

## Patterns of Trend in Canadian Streamflow

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### ABSTRACT

Numerous studies have investigated spatial patterns of trend in streamflow. However, there is no consensus on the best methods to detect streamflow trends and the spatial extent or field significance of those trends. This paper looks at two of the contentious issues in trend analysis and assessment of field significance: serial correlation and cross-correlation. Both serial and cross-correlation are known to reduce the accuracy of trend detection. The Trend-Free Pre-Whitening method was found to effectively remove the influence of serial correlation from a time series, enabling a more accurate assessment of site significance. An additional bootstrap test was developed to preserve the existing cross-correlation and to allow for a more reliable assessment of field significance.

These methods and several others were applied to the annual mean, maximum and minimum streamflow data for 213 stations in the Canadian Reference Hydrometric Basin Network. These analyses revealed relatively consistent results for upward and downward trends for the three streamflow regimes. Mapping the results of these trend analyses revealed several interesting patterns, including three wide bands of trend that stretch across the country. A three band of downward trend stretches from Pacific to Atlantic at latitudes between approximately 50° and 58°; this band is particularly noticeable for the mean and maximum flows. A band of upward trend lies to the north of the downward band and stretches from northern B.C. and the Yukon through the Northwest Territories and into Nunavut; this band is noticeable for mean, maximum and minimum flows. A second band of upward trend lies to the south of the downward band, at latitudes between 44° and 50°; this band is noticeable for the same three flow variables.

**Key words:** trend analysis, streamflow, site significance, field significance, serial correlation, cross-correlation, pre-whitening, bootstrapping

### INTRODUCTION

Atmospheric concentrations of trace gases such as carbon dioxide have indicated a dramatic increase over the last century. It has been documented that such concentrations have led to increases of 0.4 to 0.6 °C in the mean global temperature (Bloomfield, 1992). It is felt that this process could lead to climatic abnormalities that will cause alterations in precipitation amount and storm patterns. Vinnikov *et al.* (1990), Gan (1991), Groisman and Easterling (1994), and Karl and Knight (1998), Zhang *et al.* (2000) have found increases in the amount and its intensity across the US and Canada in recent years. The sensitivity of streamflow to changes in precipitation and other climate parameters is well known, and it is thus important that researchers continue to look for evidence of trends in streamflow that could be caused by climate change.

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In attempts to address this issue, a number of studies have been conducted within North American. These include the works of Anderson *et al.* (1992), Smith and Richman (1993), Lettenmaier *et al.* (1994), Burn (1994), Gan (1998), Yulianti and Burn (1998), Leith and Whitfield (1999), Lins and Slack (1999), Douglas *et al.* (2000), Whitfield and Cannon (2000), Zhang *et al.* (2001), Burn and Elnur (2001), and others. The nonparametric Mann–Kendall (MK) statistical test (Mann, 1945; Kendall, 1975, Hirsch *et al.*, 1982) has been popularly used to identify if monotonic trends exist in streamflow data. The majority of studies regarding trend-analyses have assumed that recorded streamflow series are serially independent, even though certain hydrological time series such as annual mean and annual minimum streamflow may frequently display statistically significant serial correlation. A potentially serious limitation of the MK test occurs when serial correlation exists. The existence of positive serial correlation increases the probability that the MK test detects trend when no trend exists (e.g., Cox and Stuart, 1955; von Storch, 1995). This leads to a disproportionate rejection of the null hypothesis of no trend, while the null hypothesis is actually true. Therefore, it is necessary to identify the serial correlation prior to applying the MK test.

Kulkarni and von Storch (1995) and von Storch (1995) proposed to eliminate the influence of serial correlation on the MK test by “pre-whitening”. In this method, the serial correlation component such as a lag-one autoregressive process (AR (1)) is removed from the time series and the significance of trend is then evaluated using the MK test on the pre-whitened series. This method has also been used by Douglas *et al.* (2000), Zhang *et al.* (2000, 2001), and Burn and Elnur (2001). Yue *et al.* (2000) demonstrated that the existence of positive serial correlation will cause an overestimation of the probability of trend, while negative serial correlation will cause an underestimation of the probability of trend. The study also showed that while pre-whitening can effectively remove an AR process from a series, unfortunately removal of positive serial correlation will remove part of the existing trend and removal of negative serial correlation will inflate the existing trend. Thus, pre-whitening sample data will also lead to a biased estimation of the probability of trend.

One objective of the present study is to further explore the issue of serial correlation in trend detection by applying a new procedure developed by Yue *et al.* (2000) to streamflow data for 213 stations in the Canadian Reference Hydrometric Basin Network (RHBN). The procedure, referred to here as Trend-Free Pre-Whitening (TFPW), is used to remove the influence of serial correlation within a time series prior to applying the Mann–Kendall test.

A source of error in any spatial analysis of trend (i.e. the determination of whether significant trend exists across a larger area) is the cross-correlation among stations used in the analysis. Cross-correlation has the effect of reducing the effective number of stations in the analysis; e.g. if two stations are highly correlated, the second station is merely duplicating the first and not contributing much new information. Previous trend analyses on hydro-meteorological time series such as the works of Lettenmaier *et al.* (1994) and Douglas *et al.* (2000), consider the influence of cross-correlation among sites on the trend assessment. Douglas *et al.* (2000) developed a bootstrapping approach within which the cross-correlation is preserved. In their method, an empirical cumulative distribution function (ECDF) of the regional mean of the MK statistic ( $S$ ) is estimated by bootstrapping the sample data. Then the field significance of trend is assessed by comparing the regional mean  $S_m$  to the ECDF at a given significance level. This approach could miss smaller regions of significant trend because upward trends cancel downward trends in the calculation of the regional mean  $S$ . The approach therefore might be more suitable for cases where the majority of trends within a region show uni-directional change, i.e., either upward or downward. As a large number of both upward and downward trends can exist, it is desirable to assess separately the field significance of upward and downward trends. The second objective of the study is to develop and apply a new bootstrapping approach that will separately assess upward and downward trends. The third objective of the study is to draw conclusions about spatial patterns of trend in Canadian streamflow on the basis of the results obtained by these methods and analyses.

Section 2 describes the TFPW approach, maps the results of the MK-TFPW method for the selected stations, and compares the three methods – MK-TFPW, MK, and von Storch’s pre-whitening. Section 3 shows how the binomial distribution is used to assess field significance of

trend. Section 4 develops a new bootstrapping approach for assessing the field significance of upward and downward trend and compares this approach with the binomial distribution. Several conclusions are presented in Section 5.

## SITE SIGNIFICANCE, TAKING SERIAL CORRELATION INTO ACCOUNT

### MK-TFPW approach

The MK-TFPW procedure by Yue *et al.* (2000) is applied in the following manner to reduce the effect caused by serial correlation. First, the serial correlation coefficient is computed for the data series. This can be done using the approximation suggested by Salas *et al.* (1980). To determine if the data are serially correlated, the significance of the lag-1 serial correlation at the significance level of 0.10 (two-tailed test) is assessed using the approximation in Anderson (1942) (also see Yevjevich, 1972; Salas *et al.*, 1980). If the computed lag-1 serial correlation falls within the confidence intervals, the sample data are assumed to be serially independent. Otherwise it is considered to be serially correlated. If the series is serially independent, the Mann–Kendall test is used to assess the significance of trend. If the series has significant serial correlation, the trend component is assumed to be monotonic and its slope is estimated using the approach proposed by Theil (1950) and Sen (1968) (also see Hirsch *et al.*, 1982; Gan, 1998). If the trend slope is equal to zero, then the P-value of the series is assigned a value of 0.5 and no further analysis is required. Otherwise, the trend is removed from the series ( $x_t$ ) by the assumption of linearity as

$$X'_t = X_t - b t \quad (1)$$

The serial correlation coefficient of the de-trended series is estimated, and pre-whitening is used to remove the AR process from the de-trended series as follows:

$$X''_t = X'_t - r_1 X'_{t-1} \quad (2)$$

Finally, the removed trend and the residual series are combined together, and the MK test is used to assess the significance of the trend.

To test the ability of the TFPW procedure to remove an AR(1) component, we counted the number of sites with statistically significant positive lag-1 serial correlation coefficient before and after applying the TFPW. The results presented in Table 1 show that the TFPW procedure effectively removes the AR(1) component from the data for these stations. Table 1 shows only the stations with positive serial correlation as very few stations were found to have statistically significant negative serial correlation.

Table 1. Number of sites with statistically significant positive serial correlation coefficient

Data set	Variables	Number of sites	Number of sites with positive significant serial correlation coefficient	
			Before TFPW	After TFPW
1957–1997	Mean	63	16	0
	Maximum	75	5	0
	Minimum	71	23	0
At least 40 years	Mean	59	18	1
	Maximum	68	7	0
	Minimum	60	24	1
All sites	Mean	213	51	3
	Maximum	213	29	0
	Minimum	209	77	3

### Spatial pattern of trends

The MK-TFPW procedure was applied to annual mean, annual maximum, and annual minimum daily streamflow series at 213 stations in the RHBN. The RHBN is a network of streamflow and water level stations across Canada that has been designed to address the hydrometric data requirements of scientific studies on climate change and other issues. (EC, 1999; Pilon and Kuylenstierna, 2000). These 213 sites are operated on a continuous, year-round basis. Three different data sets were used in the analyses. The first set included only the 1957–97 data for stations which operated continuously during those 40 years; this provided a uniform basis on which to compare results in different parts of the country. The second set included every year of data for stations that have at least 40 years of record; this provided a better indication of long term trends. The third set included every year of data for all 213 stations in the RHBN; this data set provided maximum spatial coverage and maximum spatial resolution for the analyses.

To assist in assessing potential patterns of trends, the sites with significant positive and negative trends are illustrated on the map. By viewing the trend results for each of these streamflow indices, similar patterns emerged for the 1957–1997 data, stations with at least 40 year records, and the all-site analysis. Therefore, for brevity, only results for the third data set of all stations are presented in Figures 1 to 3. This third data set was selected as it provided an improved spatial description of trends and patterns. On the maps, a circle indicates a station with no significant trend, an upward-pointing triangle indicates a station with significant upward trend, and a downward-pointing triangle indicates a station with significant downward trend.

By viewing Fig.1, a rather striking observation is a band of downward trend in annual mean flow that stretches across the entire country from Pacific to Atlantic, at mid-latitudes between approximately 50° and 58°. The band includes the southern half of British Columbia, Prairie Provinces, northern Ontario, northern Quebec, and northern part of Newfoundland. The pattern of trends in this band is the same as in the first and second data sets. To the north of this downward-trend band, a band of upward trend can be seen stretching from northern B.C. and the Yukon through the Northwest Territories and into Nunavut; however most of the stations in this band are of short-duration. It would be risky to draw any conclusion about long-term trend from such short-term observations. To the south of the downward-trend band, at latitudes between 44° and

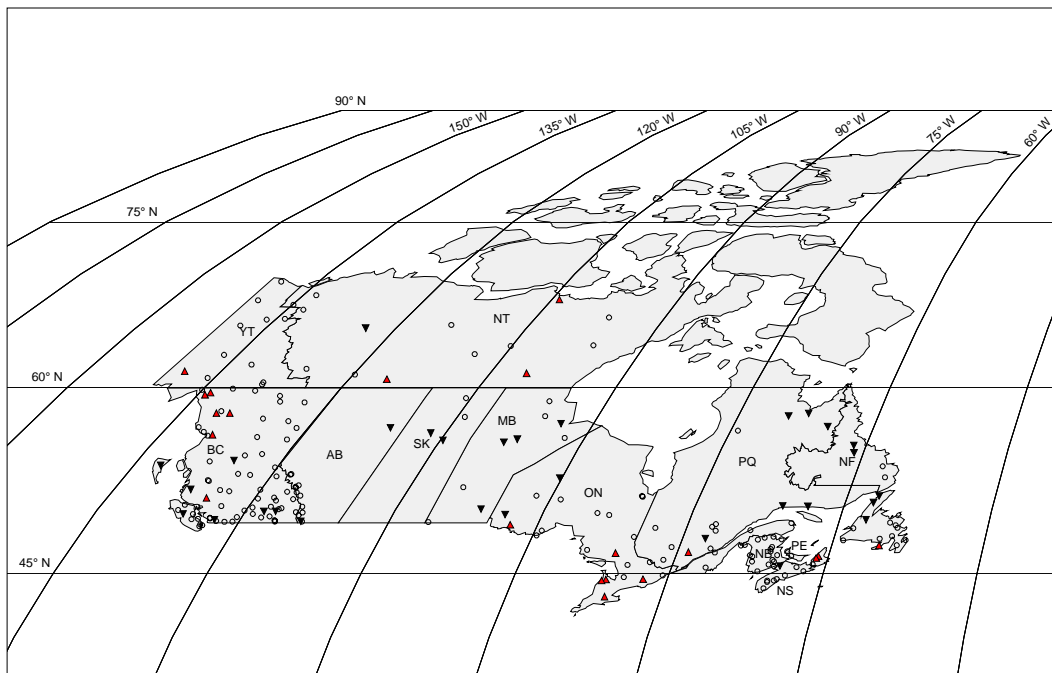


Fig. 1. Spatial illustration of significant trends in annual mean daily flows of all sites

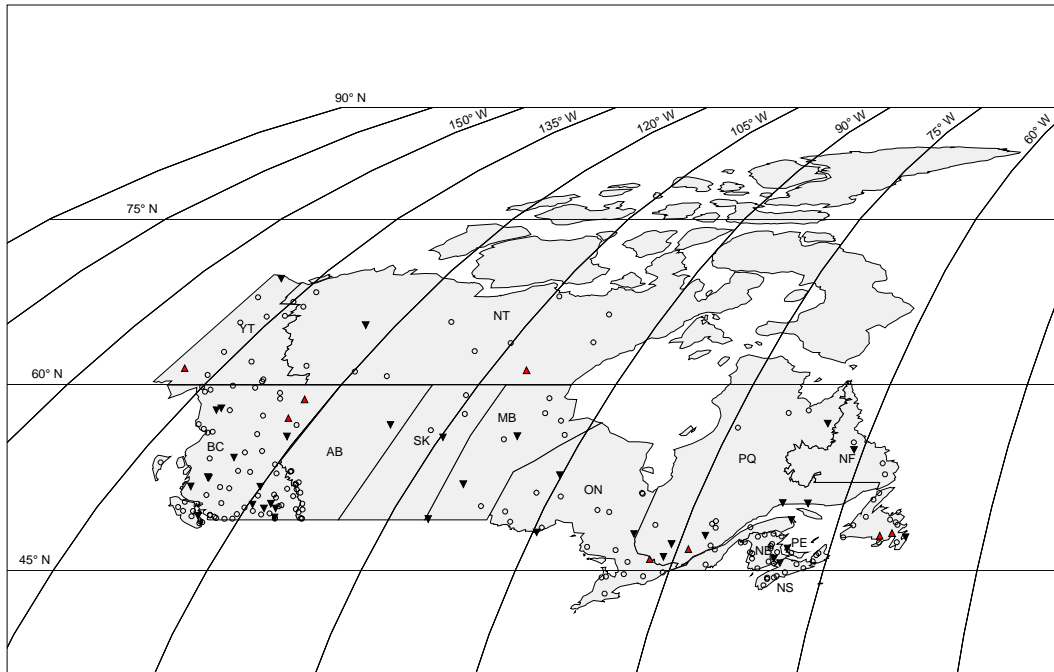


Fig. 2. Spatial illustration of significant trends in annual maximum daily flows of all sites

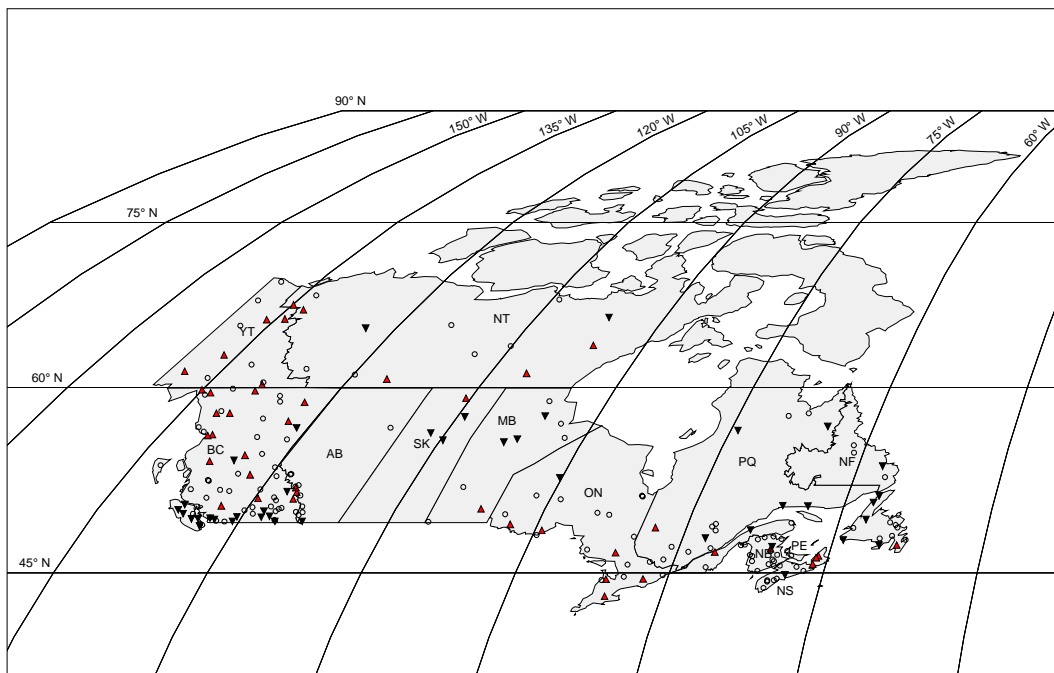


Fig. 3. Spatial illustration of significant trends in annual minimum daily flows of all sites

50°, is another band of upward trend in mean flow that stretches across the southern half of Ontario, into Quebec, and perhaps as far as the southern part of Newfoundland.

Figure 2 has one noticeable similarity to Figure 1, i.e., a broad band of downward trend in annual maximum flow stretching across the entire country at mid-latitudes from Pacific to Atlantic. This pattern is also similar to those for the other two data sets. Fig. 2 does not show any clear patterns north or south of the mid-latitude downward-trend band. There is, however, some

similarity between the patterns of annual mean and maximum flows, with less significant upward tendencies observed for maximum flow.

Figure 3 shows similar patterns as Figure 1, with three distinct bands of trend in annual minimum flow stretching across the country. The central band at mid-latitudes shows a predominantly downward trend. The northern band of upward trend in Figure 3, above latitude 58°, is consistent with the pattern seen in the other data sets, indicating short-term trend and long-term trend in annual minimum flow that are both upward. The southern band of upward trend, below latitude 50°, is also consistent with the pattern seen in the other two data sets, indicating annual minimum flows are experiencing both short-term and long-term upward trend in that region.

Table 2. Comparison of trend assessment results for all sets by different approaches

Variables	Number of sites	Number of upward trends			Number of downward trend		
		MK	Pre-wh	TFPW	MK	Pre-wh	TFPW
Mean	213	19	10	20	25	25	30
Maximum	213	8	7	8	34	27	36
Minimum	209	46	28	42	38	29	41

### Comparison of MK-TFPW, MK and MK-PW

Trend analyses were conducted on the annual mean flows of all RHBN stations using two other tests: (1) the MK test without considering serial correlation and (2) the MK test with pre-whitening (MK-PW) (Kulkarni and Von Storch, 1995; Von Storch, 1995). The numbers of significant upward and downward trends detected by these two tests are compared with the number of trends detected by the MK-TFPW test in Table 2. The trend assessment results assessed by the pre-whitening approach are much more conservative than the results of the MK and the TFPW approaches. That is, the numbers of the detected upward and downward trends by the pre-whitening approach are less than either of the two other approaches. This was noted by Yue *et al.* (2000), wherein they indicated that pre-whitening removes a portion of trend, and hence leads to a lower number of detections. Douglas *et al.* (2000) also had similar observations when analyzing streamflow for possible trend throughout the United States.

The numbers of significant trends detected by the MK and TFPW approaches are not greatly different. In one case (upward trend in minimum flow) the MK-TFPW test detected slightly fewer trends than the MK test. In all downward trend cases, the number detected by the MK-TFPW test is slightly more than by the MK test. One possibility is that some of the time series in this data set have positive serial correlation that causes the MK test to overestimate upward trend and underestimate downward trend; this scenario was discussed in Section 1. Upon closer inspection, it was noted that the stations showing significant upward or downward trends by the two approaches are not always the same sites. About 10% of the sites identified are different. The similarity of results for these two approaches suggests that there may be a very pronounced trend at these stations and that even the more conservative detection methods are able to detect the trend in these cases.

### FIELD SIGNIFICANCE WITHOUT CONSIDERING CROSS-CORRELATION

The next step in the analysis was to assess the field significance of trends detected by the MK-TFPW method. The question here is how many individual stations in a study area must be found to have significant trend before it can be concluded that there is a significant trend across the entire study area. When there is a significant trend across the entire study area, we say the study area has a field-significant trend or that the trend has field significance. When only a small number of the stations within a study area exhibit a significant trend, it can be argued that this small number of trends might be an anomaly or an accidental result of the statistical analysis and that they do not indicate a widespread trend across the study area. To be confident of field significance

at say the 95% level, we need to be sure that the probability of the individual trends being an anomaly is less than 5%.

If there is no cross-correlation among sites, then the binomial distribution can be used to assess the field significance of trend. Livezey and Chen (1983) used the binomial distribution to compute the probability related the number of stations with significant trend in a study area. The binomial distribution is

$$P(k) = \frac{n!}{k!(n-k)!} p^k (1-p)^{n-k} \quad (3)$$

where  $P(k)$  is the probability of  $k$  occurrences in  $n$  trials, and  $p$  is a certain probability associated with each occurrence. The probability of  $k$  or more occurrences being an anomaly or accidental result is

$$P'(x \geq k) = 1 - \sum_{i=0}^{k-1} P(i) \quad (4)$$

Equation (4) was used to determined whether or not field significance exists in the RHBN study area for any of the three variables (mean, maximum and minimum streamflow) within any of the three data sets (1957–97, >40 years, and all stations). In this analysis, the value for  $n$  is the number of stations in the data set,  $k$  is the number of stations that show significant trend at the significance level of 0.05 for the one-tailed test, and  $p$  is the significance level used in the trend analyses for the individual stations (0.05). The computed value of  $P'$  will therefore be the probability that the  $k$  individual trends could be an anomaly or accidental result of the statistical analysis; if  $P'$  is greater than 0.05, we can say that there is no evidence of field significance across that particular study area at the significance level of 0.05.

Table 3. Trend assessment results for 1957–1997 period

Variables	Number of sites	Upward trends			Downward trend		
		Number	(%)	Binomial prob.	Number	(%)	Binomial prob.
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
			(3)/(2)	$\geq$ (3)		(6)/(2)	$\geq$ (6)
Mean	63	8	12.70	0.01	6	9.52	0.09
Maximum	75	4	5.33	0.52	10	13.33	0.00
Minimum	71	12	16.67	0.00	11	15.28	0.00

#### Data set for 1957–1997 time period

For the period 1957 to 1997, the only stations used in this part of the analysis were the RHBN stations that have a complete streamflow record, or nearly complete record, over this 40-year period. Only the data for 1957–97 were used in this part of the analysis, even though many of these stations have data for years prior to 1957. The number of stations used in the analyses is shown in column (2) of Table 3. The number of stations found to have significant upward or downward trend at a significance level of 10% (two-tailed test) is given in columns (3) and (6), respectively. The percentage of significant trends for the 1957–1997 time period are presented in columns (4) and (7) of Table 3. If there is no cross-correlation among these stations, then at a 5% significance level we could expect as many as 5% of the stations to show, by chance, a significant upward or downward trend. Columns (4) and (7) indicate percentages somewhat higher than 5% for annual mean and minimum flows, and the significance of these departures will now be assessed. To further investigate this field significance, the probability  $P'$  of equaling or exceeding the number shown in columns (3) and (6) was computed using equation (4); the  $P'$  values are presented in columns (5) and (8). Most of the computed probabilities are <0.05, suggesting field significance for upward trend in mean and minimum flows and downward trend in mean, maximum and minimum flows.

### Data set for stations with at least 40 years of record

For stations having at least 40 years of record, the entire period of record for each of these stations was used in the analyses. This data set is expected to provide a more accurate picture of long term trends. The numbers of significant upward and downward trends are presented in columns (3) and (6) of Table 4, respectively. The percentage of significant trends for the data set with at least 40 years of record are presented in columns (4) and (7), and the corresponding  $P'$  values are shown in columns (5) and (8). These percentages, and  $P'$  values  $<0.05$ , suggest field significance for upward trend in mean and minimum flows and downward trend in maximum and minimum flows.

Table 4. Trend assessment results for stations with at least 40 year record

Variables	Number of sites	Upward trends			Downward trend		
		Number	(%)	Binomial prob.	Number	(%)	Binomial prob.
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
			(3)/(2)	$\geq (3)$		(6)/(2)	$\geq (6)$
Mean	59	10	16.95	0.00	4	6.78	0.34
Maximum	68	7	10.29	0.05	8	11.76	0.02
Minimum	60	20	33.33	0.00	9	15.00	0.00

### Data set for all stations

Table 5 shows the results for the data set containing all 213 stations. The entire period of record for each of these stations was used in the analyses. This data set provides better spatial coverage than the other two data sets analyzed in the preceding sections. However, having sites of various lengths may make it more difficult to compare site specific results. Columns (3) and (6) of Table 5 shows numbers of the trend analyses for all 213 RHBN stations. The percentages in columns (4) and (7) and the probabilities in columns (5) and (8) suggest field significance for upward trend in mean and minimum flows and downward trend in annual mean, maximum and minimum flows. It must be remembered that this data set includes some shorter data periods that are reflecting only short-duration trends rather than the longer duration trends found in sections 3.1 and 3.2.

Table 5. Trend assessment results for all sites

Variables	Number of sites	Upward trends			Downward trend		
		Number	(%)	Binomial prob.	Number	(%)	Binomial prob.
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
			(3)/(2)	$\geq (3)$		(6)/(2)	$\geq (6)$
Mean	213	20	9.39	0.01	30	14.08	0.00
Maximum	213	8	3.76	0.84	36	16.90	0.00
Minimum	209	42	20.00	0.00	41	19.52	0.00

## FIELD SIGNIFICANCE CONSIDERING CROSS-CORRELATION

As mentioned in section 1, the existence of serial and cross-correlation among stations used in a trend analysis should be considered when determining the field significance of trend. The results of the binomial distribution in section 3 using the TFPW procedure reflect the effects of serial correlation without consideration of cross-correlation. An additional bootstrap test was developed similar in spirit to the one proposed by Douglas *et al.* (2000), wherein cross-correlation among all sites is preserved. However, rather than using the regional mean of the MK statistic ( $S$ ) as an indicator of field significance, the additional bootstrap test assesses the number of upward and downward trends. This facilitates the detection of an anomalous number of upward and downward trends, regardless of the average MK statistic. The test is described as follows:



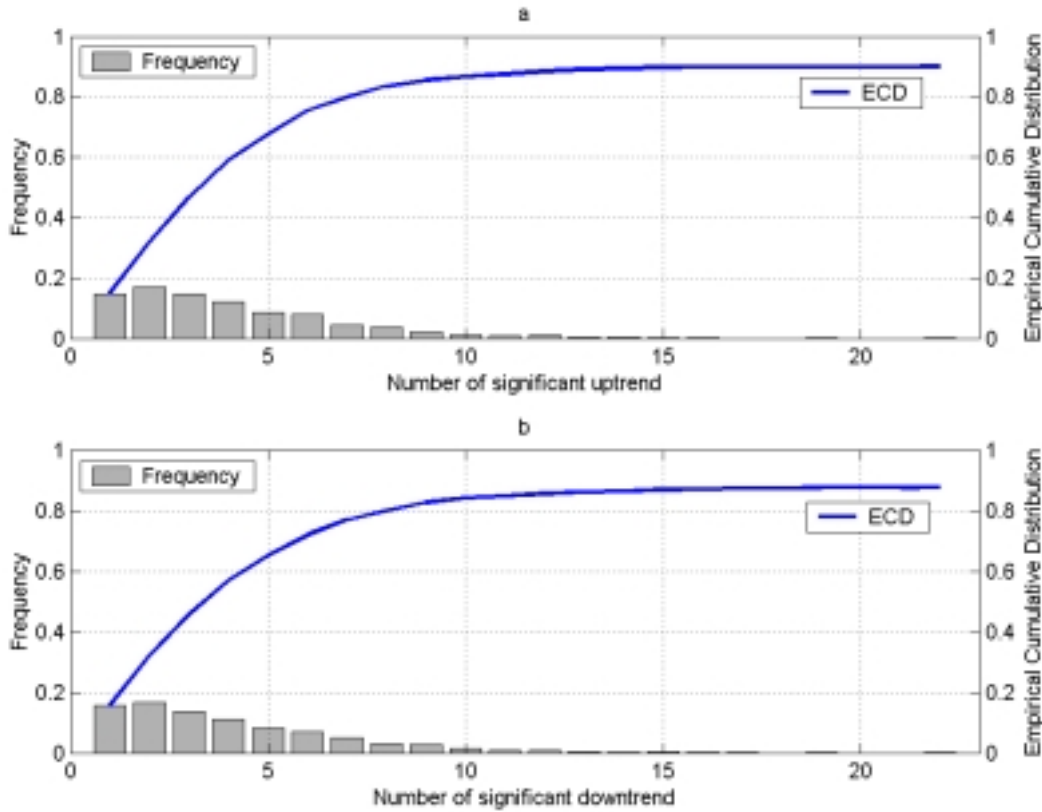


Fig. 4. Empirical frequency and empirical cumulative distribution (ECD) of the number of significant upward trends (a); downward trends (b)

- (1). The selected period or range of years, for example, [1967, 1968, 1969, . . . , 1997] is resampled randomly with replacement. Then we get a new set with different year order from the original one, for instance, [1978, 1969, 1996, 1988, . . . , 1974].
- (2). Each site within a network has an observation value corresponding to a calendar year. By rearrange the observation values of each site of the network according to the new year set obtained in Step (1), a new network can be obtained.
- (3). The MK statistic and the corresponding P-value ( $p$ ) at each site can be computed. By comparing these  $p$  values at the sites with the pre-assigned significance level of 0.05, the number ( $N_{up}^*$ ) of sites with significant upward trends and the number ( $N_{down}^*$ ) of sites with significant downward trends ( $p \leq 0.05$ ) of the network can be counted.
- (4). By repeating Step (1) – (3)  $B$  ( $= 1000$ ) times,  $B$  number of sites with significant upward and downward trends of the network can be obtained. Then the bootstrap empirical cumulative distributions (BECDs) for upward and downward trends can be estimated by

$$P^*(N^* \leq N_r^*) = r / (B + 1) \quad (N^* = N_{up}^*, N_{down}^*) \quad (5)$$

where  $r$  is the rank of  $N_r^*$  in the bootstrap sample data according to the ascending order. The field significance of upward trends for the network can be assessed by comparing the numbers of sites with significant upward trends counted from the real network with the BECD. Similarly, the field significance of downward trends for the network can also be evaluated.

The three flow variables (mean, maximum, minimum) for the 1957 to 1997 data set were analyzed using this additional bootstrapping procedure. The properties of the cross-correlation coefficients between tow sites in the network for the three flow regimes are presented in Table 6. Although the means of the cross-correlation coefficients are not so big, the positive cross-

correlation dominates the networks. The cross-correlation of the sites after applying TFPW was also computed. The two cross-correlation matrices before and after applying TFPW are almost identical. The probability values of the numbers for significant upward and downward trend (after removing the effect of serial correlation with TFPW) are presented in Table 7. For the purpose of illustration, the relative frequency and ECD curves of these numbers for annual maximum flows are depicted in Fig.4a and b, respectively. Table 7 indicates that at the significance level of 0.05, no field significant trends can be detected. These results are dramatically different from the results assessed by the binomial distribution without consideration of the effect of cross-correlation within the network, as listed in Table 3.

Table 6. Properties of cross-correlation among the sites for the 1957–1997 period

Variables	Properties of cross-correlation		
	Mean	Maximum	Minimum
Mean	0.121	0.953	-0.646
Maximum	0.052	0.957	-0.558
Minimum	0.059	0.839	-0.510

Table 7. Trend assessment results for 1957–1997 period by the bootstrap

Variables	TFPW-bootstrap				
	Number of sites	Upward trend		Downward trend	
		Number	Probability	Number	Probability
Mean	63	8	0.69	6	0.65
Maximum	75	5	0.68	10	0.84
Minimum	71	12	0.84	12	0.84

## CONCLUDING REMARKS

The site significance of trends in annual mean, annual maximum, and annual minimum daily flows for three data sets from the Canadian Reference Hydrometric Basin Network was assessed using the MK-TFPW test. The test is the standard Mann–Kendall test combined with a modified pre-whitening procedure developed by Yue *et al.* (2000) to remove the influence of serial correlation on the test. There was some evidence of spatial patterns for sites having significant trends. For annual mean flow, a band of downward trends stretches across the entire country from Pacific to Atlantic, at mid-latitudes between approximately 50° and 58°. To the north of this downward-trend band, a band of upward trend can be seen stretching from northern B.C. and the Yukon through the Northwest Territories and into Nunavut. To the south of the downward-trend band, at latitudes between 44° and 50°, is another band of upward trend in mean flow which stretches across the southern half of Ontario, into Quebec, and perhaps as far as the southern part of Newfoundland. Annual maximum flow had a general pattern of downward trends across Canada. For the annual minimum flow, a complex pattern with clustering of direction was noted. There is a downward-trend band across most part of the country from Alberta to Atlantic, at mid-latitudes between approximately 50° and 58°. A clustering downward-trend pattern appears near the southern border of British Columbia, at latitude about 50°. Apart from these two downward trend patterns, an upward-trend pattern appears in most other part of the country.

The field significance of these upward and downward trends was further investigated using the binomial distribution without consideration of the effect of cross-correlation at the significance level of 0.05. For the data set from 1957 to 1997, both field-significant upward and downward trend in annual minimum flow were detected, field-significant upward trend in annual mean flows was detected, and field-significant downward trend in annual maximum was detected. For the other two data sets, the assessment results are almost identical to those of the first data set.

An additional bootstrapping procedure was developed to extend the approach reported by Douglas *et al.* (2000) for the assessment of field significance that preserves the network's overall cross-correlation structure while taking into account impact of serial correlation on the test

statistics. The procedure was used to separately determine field significance of upward and downward trend in the data set from 1957 to 1997. The assessment results are different from those obtained from the use of the TFPW with a binomial distribution without consideration of cross-correlation. However, it may be necessary to delimit the whole country into a few sub-regions within which the climatic and geographic conditions are not significantly different. In areas of consistent pattern and high station density, the importance of cross-correlation could be much clearer. More effort is required to assess the practical significance of these initial results and the hydro-climatic processes that are producing the observed patterns of trend in Canadian streamflow.

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## REFERENCES

- Anderson, J.E., Shiao, S.Y., Harvey, K.D., 1992. Preliminary investigation of trend/patterns in surface water characteristics and climate variations. In: G.W. Kite and K.D. Harvey (Editors), *Using Hydrometric Data to Detect and Monitor Climatic Change*. Proceedings of NHRI Workshop No. 8. National Hydrology Research Institute, Saskatoon, Sask., 189–202.
- Anderson, R.L., 1942. Distribution of the serial correlation coefficients, *Annals of Meth. Statistics*, 13(1), 1–13.
- Bloomfield, P., 1992. Trends in global temperatures, *Climate Change* 21: 1–16.
- Burn, D.H., 1994. Hydrologic effects of climatic change in West Central Canada, *J. Hydrol.*, 160, 53–70.
- Burn, D.H., Hag Elnur, M.A., 2001. Climate change impact using hydrologic variables, in CCAF Workshop Meeting.
- Cox, D.R., Stuart, A., 1955. Some quick sign tests for trend in location and dispersion, *Biometrika*, 42, 80–95.
- Douglas, E.M., Vogel, R.M., Kroll, C.N., 2000. Trends in floods and low flows in the United States: impact of spatial correlation, *J. Hydrol.* 240: 90–105.
- EC (Environment Canada), 1999. Establishment of the Reference Hydrometric Basin Network (RHBN) for Canada.
- Gan, T.Y., 1991. Finding trends in air temperature and precipitation for Canada and north-eastern United States, In: G.W. Gite and K.D. Harvey (Editors), *Using Hydrometric Data to Detect and Monitor Climatic Change*. Proceedings of NHRI Workshop No. 8. National Hydrology Research Institute, Saskatoon, Sask., 57–78.
- Gan, T.Y., 1998. Hydroclimatic trends and possible climatic warming in the Canadian Prairies, *Water Resour. Res.*, 34(11): 3009–3015.
- Groisman, P.Y., Easterling, D.R., 1994. Variability and trends in total precipitation and snowfall over the United States and Canada, *J. Climate*, 7: 184–205.
- Hirsch, R.M., Slack, J.R., 1984. Non-parametric trend test for seasonal data with serial dependence, *Water Resour. Res.*, 20 (6), 727–732.
- Hirsch, R.M., Slack, J.R., Smith, R.A., 1982. Techniques of trend analysis for monthly water quality data, *Water Resour. Res.*, 18(1), 107–121.
- Karl, T.R., Knight, R.W., 1998. Secular trends of precipitation amount, frequency, and intensity in the United States. *Bull. Am. Meteorol. Soc.*, 79(2): 231–241.
- Kendall, M.G., 1975. *Rank Correlation Methods*. Griffin, London.
- Kulkarni, A., Von Storch, H., 1995. Monte Carlo experiments on the effect of serial correlation on the Mann–Kendall test of trend, *Meteorologische Zeitschrift*, 4(2), 82–85. Germany.

- Leith, R.M.M., Whitfield, P.H., 1998. Evidence of climate change effects on the hydrology of streamflows in south-central B.C., *Can. Water Resources J.*, 23: 219–231.
- Lettenmaier, D.P., Wood, E.F., Wallis, J.R., 1994. Hydro-climatological trends in the continental United States, 1948–88, *J. of Climate*, 7, 586–607.
- 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. Nonparametric tests against trend, *Econometrica*, 13, 245–259.
- Pilon, P.J., Kuylenskierna, J.K., 2000. Pristine river basins and relevant hydrological indices: essential ingredients for climate-change studies, *WMO Bulletin*, 49(3), 248–255.
- Salas, J.D., Delleur, J.W., Yevjevich, V., Lane, W.L., 1980. *Applied Modelling of Hydrologic Time Series*, Water Resources Publications, Littleton, Co., USA.
- Sen, P.K., 1968. Estimates of the regression coefficient based on Kendall's tau, *J. American Statist. Assoc.*, 63, 1379–1389.
- Smith, K., Richman, M.B., 1993. Recent hydroclimatic fluctuations and their effects on water resources in Illinois, *Climate Change* 24:249–269.
- Theil, H., 1950. A rank-invariant method of linear and polynomial regression analysis, I, II, III, *Nederl. Akad. Wetensch. Proc.*, 53, 386–392; 512–525; 1397–1412.
- Vinnikov, K.Y., Groisman, P.Y., Lugina, K.M., 1990. Empirical data on contemporary global climate changes (temperature and precipitation), *J. Climate*, 3: 662–677.
- von Storch, H., 1995. Misuses of statistical analysis in climate research. In *Analysis of Climate Variability: Applications of Statistical Techniques*, eds. by H.V. Storch and A. Navarra, Springer-Verlag Berlin, 11–26.
- Whitfield, P.H., Cannon, A.J., 2000. Recent variations in climate and hydrology in Canada, *Can. Water Resour. J.*, 25: 19–65.
- Yevjevich, V., 1972. *Stochastic Processes in Hydrology*, Water Resources Publications, Fort Collins, CO., USA.
- Yue, S., Pilon, P., Phinney, B., Cavadias, G., 2000. The influence of autocorrelation on the ability to detect trend in hydrological series, *Hydrol. Processes* (in review).
- Yulianti, J.S., Burn, D.H., Investigating links between climatic warming and low streamflow in the Prairies Region of Canada, *Can. Water Resour. J.*, 23(1), 45–60, 1998.
- Zhang, X., Vincent, L.A., Hogg, W.D., Niitsoo, A., 2000. Temperature and precipitation trends in Canada during the 20<sup>th</sup> century, *Atmosphere Ocean*, 38(3): 395–429.
- Zhang, X., Harvey, K.D., Hogg, W.D., Yuzyk, T.R., 2001. Trends in Canadian streamflow, *Water Resour. Res.*, 37(4): 987–998.