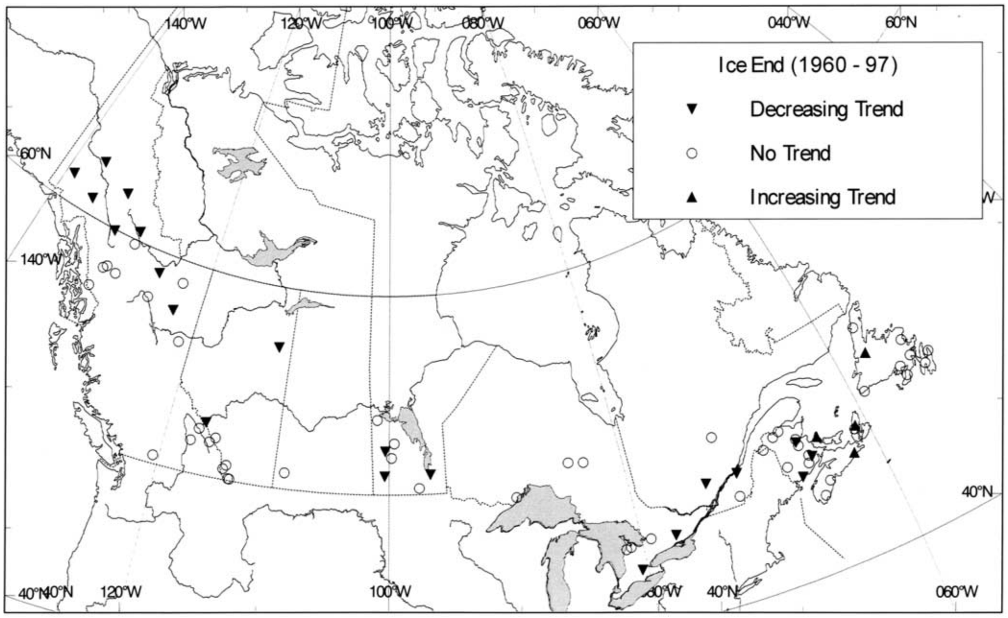

Fig. 3. Trend results for the end of ice conditions for the 1960–1997 study period.

of the Atlantic climatic region while increasing trends occur in the east part of the Atlantic climatic region. These regional patterns agree with results from Zhang et al. (2001).

Fig. 3 shows the results for the date of the end of ice conditions for the 1960–1997 study period. Table 2 reveals that this variable also exhibits more significant trends than are expected to occur by chance. As can be

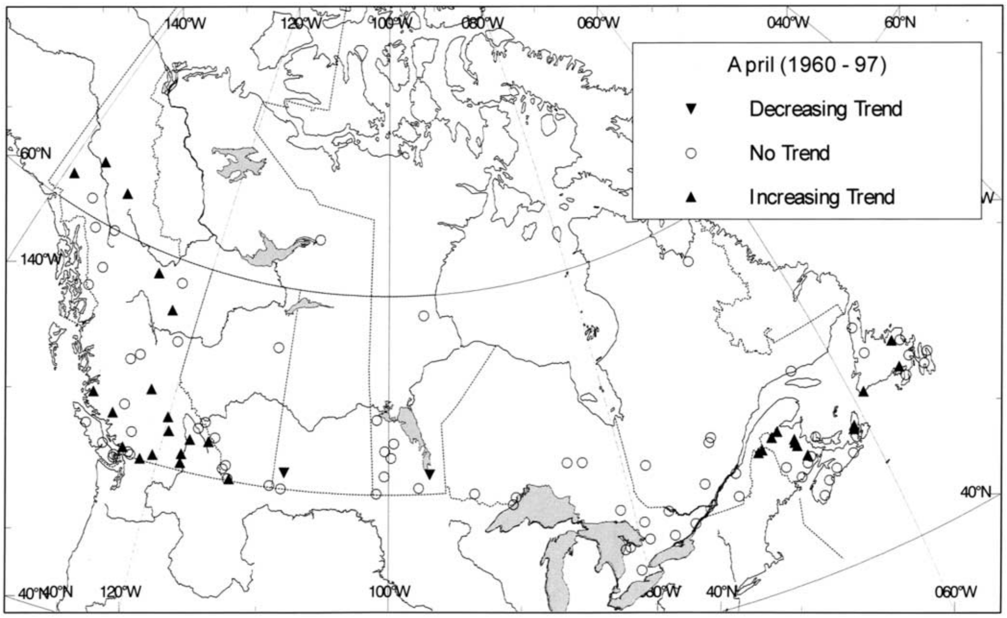

Fig. 4. Trend results for the April flow for the 1960–1997 study period.

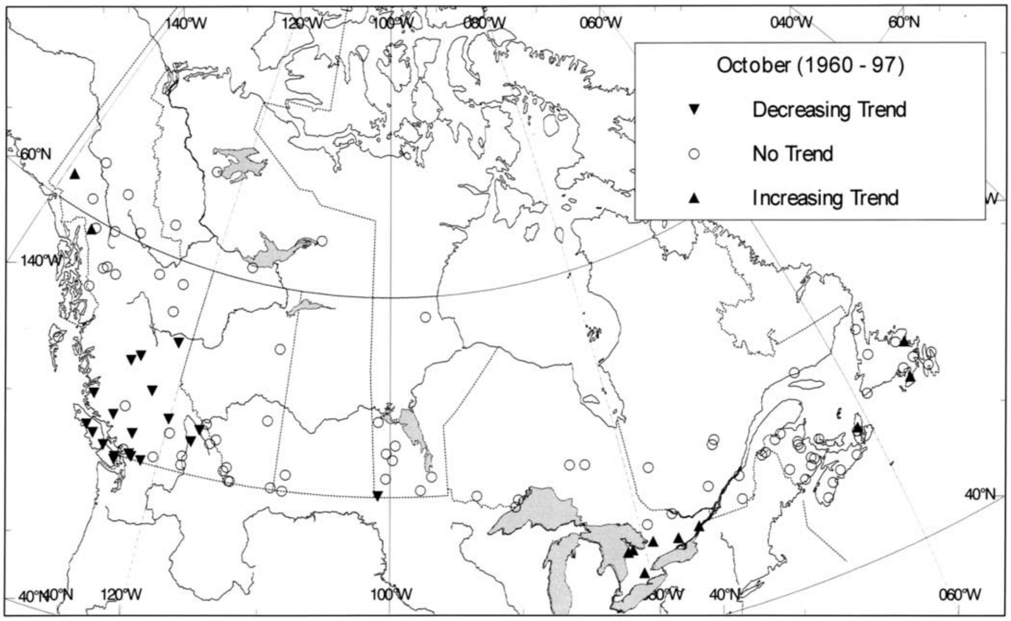

Fig. 5. Trend results for the October flow for the 1960–1997 study period.

seen from Fig. 3, the vast majority of the trends identified are decreasing trends, implying earlier onset of melting conditions in the spring in more recent years. There are noticeable spatial groupings of stations with significant trends. There are groups of stations with decreasing trends in the Yukon North British Columbia Mountains and in the North West Forest climatic regions, a grouping in the Prairies climatic region, three stations in the Great Lakes St. Lawrence climatic region and a group in the west portion of the Atlantic climatic region. Stations with increasing trends are located in the eastern part of the Atlantic climatic region. These results are also in agreement with those of Zhang et al. (2001).

Fig. 4 presents the results for the April flow for the 1960–1997 study period. Table 2 shows that this is again a hydrologic variable with a strong trend result. The majority of the trends are increasing trends and are seen to occur primarily in the west in the Pacific, the South British Columbia Mountains, and the Yukon North British Columbia Mountains climatic regions as well as in the east in the Atlantic climatic region.

Fig. 5 shows the results for the month of October flow for the 1960–1997 study period. Table 2 reveals that this variable exhibits a number of trends that is field significant at the 10% level and consists of both increasing and decreasing trends. Fig. 5 shows distinct spatial groupings of the increasing and decreasing trends. Decreasing trends occur in the Pacific and South British Columbia Mountains climatic regions. Increasing trends are concentrated in the northwestern part of the study area, in the Great Lakes St. Lawrence climatic region, and in the eastern portion of the Atlantic climatic region.

4.3. Summary of trends

This section summarizes the noteworthy trends based on the 1960–1997 study period. The results are summarized by climatic region (see Fig. 1 for a definition of the climatic regions) in an attempt to identify the different impacts that occur in different regions of the country.

The Pacific climatic region is generally characterized by a decrease in water availability. This is apparent in a decrease in the annual flow and the monthly flow from May to October. The April flow exhibits an increasing trend likely because of a shift in the timing of the spring runoff. The peak flow tends to occur in late spring or early summer for the catchments from the Pacific climatic region that exhibit a trend in the

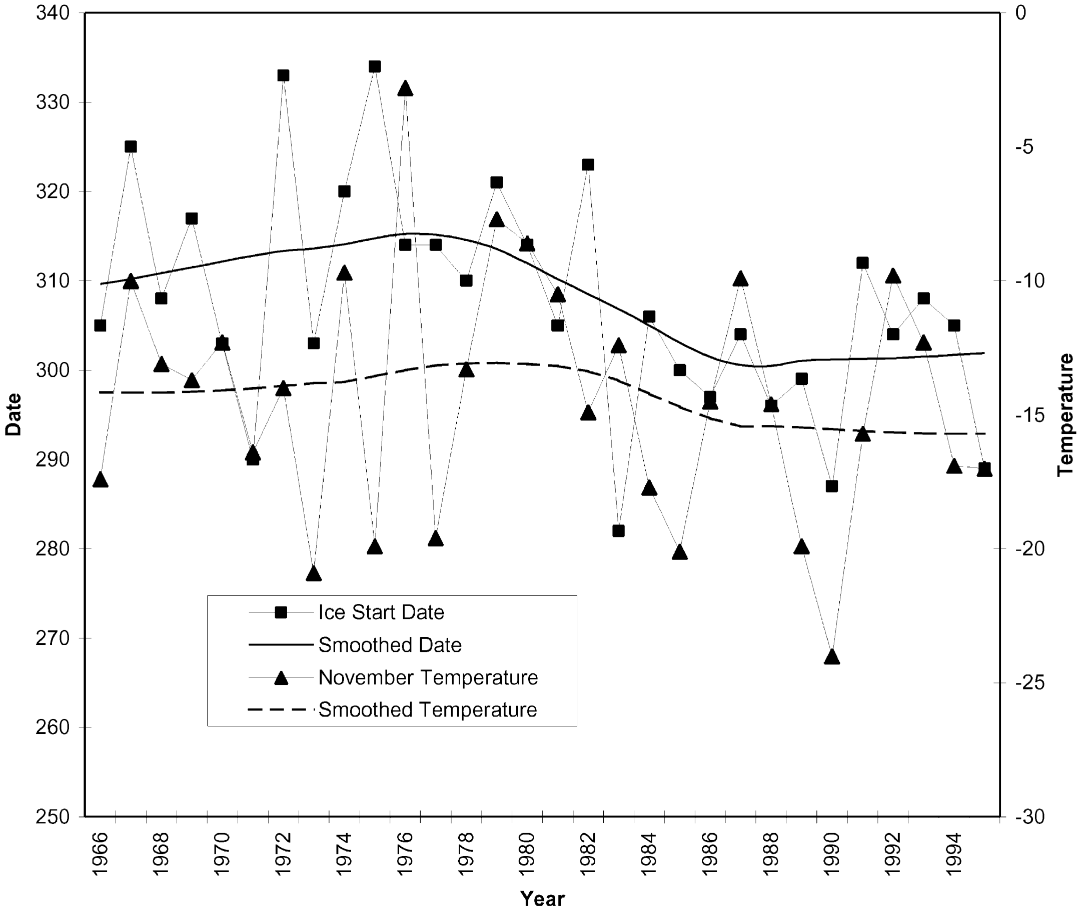

Fig. 6. Time series plots for ice start date and November temperature for the Kluane River.

April flow. The peak flow tends to occur in the winter months for catchments from this climatic region that do not experience a trend in April.

The South British Columbia Mountains climatic region has decreasing monthly flows in February, and June–October. Increasing flow is noted for the months of April and May, again likely attributable to a shift in the timing of the runoff for this region. The main runoff period for catchments in this region typically starts in April. The date on which ice conditions start exhibits a decreasing trend implying that freeze-up is occurring earlier in the more recent years.

The Yukon North British Columbia Mountains climatic region displays particular sensitivity in the variables related to the timing of events. The ice start dates and the ice end dates exhibit decreasing trends implying earlier occurrence of freeze up and break up of river ice in the more recent years. Increasing flows are noted for February through May.

The Prairies climatic region exhibits a decreasing trend for the ice end date implying earlier occurrence of this event in more recent years. Increasing flows are noted for the months of January–March, again likely related to an earlier onset of spring runoff.

The North West Forest climatic region exhibits a decreasing trend in the end of ice conditions implying earlier occurrence of the spring melt period. The months of February and March exhibit increasing trends while December exhibits a decreasing trend.

The North East Forest climatic region displays changes in the annual maximum daily flow comprising a decreasing trend in the flow magnitude and in

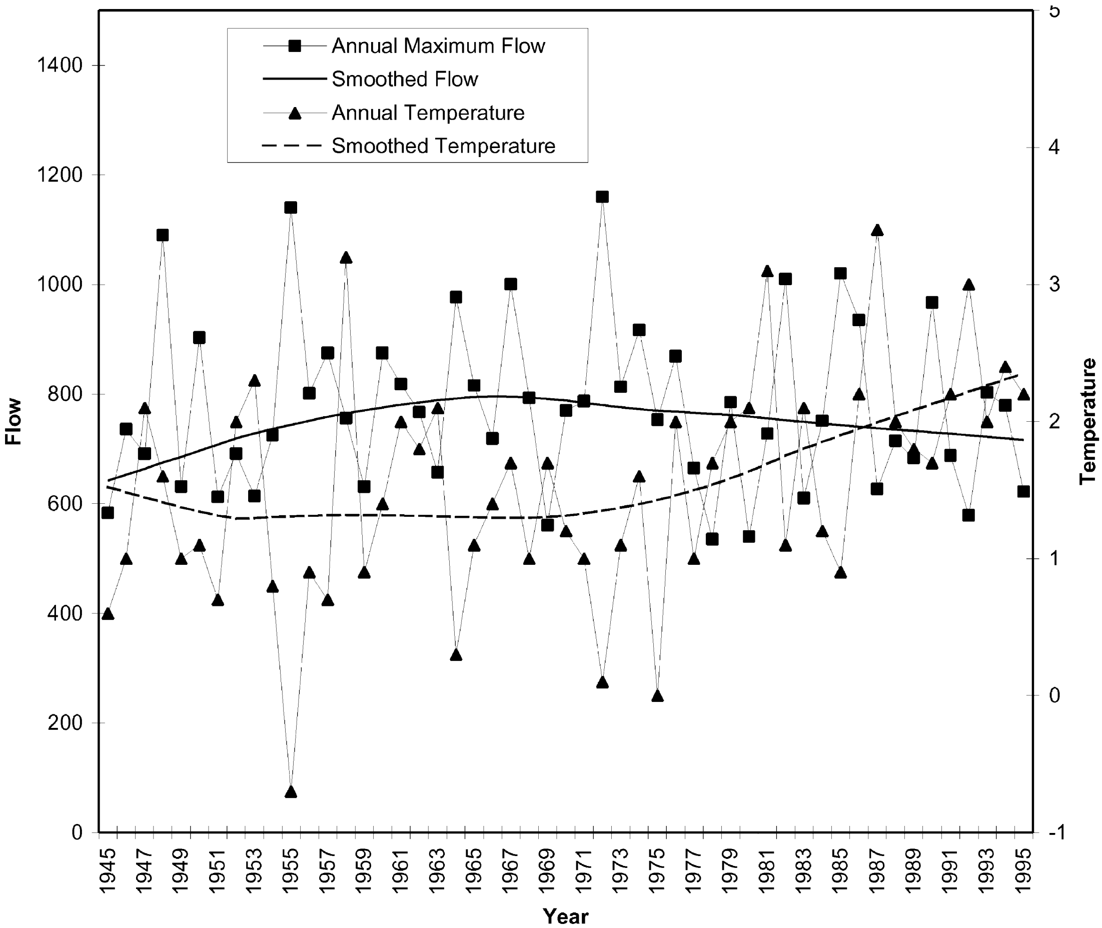

Fig. 7. Time series plots for annual maximum flow and annual temperature for the Quesnel River.

the date of occurrence. The latter implies that the more recent flood events are occurring earlier in the year. The annual maximum flow event tends to occur between the middle of April and the middle of June in this climatic region. The ice start date exhibits a decreasing trend, implying the more recent freeze up events are occurring earlier in the year. Associated with an earlier start to the freeze up is an increasing trend in the number of ice days. The flows in February and March exhibit an increasing trend, while the flows in June, August and September exhibit a decreasing trend.

The Great Lakes St. Lawrence climatic region exhibits an increase in the annual flow. The date on which ice conditions end displays a decreasing trend implying that the more recent events are occurring earlier in the year. The number of days with ice conditions also exhibits a decreasing trend. The flows in January, October and November all exhibit an increasing trend.

The Atlantic climatic region displays decreasing trends in the date of the annual maximum flow implying that more recent years have earlier flood events. The annual maximum flow event tends to occur at different times at different locations within the Atlantic climatic region. The annual maximum flow tends to occur between March and May in the western portion of the Atlantic region with the occasional maximum flow event occurring in October or November. In the eastern portion of the Atlantic region, the annual maximum event tends to occur either in the period from the middle of February to the middle of May or in the October–November period. The

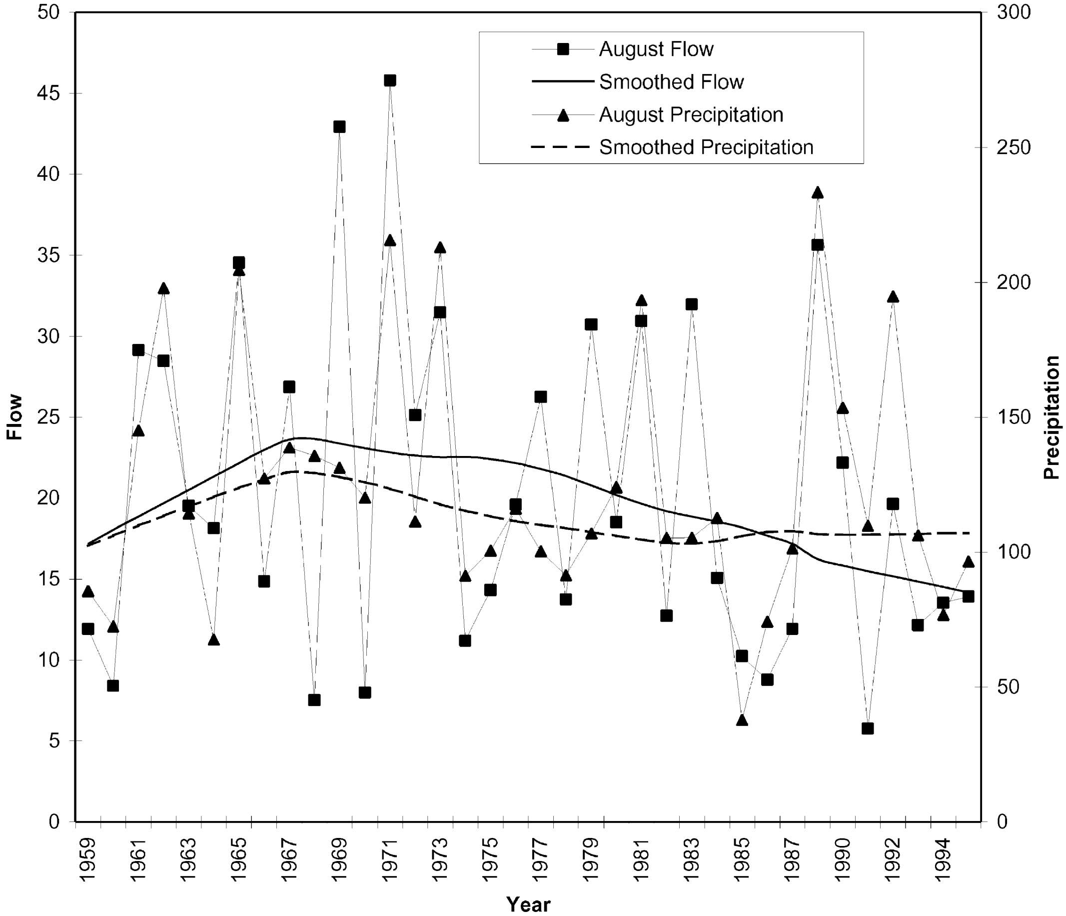

Fig. 8. Time series plots for August flow and August precipitation for the Torrent River.

number of days with ice conditions exhibits an increasing trend, as does the flow in March and April. The date on which ice conditions end displays both increasing and decreasing trends (see also Fig. 3).

The remaining climatic regions have too few stations with sufficient data during the 1960–1997 study period to characterize the regional behavior.

4.4. Relationship between hydrologic variables and meteorological variables

This section presents graphs of selected hydrologic variables and a representative meteorological variable for select locations. At each location, the correlations between the hydrologic variables and the meteorological variables were evaluated and pairs of variables that demonstrated a relationship were examined further. The available meteorological variables consisted of the monthly and annual values for the temperature and precipitation for locations in close proximity to the corresponding hydrometric gauging station. The meteorological stations that were selected were the stations closest to the associated hydrometric gauging stations.

Fig. 6 presents the results for a catchment from the Yukon North British Columbia Mountain climatic region. Shown are the results for the ice start date and the November temperature for the Kluane River. Fig. 6 shows the data values for the ice start date plotted as solid symbols as well as a smoothed representation of this series. Note that the light dashed lines joining the solid symbols are for illustrative purposes only to aid in the determination of the pattern in the data. Also shown are data points, plotted as solid symbols, and a smoothed representation for the temperature series. The smoothing, for both cases, is accomplished using the LOWESS technique (Cleveland, 1979). The ice start date exhibits a decreasing trend that is significant at the 5% level while the November temperature series exhibits a weak decreasing trend that is not significant at the 10% level. The smoothed representation of the two series reveals that the ice start date and the November temperature series exhibit a similar pattern over the period of record. This similarity in pattern implies that changes in temperature during November might be expected to be associated with corresponding changes in the start of ice conditions. Apparent from Fig. 6 is the non-uniformity of the pattern in both the ice start dates and the November temperature values.

Fig. 7 shows the annual maximum flow and the annual temperature for the Quesnel River in the South British Columbia Mountains climatic region. The annual maximum flow for this catchment exhibits a decreasing trend that is significant at the 10% level. The annual temperature series for the meteorological station close to this catchment exhibits an increasing trend that is significant at the 1% level. The correlation between the annual maximum flow data and the annual temperature data, which is significant at the 1% level, is negative implying that increased temperature values can be expected to be associated with decreasing annual maximum flows. The inverse relationship between the two variables is most apparent from the smoothed representations of the series shown in Fig. 7. Increased temperature can be expected to result in a reduction in the accumulated snowpack and hence a reduction in the annual maximum flow, which tends to result from snowmelt.

Fig. 8 shows the results for the August flow and August precipitation for the Torrent River in the Atlantic climatic region. The August flow exhibits a decreasing trend that is significant at the 10% level. The August precipitation exhibits a very weak decreasing trend that is not significant at the 10% level. The flow and precipitation for this catchment demonstrate a strong positive correlation that is significant at the 1% level. This relationship is apparent from both the data points and in the smoothed representation of the two series presented in Fig. 8. It is evident from Fig. 8 that the temporal pattern in both variables is not uniform. There is an increasing tendency for both the precipitation and the flow until the late 1960s, which is followed by a decreasing tendency. The decreasing tendency is stronger in the flow than in the precipitation.

5. Conclusions and recommendations

The application of a trend detection framework to Canadian catchments has resulted in the identification of more significant trends than are expected to occur by chance. Spatial and temporal differences were noted in the occurrence and the direction of trends implying that a systematic framework is essential for detecting trends that might arise as a result of climatic change. Spatial differences in the trend results can be expected to occur as a result of spatial differences in the changes in precipitation and temperature and spatial differences in the catchment characteristics that translate meteorological inputs into a hydrologic response. Temporal differences in the trends likely reflect non-uniform changes in the meteorological variables.

Several hydrologic variables were noted to have particularly strong trend results. There is a decreasing trend in the annual maximum flow in the south and an increasing trend in the north. The date that ice conditions end is noted to have a decreasing trend implying that ice conditions are ending earlier in more recent years, probably as a result of earlier onset of spring melt conditions. From the monthly flow variables, March, April, June, and October were observed to have strong trend results. March and April both display an increasing trend indicative of an earlier onset of spring snowmelt. Flows in June display a decreasing trend while flows in October display increasing trends in the east and in the north and decreasing trends in the west.

The similarities in trends and patterns in the hydrologic variables and in meteorological variables at select locations imply that the trends in hydrologic variables are related to trends in meteorological variables. The results indicate that the temporal patterns in the variables have not been uniform and that the hydrologic variables may accentuate trends and patterns that exist in the meteorological variables that act as inputs to the hydrologic cycle.

Future work will address the issue of trend attribution and will attempt to establish a linkage between climatic change and the observed hydrologic trends. At present, it is not appropriate to state that the observed trends have occurred as a result of climatic change.

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References

Anderson, J.E., Shiau, S.-Y., Harvey, K.D., 1992. Preliminary investigation of trend/patterns in surface water characteristics and climate variations. In: Kite, G.W., Harvey, K.D. (Eds.). Using Hydrometric Data to Detect and Monitor Climatic Change. Proceedings of NHRI Workshop No. 8National Hydrology Research Institute, Saskatoon, SK, pp. 189–201.

Askew, A.J., 1987. Climate change and water resources. In: Solomon, S.I., Beran, M., Hogg, W. (Eds.). The Influence of Climate Change and Climatic Variability on the Hydrologic Regime and Water Resources, vol. 168. IAHS Publishers, pp. 421–430.

Burn, D.H., 1994a. Hydrologic effects of climatic change in west-central Canada. Journal of Hydrology 160, 53–70.

Burn, D.H., 1994b. Identification of a data collection network for detecting climatic change. Canadian Water Resources Journal 19, 27–38.

Burn, D.H., Soulis, E.D., 1992. The use of hydrologic variables in detecting climatic change: possibilities for single station and regional analysis. In: Kite, G.W., Harvey, K.D. (Eds.). Using Hydrometric Data to Detect and Monitor Climatic Change. Proceedings of NHRI Workshop No. 8National Hydrology Research Institute, Saskatoon, Saskatchewan, pp. 121–130.

Cleveland, W.S., 1979. Robust locally weighted regression and smoothing scatterplots. Journal American Statistical Association 74, 829–836.

Douglas, E.M., Vogel, R.M., Kroll, C.N., 2000. Trends in floods and low flows in the United States: impact of spatial correlation. Journal of Hydrology 240, 90–105.

Gan, T.Y., 1992. Finding trends in air temperature and precipitation for Canada and North-eastern United States. In: Kite, G.W., Harvey, K.D. (Eds.). Using Hydrometric Data to Detect and Monitor Climatic Change. Proceedings of NHRI Workshop No. 8National Hydrology Research Institute, Saskatoon, SK, pp. 57–78.

Gan, T.Y., Kwong, Y.T., 1992. Identification of warming trends in northern Alberta and southern Northwest Territories by the non-parametric Kendall's test. In: Kite, G.W., Harvey, K.D. (Eds.). Using Hydrometric Data to Detect and Monitor Climatic Change. Proceedings of NHRI Workshop No. 8National Hydrology Research Institute, Saskatoon, SK, pp. 43–56.

Gleick, P.H., 1989. Climate change, hydrology, and water resources. Reviews of Geophysics 27, 329–344.

Gullet, D.W., 1992. Development of an historical Canadian climate database for temperature. In: Kite, G.W., Harvey, K.D. (Eds.). Using Hydrometric Data to Detect and Monitor Climatic Change. Proceedings of NHRI Workshop No. 8National Hydrology Research Institute, Saskatoon, SK, pp. 27–31.

Harvey, K.D., Pilon, P.J., Yuzyk, T.R., 1999. Canada's Reference Hydrometric Basin Network (RHBN). Partnerships in Water Resources Management, Proceedings of the CWRA 51st Annual Conference, Nova Scotia.

Hirsch, R.M., Slack, J.R., Smith, R.A., 1982. Techniques of trend analysis for monthly water quality data. Water Resources Research 18, 107–121.

IPCC, 1996. Climate change 1995: the second IPCC scientific assessment. In: Houghton, J.T., Meira Filho, L.A., Callendar, B.A. (Eds.). Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK.

Kendall, M.G., 1975. Rank Correlation Measures. Charles Griffin, London.

Lettenmaier, D.P., Wood, E.F., Wallis, J.R., 1994. Hydro-climatological trends in the continental United States 1948–1988. Journal of Climate 7, 586–607.

Lins, H.F., Michaels, P.J., 1994. Increasing US streamflow linked to greenhouse forcing. EOS, Transactions, American Geophysical Union 75, 284–285.

Lins, H.F., Slack, J.R., 1999. Streamflow trends in the United States. Geophysical Research Letters 26 (2), 227–230.

Livezey, R.E., Chen, W.Y., 1983. Statistical field significance and its determination by Monte Carlo techniques. Monthly Weather Review 111, 46–59.

Mann, H.B., 1945. Non-parametric tests against trend. Econometrica 13, 245–259.

Mortsch, L., Hengeveld, H., Lister, M., Lofgren, B., Quinn, F., Slivitzky, M., Wenger, L., 2000. Climate change impacts on the hydrology of the Great Lakes-St. Lawrence system. Canadian Water Resources Journal 25 (2), 153–179.

Pilon, P.J., Winkler, T., Harvey, K.D., Kimmett, D.R., 1991. Hydrometric data in support of climate change studies in Canada. Presented at NATO Advanced Research Workshop on Opportunities for Hydrological Data in Support of Climate Change Studies, Lahnstein, Germany, 26–30 August 1991.

Robson, A.J., Jones, T.K., Reed, D.W., Bayliss, A.C., 1998. A study of national trend and variation in UK floods. International Journal of Climatology 18, 165–182.

von Storch, H., Navarra, A. (Eds.), 1995. Analysis of Climate Variability Springer, New York.

Westmacott, J.R., Burn, D.H., 1997. Climate change effects on the hydrologic regime within the Churchill-Nelson River Basin. Journal of Hydrology 202, 263–279.

Whitfield, P.H., Cannon, A.J., 2000. Recent variations in climate and hydrology in Canada. Canadian Water Resources Journal 25 (1), 19–65.

Yulianti, J.S., Burn, D.H., 1998. The impact of climate change on low streamflow in the prairies region of Canada. Canadian Water Resources Journal 23 (1), 45–60.

Zhang, X., Harvey, K.D., Hogg, W.D., Yuzyk, T.R., 2001. Trends in Canadian streamflow. Water Resources Research 37 (4), 987–998.