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Canadian streamflow trend detection: impacts of serial and cross-correlation

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Abstract The nonparametric Mann-Kendall (MK) statistical test has been widely applied to assess the significance of trends in hydrological time series. It is known that the existence of serial correlation in a time series will affect the ability of the test to assess the site significance of a trend; and the presence of cross-correlation among sites in a network will influence the ability of the test to evaluate the field significance of trends over the network. This study proposes to use a trend-free pre-whitening (TFPW) procedure to remove serial correlation from time series, and hence to eliminate the effect of serial correlation on the MK test. An additional bootstrap test with preserving the cross-correlation structure of a network is proposed to assess the field significance of upward and downward trends over the network separately. At the significance level of 0.05, the site significance of trends in Canadian annual minimum, mean, and maximum daily streamflows with 30-, 40- and 50-year records was assessed by the MK test with the TFPW procedure (TFPW-MK). The spatial illustration of the significant trends at sites indicates that: (a) the 30-year annual minimum and mean daily flows significantly decreased in the regions of southern British Columbia (BC), around the centre of Prairie Provinces, and in Atlantic Provinces, and significantly increased in the region of northern BC and Yukon Territory; and (b) the annual maximum daily flow significantly decreased across southern Canada. The field significance of trends over the whole country was evaluated by the bootstrap test at the significance level of 0.05 and none of the three flow regimes experienced field-significant changes.

Key words streamflow; trend analysis; Mann-Kendall test; bootstrap test; serial correlation; cross-correlation; pre-whitening; statistical hydrology

Détection de tendance dans les séries canadiennes de débits: impacts des corrélations sérielles et croisées

Résumé Le test statistique non-paramétrique de Mann-Kendall (MK) a été largement utilisé pour évaluer la signifiance des tendances dans les séries temporelles hydrologiques. Or la présence de corrélations croisées entre sites d'un réseau influence la pertinence de ce test pour évaluer la signifiance réelle des tendances indépendamment du réseau. Cette étude propose d'utiliser une procédure préliminaire de décorrélation indépendante des tendances afin d'éliminer toute corrélation sérielle des séries temporelles, et donc de gommer l'effet de la corrélation sérielle sur le test de MK. Un test bootstrap supplémentaire, préservant la structure des corrélations croisées d'un réseau, est proposé pour évaluer les signifiances réelles des tendances respectivement infra- et supra-réseau. Au niveau de signification 0.05, la signifiance des tendances dans les données canadiennes de débits journaliers minimum, moyen et maximum annuels au niveau des stations , pour des séries longues de 30, 40 et 50 ans, a été estimée grâce au test de MK après mise en œuvre de la procédure de décorrélation. L'analyse spatiale des tendances significatives au niveau des stations indique que: (a) les débits journaliers minimum et moyen annuels sur 30 ans décroissent de manière significative dans les régions du Sud de la Colombie Britannique, autour du centre des Provinces de la prairie et dans les Provinces de l'Atlantique, et croissent de manière significative dans le Nord de la Colombie

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Britannique et dans le Territoire du Yukon; et (b) le débit journalier maximum annuel décroît de manière significative dans le Sud du Canada. La signifiance réelle des tendances à travers le pays dans son ensemble a été évaluée grâce au test bootstrap au niveau de signification 0.05 et il apparaît qu'aucun des trois débits caractéristiques ne présente de changement significatif.

Mots clefs écoulement fluvial; analyse de tendance; test de Mann-Kendall; test bootstrap; corrélation sérielle; corrélation croisée; pré-blanchiment; hydrologie statistique

INTRODUCTION

It has been documented that the global average surface temperature has increased by 0.6±0.2°C over the 20th century (IPCC, 2001) due to atmospheric concentrations of trace gases such as carbon dioxide. It is felt that this process could lead to abnormalities in other climate parameters such as precipitation and evapotranspiration in a specific region. Vinnikov *et al.* (1990), Groisman & Easterling (1994), Karl & Knight (1998) and Zhang *et al.* (2000, 2001b) have reported increases in annual precipitation across the United States and Canada in recent years. Streamflow is sensitive to the changes in precipitation and evapotranspiration. Thus, it is informative to investigate if there exists any evidence of trend in streamflow, which could be caused by climate change.

A number of studies have been conducted within North America to investigate whether or not trends exist in streamflow series. Examples include the works of Smith & Richman (1993), Lettenmaier *et al.* (1994), Burn (1994), Gan (1998), Yulianti & Burn (1998), Leith & Whitfield (1998), Lins & Slack (1999), Douglas *et al.* (2000), Whitfield & Cannon (2000), Zhang *et al.* (2001a), Burn & Hag Elnur (2002), and others. The majority of studies regarding trend analyses have assumed that recorded streamflow series are serially independent, even though annual mean and annual minimum streamflow may frequently display statistically significant serial correlation. Von Storch (1995) demonstrated that the existence of positive serial correlation within a time series increases the possibility that the Mann-Kendall (MK) test (Mann, 1945; Kendall, 1975) detects the significance of a trend. This may lead to rejection of the null hypothesis of no trend, while the null hypothesis is actually true.

In order to eliminate the influence of serial correlation on the MK test, Kulkarni & von Storch (1995) and von Storch (1995) proposed to pre-whiten a series prior to applying the MK test. That is, the serial correlation component, such as a lag-one autoregressive process (AR(1)) is removed from a time series and the significance of a trend is then evaluated by using the MK test to the pre-whitened series. This method has been used in trend detection studies (e.g. Douglas *et al.*, 2000; Zhang *et al.*, 2000, 2001a,b; Burn & Hag Elnur, 2002). In the case that no trend exists within a time series, von Storch (1995) demonstrated that pre-whitening can effectively reduce the effect of serial correlation on the MK test. Should a trend exist in a serially correlated time series, it is not certain whether or not pre-whitening can effectively eliminate the effect of serial correlation on the MK test. Douglas *et al.* (2000) demonstrated that pre-whitening can reduce the detection rate of the significant trend by the MK test. Yue *et al.* (2002b) investigated this issue by simulation experiments where both a trend and an AR(1) process existed in a time series. Their study indicates that pre-whitening a positive AR(1) process will remove a portion of the trend, and hence leads to an acceptance of the null hypothesis of no trend while the null hypothesis might be false.

In order to more effectively reduce the effect of serial correlation on the MK test, a modified pre-whitening procedure, termed trend-free pre-whitening (TFPW), was proposed by Yue *et al.* (2002b). A detailed description of this approach is given below.

This study further demonstrates theoretically the ability of pre-whitening to eliminate the effect of serial correlation on the MK test when a trend exists in a time series. The MK test with the TFPW procedure (TFPW-MK) is applied to assess the site significance of trends in three Canadian flow regimes, namely annual minimum, mean, and maximum daily flows of three time frames: 1967–1996, 1957–1996 and 1947–1996.

Similar to the existence of serial correlation in a time series, the presence of positive cross-correlation in a network will inflate the rate of rejecting the null hypothesis of no field significance of trends while it is true (Douglas *et al.*, 2000). The present study proposes an additional bootstrap test, which is similar in spirit to the method of Douglas *et al.* (2000), to assess the field significance of upward and downward trends separately in the above flow regimes over the whole country. This method is also presented below. Next, the proposed approaches are applied to assess the significance of trends in the streamflow data and the final section summarizes the results of the study.

METHODOLOGY

Site significance test with the trend-free pre-whitening (TFPW)

The ability of pre-whitening to eliminate the effect of serial correlation on the MK test Yue *et al.* (2002b) documented by Monte Carlo simulation that when both trend and AR(1) processes exist in a time series, removal of the AR process by von Storch's pre-whitening will remove a portion of the trend. By assuming that a time series consists of a linear trend ($T_t = \beta \cdot t$) and an AR(1) process ($A_t = \rho_1 \cdot A_{t-1} + \varepsilon_t$, where ρ_1 is the lag-one serial correlation coefficient and ε_t is a noise) with a noise as follows:

$$X_t = T_t + A_t \tag{1}$$

The series is pre-whitened by von Storch' s approach as:

$$X'_t = X_t - \rho_1 X_{t-1} \tag{2}$$

By rewriting equation (2) as:

$$\begin{aligned} X'_t &= \beta t + A_t - \rho_1[\beta(t-1) + A_{t-1}] = (1-\rho_1)\beta t + A_t - \rho_1 A_{t-1} + \rho_1\beta \\ &= (1-\rho_1)\beta t + \varepsilon_t + \rho_1\beta \end{aligned} \tag{3}$$

it can be seen that the AR(1) process no longer exists in the pre-whitened series and pre-whitening does remove the AR(1) process from the series. However, the slope of the pre-whitened series is $\beta' = (1-\rho_1)\beta$, which is no longer equal to the true slope, β. If $\rho_1 > 0$, then $|\beta'| < |\beta|$, i.e. removal of positive AR(1) by pre-whitening will remove a portion of trend. If $\rho_1 < 0$, then $|\beta'| > |\beta|$, i.e. removal of negative AR(1) by pre-whitening will inflate the existing trend. Therefore, when trend does exist in a time series, pre-whitening is not suitable for eliminating the influence of serial correlation on the MK test.

From equation (1), one can see that if a trend is evident and if the trend can be approximated by a linear trend, then removing the trend first cannot affect the existing AR(1) process. The simulation study of Yue *et al.* (2002b) also demonstrates the above points. That is, (a) the existence of a trend will contaminate the estimate of serial correlation while the presence of an AR process can not affect the estimate of the slope of the trend, and (b) removal of the trend as the first step will not affect the true AR process within a time series while eliminating the influence of the trend on the estimate of an AR process. Based on these results, Yue *et al.* (2002b) proposed the TFPW procedure, which is outlined in the following subsection.

Trend-free pre-whitening The TFPW-MK procedure of Yue *et al.* (2002b) is applied in the following manner to detect a significant trend in a serially correlated time series.

1. The slope (β) of a trend in sample data is estimated using the approach proposed by Theil (1950) and Sen (1968). The original sample data X_t were unitized by dividing each of their values with the sample mean $E(X_t)$ prior to conducting the trend analysis (see Yue *et al.*, 2002b). By this treatment, the mean of each data set is equal to one and the properties of the original sample data remain unchanged. The trend is assumed to be linear, and the sample data are detrended by:

   $$Y_t = X_t - T_t = X_t = \beta \cdot t \qquad (4)$$

2. The lag-1 serial correlation coefficient (r_1) of the detrended series Y_t is computed (see Salas *et al.*, 1980). If r_1 is not significantly different from zero, the sample data are considered to be serially independent and the MK test is directly applied to the original sample data. Otherwise, it is considered to be serially correlated and pre-whitening is used to remove the AR(1) process from the detrended series as follows:

   $$Y'_t = Y_t - r_1 \cdot Y_{t-1} \qquad (5)$$

   The residual series after applying the TFPW procedure should be an independent series.

3. The identified trend (T_t) and the residual Y'_t are combined as:

   $$Y''_t = Y'_t + T_t \qquad (6)$$

   The blended series (Y''_t) just includes a trend and a noise and is no longer influenced by serial correlation. Then the MK test is applied to the blended series to assess the significance of the trend.

A bootstrap test for assessing the field significance of trends

Douglas *et al.* (2000) developed a bootstrapping approach with preserving the cross-correlation among sites in a network to eliminate the effect of cross-correlation on the assessment results. In their method, an empirical cumulative distribution of the regional average of the MK statistics (S) is obtained by bootstrapping sample data. If both upward and downward trends exist within a network, they will cancel each other in the calculation of the regional average MK statistic S. Thus, the approach proposed by Douglas *et al.* (2000) might be suitable only for the case that the majority of trends within a network show uniform, i.e. either upward or downward. In the case that both upward and downward trends exist, it is desirable to assess the field significance of upward and downward trends over the network separately.

This study proposes an additional bootstrapping approach that is similar in spirit to the method of Douglas *et al.* (2000). However, rather than using the regional average of the MK statistic (S) as an indicator for representing the field significance of trends, the additional approach assesses the field significance of upward and downward trends separately over a region. This facilitates the detection of an anomalous number of upward and downward trends. The approach is described as follows:

(a) The selected calculation period or range of years, for example [1967, 1968, 1969, ..., 1996] is resampled randomly with replacement. Then a new set is obtained with different year order from the original one but with the same length, for instance [1978, 1978, 1969, 1996, 1988, …, 1974].

(b) Each site within a network has an observation value corresponding to a calendar year. By rearranging the observation values of each site of the network according to the new year set obtained in step (a), a new network can be obtained.

(c) The MK statistic and the corresponding P value (p) at each site are computed (see Yue *et al.*, 2002a). At the significance level of α (= 0.05), the number (N^*_{up}) of sites with significant upward trends and the number (N^*_{down}) of sites with significant downward trends ($p \le 0.05$) of the network can be counted.

(d) By repeating steps (a)–(c) B (= 1000) times, B number of N^*_{up} ($N^{*1}_{\text{up}}, N^{*2}_{\text{up}}, N^{*3}_{\text{up}}, \ldots, N^{*B}_{\text{up}}$) and N^*_{down} ($N^{*1}_{\text{down}}, N^{*2}_{\text{down}}, N^{*3}_{\text{down}}, \ldots, N^{*B}_{\text{down}}$) of the network, respectively, can be obtained. Then the bootstrap empirical cumulative distributions (BECDs) of the numbers of upward and downward trends can be estimated by:

$$P^*\left(N^* \le N^{*r}\right) = \frac{r}{B+1} \qquad \left(N^* = N^*_{\text{up}}, N^*_{\text{down}}\right) \tag{7}$$

where r is the rank of N^{*r} in the bootstrap sample data according to the ascending order. The probability value of the number ($N^{\text{up}}_{\text{obs}}$) of significant upward trends for the real network can be assessed by comparing the number ($N^{\text{up}}_{\text{obs}}$) with the BECD, i.e. $P_{\text{obs}} = P^*\left(N^{\text{up}}_{\text{obs}} \le N^{*r}\right)$. The corresponding P value (p_F) is given by:

$$p_F = \begin{cases} P_{\text{obs}} & \text{for } P_{\text{obs}} \le 0.50 \\ 1.0 - P_{\text{obs}} & \text{for } P_{\text{obs}} > 0.50 \end{cases} \tag{8}$$

At the significance level of 0.05, if $p_F \le 0.05$, then the trend over a network is judged to be field-significant. Similarly, the field significance of downward trends for the network can be evaluated. In the above procedure, if one directly resamples the sample data at a site rather than the year series as in steps (a) and (b), then the BECD without preserving cross-correlation structure of a network can be obtained.

APPLICATION

The streamflow observation stations for this study are from the Reference Hydrometric Basin Network (RHBN) database, which is a network of streamflow and water level stations across Canada (Environment Canada, 1999; Pilon & Kuylenstierna, 2000). The basins in RHBN are identified to have either pristine or stable hydrological conditions, with more than 20 years of good quality record.

Suitability of linear approximation to monotonic trends

This study uses a linear trend to approximate the monotonic changes in Canadian streamflow data should such changes exist. To investigate the suitability of the linear trend approximation, visual observation was done by plotting streamflow data against their occurrence year. The visual inspection shows that a linear trend is a reasonable approximation to a monotonic trend when it exists. For the purpose of illustration,

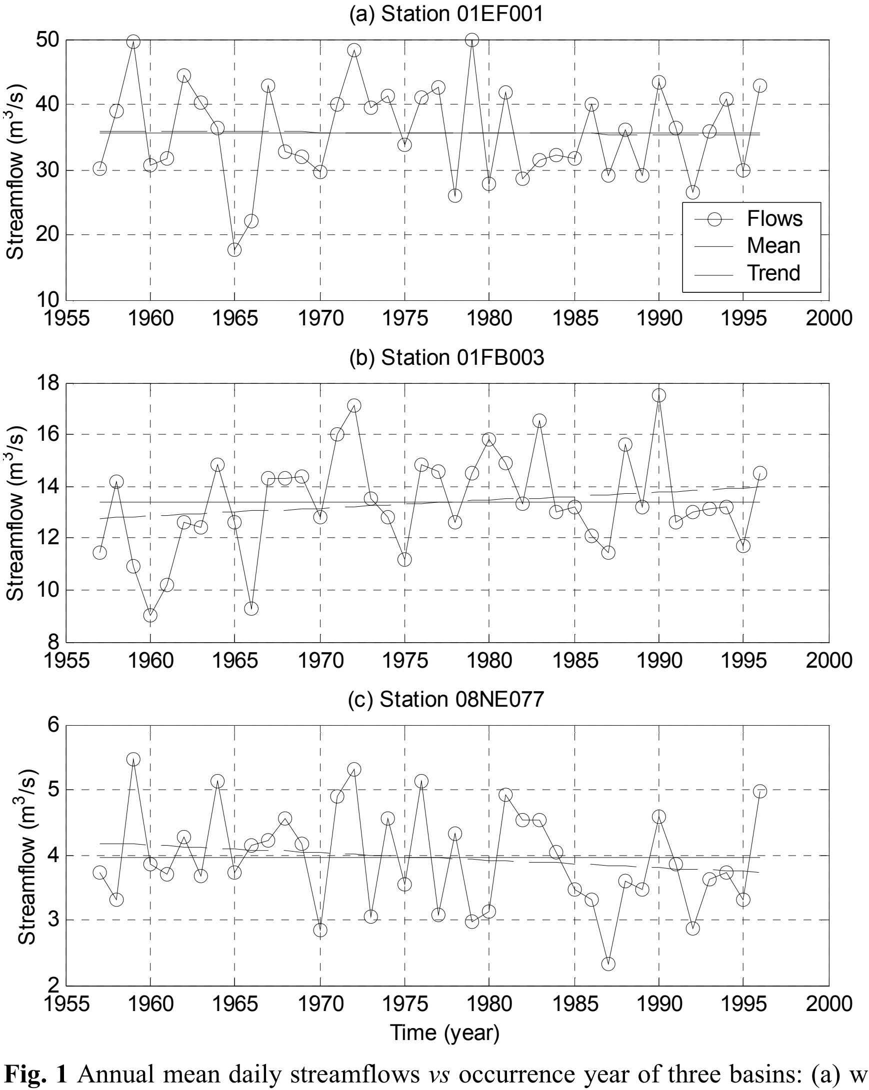


Fig. 1 Annual mean daily streamflows *vs* occurrence year of three basins: (a) without trend; (b) with upward trend; and (c) with downward trend.

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

Data set	Variables	Number of sites	Positive serial correlation: Before TFPW	After TFPW
1967–1996	Minimum	148	47	0
	Mean	139	23	1
	Maximum	149	17	0
1957–1996	Minimum	71	22	0
	Mean	63	16	0
	Maximum	75	5	0
1947–1996	Minimum	37	12	0
	Mean	33	3	0
	Maximum	42	2	0

annual mean daily streamflows with 40-year records at station 01EF001 almost without trend, at station 01FB003 with upward trend, and at station 08NE077 with downward trend are displayed in Fig. 1(a)–(c), respectively.

To demonstrate the ability of the TFPW procedure to remove an AR(1) component, the number of sites with statistically significant positive lag-1 serial correlation coefficient at the significance level of 0.05 for the one-tailed test (Salas *et al.*, 1980) before and after applying the TFPW are presented in Table 1. Only a few stations were found to have statistically significant negative serial correlation and are not presented. It can be seen that the TFPW procedure effectively removes the AR(1) component from the data.

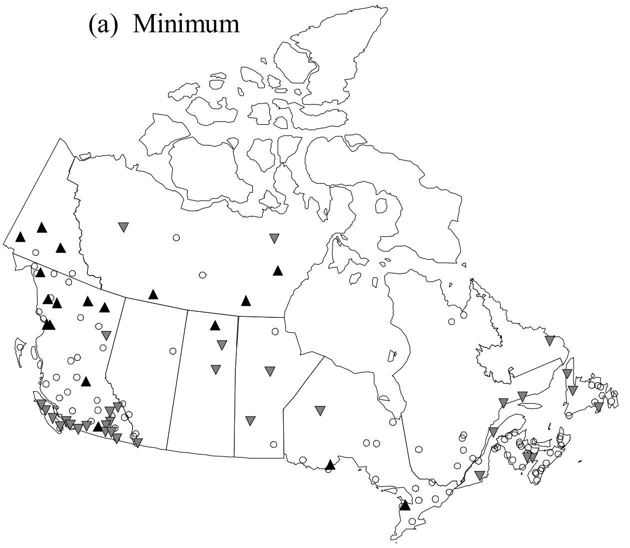
Site significance assessment

The MK test with the TFPW procedure (TFPW-MK test) was applied to assess the site significance at the significance level of 0.05 of trends in annual minimum, mean, and maximum daily flows for 30-, 40-, and 50-year periods, all ending in 1996. Table 2 presents the number of available sites and the percentages of the number of sites with significant upward and downward trends for these data sets. These results are different from those of Zhang *et al.* (2001a), who assessed significance of trends in the same data sets by the MK test with von Storch's pre-whitening. The difference is especially evident in the percentage of sites with significant upward trends in annual minimum daily flow. The results of Zhang *et al.* (2001a) are considerably lower than the assessment results of the present study. The possible reason is that they employed von Storch's pre-whitening procedure to remove AR(1) processes prior to applying the MK test, and pre-whitening removed a part of the existing trend, as explained above.

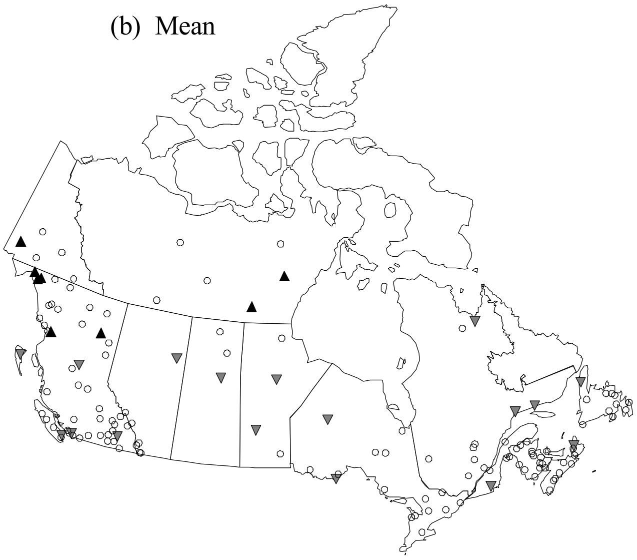
Table 2 Percentage of basins with significant upward and downward trends at the significance level of 0.10.

Variables	1967–1996: Number of sites	Up	Down	1957–1996: Number of sites	Up	Down	1947–1996: Number of sites	Up	Down
Minimum	148	12.2	23.0	71	16.9	16.9	37	24.3	16.2
Mean	139	5.8	12.2	63	12.7	9.5	33	6.1	9.0
Maximum	149	2.0	16.8	75	6.7	13.3	42	4.8	26.2

(a) Minimum



(b) Mean



(c) Maximum

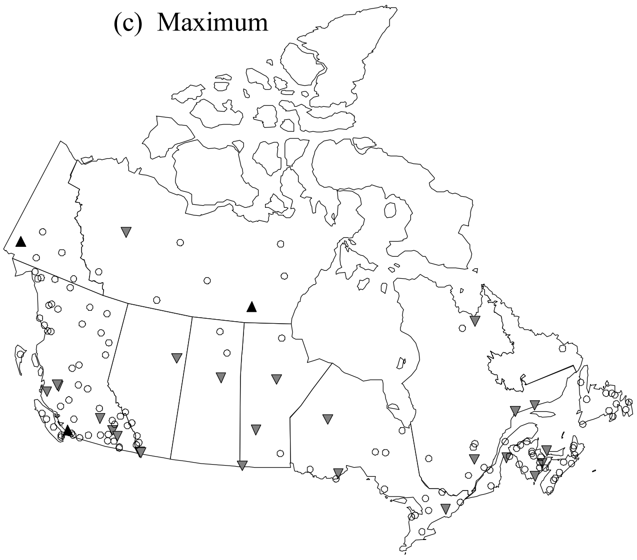


Fig. 2 Spatial illustration of significant trends in 30-year time frame flows: (a) minimum; (b) mean; and (c) maximum. See text for explanation of symbols.

Table 2 indicates that for all the three time frames, the percentages of sites with both significant upward and downward trends in annual minimum daily flows and the percentages of sites with significant downward trends in annual maximum daily flows are quite different from the expected number at the significance level of 0.05, which is based on the binomial distribution theory without consideration of cross-correlation among the sites within the observation network (Bulmer, 1979). It may be inferred that some significant changes occurred in some regions. To look for the spatial pattern of possible changes, the sites with significant trends are illustrated in the geographic maps. Only the spatial distribution of significant trends in annual minimum, mean, and maximum daily flows with 30-years (1967–1996) is shown in Fig. 2, due to space limitations. On the maps, a circle, an upward-pointing triangle, and a downward-pointing triangle represent a station with no significant trend, with significant upward trend, and with significant downward trend, respectively. Figure 2(a) shows that annual minimum daily streamflow significantly decreased in the regions of southern British Columbia (BC), around the centre of Prairie Provinces (Alberta (AB), Saskatchewan (SK), and Manitoba (MB)) and in Atlantic provinces (New Brunswick (NB), Nova Scotia (NS), Newfoundland (NF), and Prince Edward Island (PE)), and significantly increased in the region of northern BC and Yukon territory (YT). Figure 2(b) indicates that annual mean daily streamflow experienced almost the same spatial changes as annual minimum daily streamflow. In Fig. 2(c) it can be seen that annual maximum daily streamflow significantly decreased across southern Canada (south to the latitude 60°N).

The spatial change patterns in 40-year annual minimum, annual mean, and annual maximum daily streamflows are similar to those in 30-year data. However, an upward trend pattern in annual minimum flow with 40-year records emerged along the southern border of Ontario near the Great Lakes. The annual minimum flow with 50-year records does not show any spatial trend patterns as there are only 37 observation stations available across the whole country. The annual mean and maximum flows of 50-year records display the same tendency as those in 30-year data while the available stations are fewer.

Field significance of trends

The presence of cross-correlation in a network will affect the ability of a test to assess the field significance of trends over the network. The cross-correlation coefficient between two sites can be computed using the formula in Salas *et al.* (1980). The histograms of the cross-correlation coefficients among the sites of annual minimum, mean, and maximum daily flows of three time frames: 1967–1996, 1957–1996 and 1947–1996 were plotted. From these diagrams it could be seen that the number of pairs of sites with positive cross-correlation is much greater than that with negative cross-correlation and that positive cross-correlation dominates the streamflow observation network. For the purpose of illustration, only the histograms of the time frame from 1967 to 1996 are displayed in Fig. 3.

The bootstrap test with preserving the cross-correlation structure in the network and with the TFPW to remove serial correlation at sites was applied to assess the field significance of trends in the three flow regimes over the whole country. For the purpose of illustration, the BECDs of the number of significant upward and downward

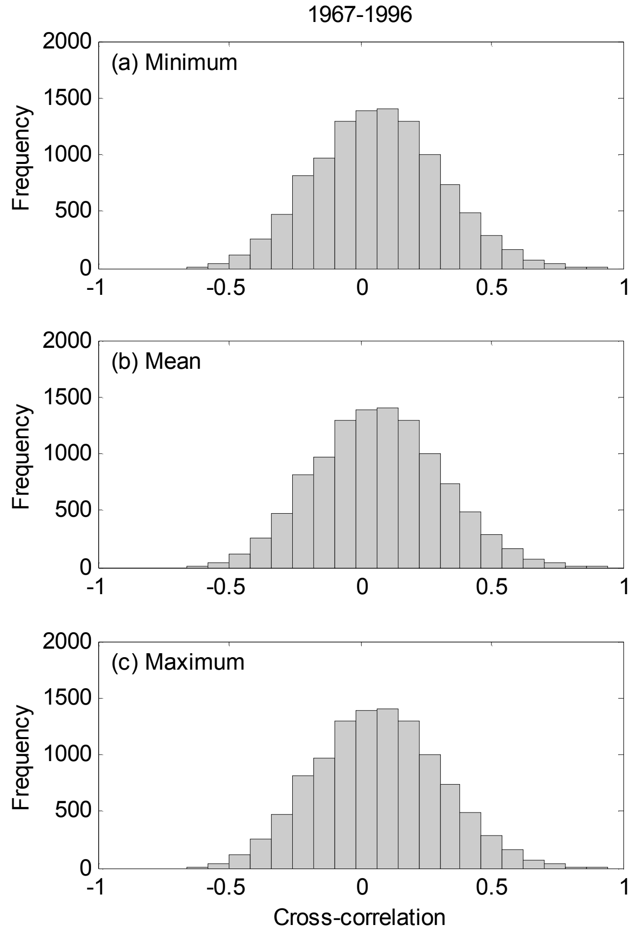


Fig. 3 Histograms of cross-correlation coefficients of the network for the time frame 1967–1996: (a) minimum; (b) mean; and (c) maximum.

trends for the annual minimum daily flow from 1967 to 1996, with preserving the cross-correlation structure of the network, are displayed in Fig. 4(a) and (b), respectively. The corresponding BECDs without preserving the cross-correlation structure are illustrated in Fig. 5(a) and (b). By comparing Fig. 4 with Fig. 5, it is evident that the probability distributions of the number of significant upward and downward trends with and without consideration of the effect of cross-correlation are dramatically different in both their magnitude and shape. The field assessment results, i.e. the *P* values given by equation (8), of the test with and without consideration of the effect of cross-correlation are presented in Table 3. Without consideration of cross-correlation and at the significance level of 0.05, the field significance of upward and downward trends in 30- and 40-year annual minimum daily flows was detected, which is marked by the shaded numbers. The field significance of downward and upward trends, respectively in 30- and 40-year annual mean daily flows was identified. The field significance of downward trends in both 30- and 40-year annual maximum daily flows was evaluated. However, with the consideration of the influence of cross-correlation among the sites, none of these flow regimes were assessed to be field-significant at the significance level of 0.05. Only field significance of downward trends was detected in 30-year annual minimum and maximum daily flows in the whole network at the

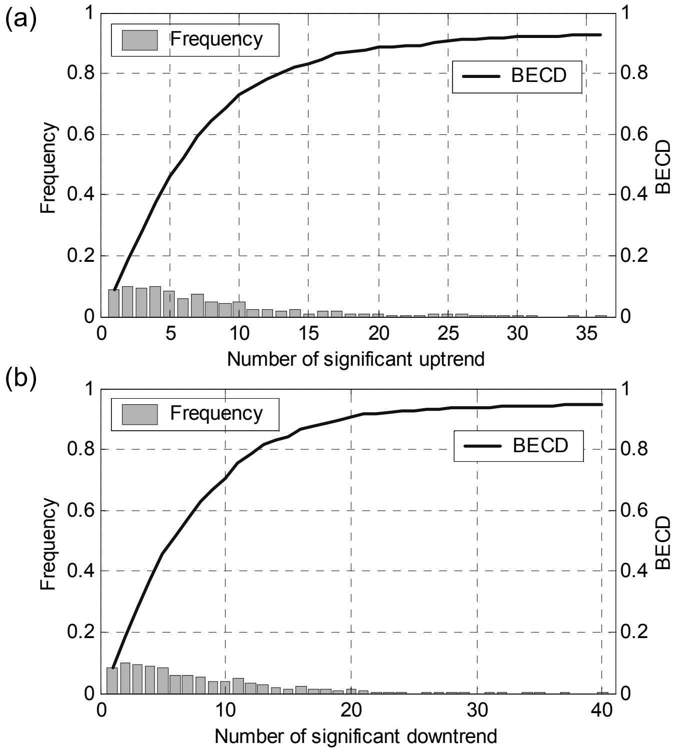


Fig. 4 BECDs of the number of significant trends of 30-year annual minimum daily flows with preserving the cross-correlation structure of the network: (a) upward; and (b) downward.

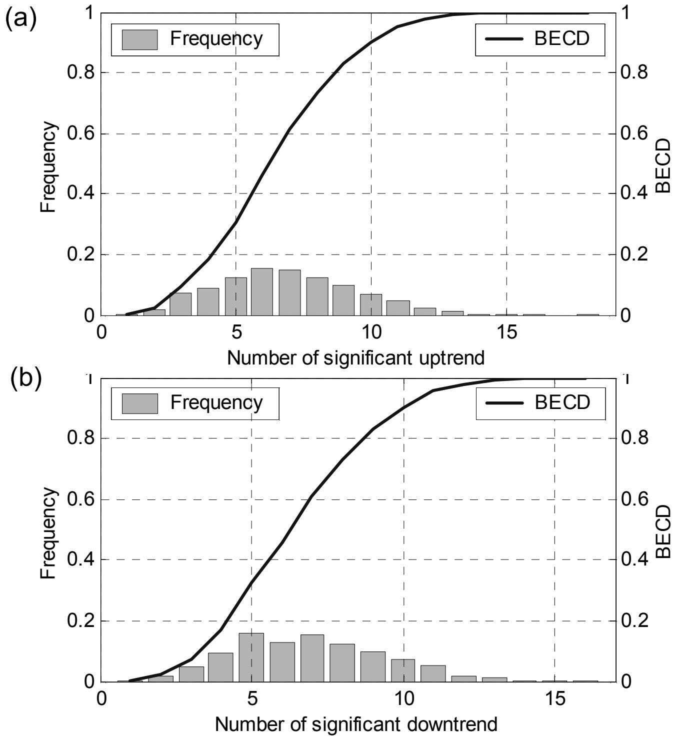


Fig. 5 BECDs of the number of significant trends of 30-year annual minimum daily flows without preserving the cross-correlation structure of the network: (a) upward; and (b) downward.

Table 3 Field significance assessment results by the bootstrap test.

Cases	Variables	1967–1996: Up	1967–1996: Down	1957–1996: Up	1957–1996: Down	1947–1996: Up	1947–1996: Down
With cross-correlation	Minimum	0.12	**0.06**	0.13	0.15	0.31	0.32
	Mean	0.35	0.18	0.30	0.38	0.33	0.40
	Maximum	0.26	**0.06**	0.36	0.18	0.43	0.26
Without cross-correlation	Minimum	0.00	0.00	0.03	0.03	0.16	0.16
	Mean	0.22	0.00	0.05	0.08	0.42	0.27
	Maximum	0.08	0.00	0.18	0.03	0.46	0.13

The shaded and bold numbers respectively indicate significant at the significance levels of 0.05 and 0.10.

significance level of 0.10, which is indicated by the bold numbers. These assessment results are different from those of Zhang *et al*. (2001a), who applied the approach of Livezey & Chen (1983), but without consideration of cross-correlation.

CONCLUDING REMARKS

This paper applied the trend-free pre-whitening (TFPW) procedure to eliminate the effect of serial correlation on the MK test for assessing the site significance of a trend. It also proposed an additional bootstrap test with preserving cross-correlation structure in a network and with the TFPW to remove serial correlation at a site for assessing separately the field significance of upward and downward trends over the network. It was noticed that the BECDs, with and without consideration of cross-correlation within a network, are dramatically different in both their magnitude and shape.

The site significance of trends in annual minimum, mean, and maximum daily flows with 30-, 40-, and 50-year records was assessed by the MK test with the TFPW procedure at the significance level of 0.05. The geographic mapping of the assessment results indicates that the 30-year annual minimum and mean daily flows significantly decreased in the regions of southern British Columbia (BC), around the centre of Prairie Provinces, and in Atlantic provinces, and significantly increased in the region of northern BC and Yukon Territory. An upward trend pattern in annual minimum and mean daily flows of 40-year data emerged along the southern border of Ontario near the Great Lakes. Annual maximum daily streamflow of all three time frames significantly decreased across southern Canada.

The additional bootstrap test was applied to assess the field significance of the upward and downward trends in the three flow regimes over the whole country. At the significance level of 0.05, none of these flow regimes show statistically field-significant trend. At the significance level of 0.10, the field significance of downward trends in 30-year annual minimum and maximum daily flows was detected over the country.

A further investigation of the reasons for the identified spatial patterns of change in streamflow (Fig. 2) may be needed to ascertain the physical attribution of the factors forcing the trends. This aspect is beyond the scope of this paper.

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