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Effect of Short- and Long-term Memory on Trend Significancy of Mean Annual Flow by Mann-Kendall Test

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ABSTRACT

Climate variability and change is threatening water resources around the world. One hundred and fourteen (114) stations from Reference Hydrometric Basin Network (RHBN) around Canada with at least 30 years continuous data (up to 2011) were selected to study the trend in mean annual runoff for different periods of 30 to 100 years in step 10 years by non-parametric Mann-Kendall test. Effect of short term persistent (STP) and long term persistent (LTP) on this test were made through lag 1 serial correlation (ρ_1) and Hurst exponent (H), respectively. ρ_1 for about one third of the total cases considered was negative. H, based on “equivalent Normal deviate” (eNv), was slightly right-skewed with minimum and maximum values of 0.20 and 0.87, respectively. About half of the data sets were anti-persistent ($H<0.5$). No regional pattern was found for ρ_1 and H. Based on five stations with around 100 years data it was shown that ρ_1 and H are unstable for record length, roughly, up to 50 years. ρ_1 and H were highly correlated (r=0.86). H from eNd were smaller than H from original data by around 10% with high correlation (r=0.87). Under classic Mann-Kendall trend test, different time periods of different stations showed different trend direction and significancy, which admits for abrupt change in trend direction and significancy for different time periods. On overall, more than 60% of cases there were no significant trends (i.e. p-value>0.1). The number of positive and negative trend, were nearly the same, though fluctuating for different time spans. p-value after pre-whitening was highly correlated with those of before pre-whitening, for both negative and positive trends. There were about 16% of cases that pre-whitening decreased the p-values of the Mann-Kendall trend test, where nearly all of them were negatively trended. The effect of LTP on Mann-Kendall trend test was minor due to inconsistency of originally significant trend case and significant H of greater than 0.5. For recent 30 years length of record (1982-2011), British Columbia is experiencing positive trend in the west and negative trend in the east. Most parts of the New Brunswick are experiencing the positive trend, while negative trend is due to Southeast of Ontario. For the longer duration of 40 years, trend statistics and geographical pattern were changed. While the significant trends are decreased, more significant negative trends are governed over New Brunswick. There is no positive trend in British Colombia in the past 50 years (1962-2011) while there are both negative and positive trends in New Brunswick which negative trends are switched to positive trends in south east of Ontario. For long duration of > 70 years, there are only positive trends in Southeast of Canada (South New Brunswick and South East of Ontario) while central and east of Canada have experienced a negative trend.

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1. INTRODUCTION

All people need water, forever. So, planning for available water and what it should be in the future is of prime importance [1-2]. The general public has become more aware of climate change and climate variability and their potential impacts on water availability. This has led to greater acceptance of the need for further study and may, in turn, lead to actions to address perceived impacts. Concern has increased that climate change and variability might have impacts on hydrologic extremes (i.e., floods and droughts) as well as affecting the overall level of water availability. This realization has led to greater appreciation of the importance of understanding extremes of water availability and the impact change might have on society, the economy and the environment.

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There are numerous reports in the literature that focused on detecting trends in hydrological time series. It may be postulated that the trend phenomenon is rather region-based. So, 'regional inconsistency' or 'spatial non-uniformity', where neighbouring stations may have significant, yet opposite trends (e.g. [3-4]) demands for more rational explanations [5]. Different researchers were (and are) paying attention to trend of different components of hydrologic cycles, including precipitation [6], temperature [7], evaporation [8], groundwater storage [9], and streamflow [10]. Some other phenomena such as floods [11], seasonal flow [12], low flow [13] and its timing [14] are also acknowledged.

The impacts of climate change and variability on water bodies of importance to Canadians is not well known, with certainty. Several studies [6, 11, 15-22] have investigated trend in the flow of rivers and streams occurring in natural basins across Canada or downstream of hydraulic structures (e.g. [23]). Different aspects of the hydrological regime have also been analyzed, such as seasonal patterns [12], average flow conditions [24] and their extremes (e.g. [11]). These studies have found that different areas display markedly different trends and tendencies in stream flow, and there is no simple description possible for natural rivers and streams across Canada. Individual station results indicate that annual minimum and mean daily flows are increasing significantly in northern British Columbia, Yukon Territory and southern Ontario, with evidence of decreasing tendencies concentrated in southern British Columbia. Studies show that maximum flows are tending to decrease significantly across most of Canada, similar to those reported for the U.S. by Lins and Slack [10]. In essence, changes are occurring, but not in simple ways. However, most of the researches on mean annual flow have not been focussed on the country as a whole, while the record lengths in different studies differ to some extent, which hinder a sound conclusion. River flow characteristics are highly dependent to other climatic forcing such as precipitation, temperature, evaporation. However, these forcing may undergo different trends so river characteristics may not be predicted with certainty. As an example, increasing in temperature may melt the ices and so increase the runoff [25] or not [26] while increases the evaporation. It may decrease the runoff [2] and cancel the effect of increase in precipitation (e.g. [1]).

Diagnostic studies require statistical testing methodologies. There has been a tendency to develop increasingly sophisticated approaches that more fully address limitations of earlier approaches and allow spatial inferences to be made. These approaches have led to an increased understanding of the patterns of trend in streamflow [5, 14, 15, 17, 18, 20, 21]. However, the number of sites in various hydrological networks available for diagnostic studies is decreasing. Statistically based diagnostic studies require networks with long-term stations with adequate geographical coverage to provide the capacity to discern whether a trend is or is not occurring and where a trend might be occurring [20]. Long-term data are needed to depict and separate accurately the characteristics of natural climate variability from climate change. Literature addresses many statistical tests to manifest trend in time series. However, among them, Mann-Kendall is more widely used, which is based originally for stationary series. In the context of loose stationarity (e.g. [27]), this test, and other similar ones, needs modification. Such a modification may be done at two different levels, i.e. under short term persistence (STP), which is due to positive serial correlation and long term persistence (LTP), which demands for cyclic persistence in the data commonly exhibited through Hurst exponent. Two opportunities are available for the first case, which are pre-whitening (e.g. [28]) and modification of the trend test (e.g. [29]). However, for the second case, the variance of the test statistics should be adjusted, commonly through variance inflation factor (e.g. [5]).While the first issue (i.e. effect of STP) is well documented in hydrological researches, there are only a few documents available which handle the effect of LTP on Mann-Kendall trend test. Hamed [5] and Villarini et al. [30] focused on river streamflow around the world, and USA, respectively. Ehsanzadeh and Adamowski [14] considered low flow timing of Canadian rivers. Ehsanzadeh et al. [4] analyzed the river flows ending to lake Winnipeg.

So, the main trust of this paper is on a focus on trends in mean annual flows of Canadian rivers, considering the effects of STP and LTP.

2. HYDROMETRIC STATIONS

Reference Hydrometric Basin Network (RHBN) [31, 32] is the most valuable data source for Canadian streamflow data. The majority of researches have been conducted by these data (e.g. [4, 28]. This network has decreased in size from its original design and currently contains 200 plus stations representing basins with at least 20 years of record under stable or pristine conditions [33] with minimal anthropogenic influences. Hydrometric stations within the RHBN, are of particular importance for studies oriented to climate variability and change. However, analysis of the characteristics of stations indicates certain limitations. The network tends to be composed of large basins in the north and smaller basins in the south, with certain provinces having large gaps in spatial coverage, especially there are no RHBN stations north of 70°N latitude. This underscores the importance of long-term continued funding to targeted hydrological data collection for monitoring ambient conditions, and the need to supplement the current network to allow smaller basins to be brought on-line in the North and to fill major geographic gaps.

Trend analysis and detection needs to long record length of selected stations with complete data sets. Not all stations have complete and continuous data. So, we restricted themselves to a minimum of the latest 30 years, which accounts for 114 RHBN stations up to 2011. Yet, data for some of the stations ends at 2010. The mean and median of record lengths are 51 and 46, respectively. There were 44 (9) stations with a minimum record length of 50 (90) years (Table 1). The majority of stations (109 out of 114, 96%) are located south of 60°N latitude (Figure 1).

TABLE 1. Number of RHBN stations in different record length classes

Length records greater than:							
29	39	49	59	69	79	89	99
114	90	44	28	12	12	9	1

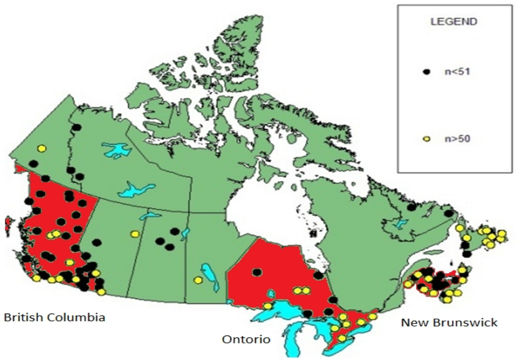


Figure 1. Selected RHBN stations for trend analysis in mean annual flow. British Colombia, Brunswick and Ontario are highlighted in red color.

3. 1. Original Mann-Kendall Trend Test

The Mann–Kendall trend test [34-35] is non-parametric and is based on the correlation between the ranks of a time series and their time order. For a time series $X=\{x_i, i-1:n\}$, the test statistic is given by

$$S=\sum_{i<j} sign(x_j-x_i)=\begin{cases}1 & x_j<x_i\\ 0 & x_j=x_i\\ -1 & x_j>x_i\end{cases} \tag{1}$$

Under the assumption that the data are independent and identically distributed, the mean of the S statistics equals to zero and its variance, corrected for tied ranks or equal observations, is given by [35]:

$$V_0(S)=18^{-1}n(n-1)-\sum_{j=1}^{m}18^{-1}t_j(t_j-1)(2t_j+5) \tag{2}$$

where, m is the number of groups of tied ranks, each with t_j tied observations. S is asymptotically normally distributed. So, the significance of trends can be tested by comparing the standardized variable u (one unit is subtracted or added due to continuity correction) with the standard normal variate at any significance level α [35].

$$u=\frac{S-sign(S)}{\sqrt{V_0(S)}} \tag{3}$$

3. 2. Modification of Mann-Kendall Trend Test due to STP

We adopted simple pre-whitening of von Storch [36] to account for serial correlation which used by many researchers, including Zhang et al. [28]. Each time series is pre-whitened if lag 1 serial correlation (ρ) is greater than 0.1. Thus, time series $X=\{x_i, i=1:n\}$ will be corrected to $X_c=\{(x_i-\rho x_{i-1}), i=1:n\}$. Then, the original Mann-Kendall trend test is applied to X_c time series.

3. 3. Modification of Mann-Kendall trend test due to LTP

LTP is commonly identified by the so called Hurst exponent, H, which is the scaling coefficient of historical time series, X_t. The log-likelihood function of n Normal observations with a scaling coefficient H is given by [37]:

$$\log L(\mu,\gamma_0,H)=-\tfrac{1}{2}\log|C_n(H)|-\frac{(X-\mu)^T[C_n(H)]^{-1}(X-\mu)}{2\gamma_0}-\tfrac{n}{2}\log\gamma_0 \tag{4}$$

where, γ_0 is the variance of X_t and $C_n(H)$ is an $n\times n$ correlation matrix for a given scaling coefficient H whose elements for every i and j between 1 and n is equal to:

$$\rho_{|j-i|}=\rho_\ell=\tfrac{1}{2}\left((\ell+1)^{2H}-2\ell^{2H}+(\ell-1)^{2H}\right) \tag{5}$$

To solve (4) in a recursive manner, first ML estimates of mean μ and variance γ_0 for a fixed H is advised [37], as follows:

$$\begin{cases}\hat{\mu}=\left\{X^T[C_n(H)]^{-1}1\right\}/\left\{1^T[C_n(H)]^{-1}1\right\}\\ \hat{\gamma}_0=n^{-1}S(\hat{\mu},H)\end{cases} \tag{6}$$

where, $S(\hat{\mu},H)$ is the numerator of the middle term in RHS of Equation (4). Then, Equation (4) is relaxed to:

$$\log L_{max}(H)=-\tfrac{1}{2}\log|C_n(H)|-\tfrac{n}{2}\log\left(\frac{S(\hat{\mu},H)}{n}\right) \tag{7}$$

To learn the effect of LTP on Mann-Kendall test, Hamed [5] introduced the 'equivalent Normal variate' concept in the form of

$$Z_t = \Phi^{-1}\left(\frac{R_t}{n+1}\right) \tag{8}$$

where, R_t is the rank of de-trended observation x_t, and $\Phi^{-1}(\cdot)$ is the inverse standard Normal distribution function. The algorithm of McLeod and Hipel [37] may be simplified since mean and variance of Z is constant, so the log-likelihood function of Equation (4) can be relaxed to:

$$\log L(H) = -\tfrac{1}{2}\log\left|C_n(H)\right| - \frac{Z^T\left[C_n(H)\right]^{-1}Z}{2\gamma_0} \tag{9}$$

The estimated H is approximately Normally distributed which its mean and standard deviation are depend only on n, and can be estimated from $\mu_H = 0.5 - 2.874n^{-0.9067}$ and $\sigma_H = 0.7765n^{-0.50} - 0.0062$, respectively [5]. So, a significancy test in the form of H_0:H=0.5 against the alternative hypothesis H_1:$H \neq 0.5$ can be easily advised. Once Hurst exponent, H, is significantly greater than 0.5, the variance of Mann-Kendall trend test, which now also depends on H, should be computed as follows [5]:

$$V(S) = \sum_{i<j}\sum_{k<l}\tfrac{2}{\pi}\sin^{-1}\left(\frac{\rho_{jl}-\rho_{il}-\rho_{jk}+\rho_{ik}}{\sqrt{(2-2\rho_{ij})(2-2\rho_{kl})}}\right) \tag{10}$$

where, all subscripts of i, j, k, and l are due to the interval of 1:n. Upon correction of the variance, Equation (3) is advised to conduct a significancy test for trend.

3. 4. Trend Analysis The trend tests were done for each station and for different record lengths of the most recent 30, 40, … years under original Mann-Kendall trend test and its corrected versions considering ST and LT, as discussed above. All tests were made for different significancy levels of 0.10, 0.05, and 0.025.

4. RESULTS AND DISCUSSION

4. 1. Specifications of STP and LTP Lag 1 serial correlation coefficient (ρ_1) of equal to 0.1 is adopted as a suitable measure of short-term memory [14, 28, 38]. Among the 408 cases of time series with the most recent record lengths of 30, 40, 50, … years, there were 135 (33%) and 273 (67%) cases corresponding to negative and positive lag-1 serial correlation, respectively. This pattern was nearly the same for all time periods (Table 2). While it is possible to obtain a negative autocorrelation in a statistical point of view, observed negative autocorrelation may be attributed to different unknown or known factors including measurement errors. Although negative serial correlation may not have a physical meaning in reality, it is not uncommon to observe them in hydrologic time series. Rivard and Vigneault [39] declared that 'while conducting a project on trend detection using streamflow and base-flow series across Canada, it was observed that some significant trends were negative, and their number was much higher than it had been expected'. Arnell et al. [40] reported that out of 112 catchments across the UK with a common record length of only 20 years at annual scale, 1 and 12 catchments showed significant negative and positive serial correlation coefficients, respectively, at 5% significance level. At seasonal scale (winter, spring, summer, autumn), there were 0, 1, 0, 7 for negative serial correlation, as compared to 2, 2, 14, and 14 for positive serial correlations. Fanta et al. [41] analyzed river flow data of 502 gauging stations from nine southern African countries with a relatively short data. The minimum record length was just 15 years, about 191 stations had record length of greater than 30 years and only very few stations were of length greater than 50 years. Out of these data sets, Fanta [42] showed that about 160 stations (32%) have negative serial correlation with a minimum of -0.5. Relative percentages of negative and positive serial correlations for the above literature are in harmony with those of ours. On the other hand, Ehsanzadeh and Adamowski [14], who studied the trends in timing of low stream flows in Canada, reported somewhat greater percentages for negative serial correlations (Table 2). Record length of the stations used by Ehsanzadeh and Adamowski [14] are shorter than ours, which based on their report are between 16 and 92 years (up to 2003). Many of the hydrologic statistics, including serial correlation, are rather sensitive to record length, while they are highly unstable at short record length.

TABLE 2. Dependency of sign of lag 1 serial correlation (ρ_1) to length of record.

Record length up to 2011	Total of cases	$\rho_1<0$	$\rho_1>0$
30	114	43 (38)[+]	71 (62)
40	90	36 (40)	54 (60)
50	44	9 (20)	35 (80)
60	28	7 (25)	21 (75)
70	12	4 (33)	8 (67)
80	12	5 (42)	7 (58)
90	9	3 (33)	6 (67)
100	1	0 (0)	1 (100)
overall	408	135 (33)	273 (67)
a[++]	201	92 (46)	108 (54)
b	192	109 (57)	83 (43)

[+] Percentage of the cases corresponding to its record length.

[++] 'a' and 'b' are Summer and Winter 7-day low flows, respectively (Ehsanzadeh and Adamowski, 2010; [14]).

There was no geographical pattern for lag 1 serial correlation across the Canada (Figure 2). Ehsanzadeh and Adamowski [14] also could not find any regional pattern for positive/negative of timing of summer/winter 7-day low flows across the Canada. Over the continental of Canada, ρ_1 showed a rather weak correlation (r=-0.3) with record length, which was computed based on average ρ_1 values corresponding to different classes of record length (Figure 3). One may expect for unstable hydrologic parameters under short record length. So, how lag1 serial correlation stabilizes for increasingly record length, is shown in Figure 4 for 5 stations with the highest record length of more than 95 years. However, avoiding implementation of rigorous statistical tests, it seems that nearly all ρ_1s are going to be stabilized after 50 years.

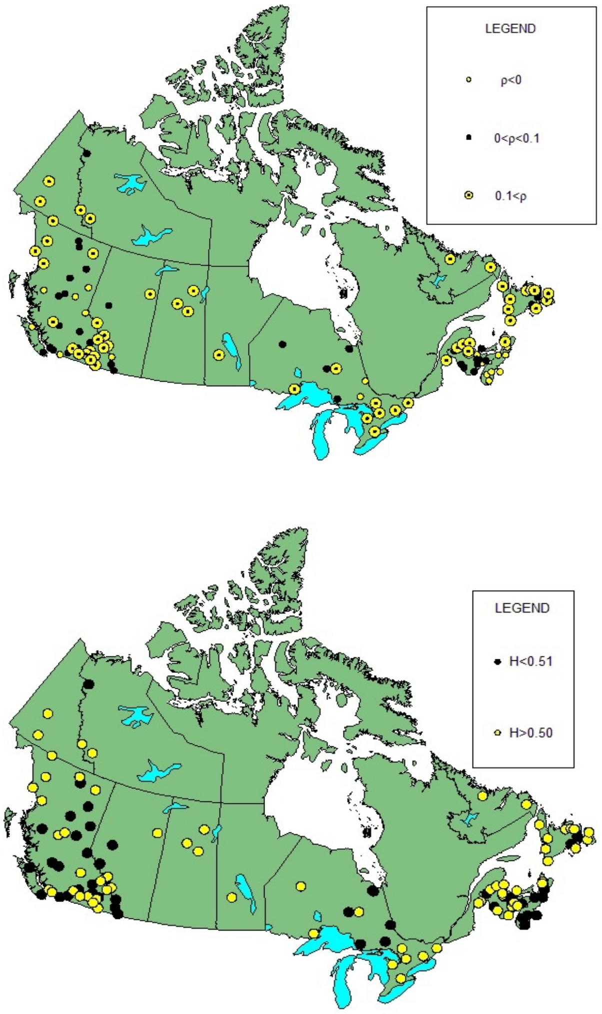


Figure 2. Geographical pattern for lag 1 serial correlation (top) and Hurst exponent (bottom) of mean annual flow time series across Canada.

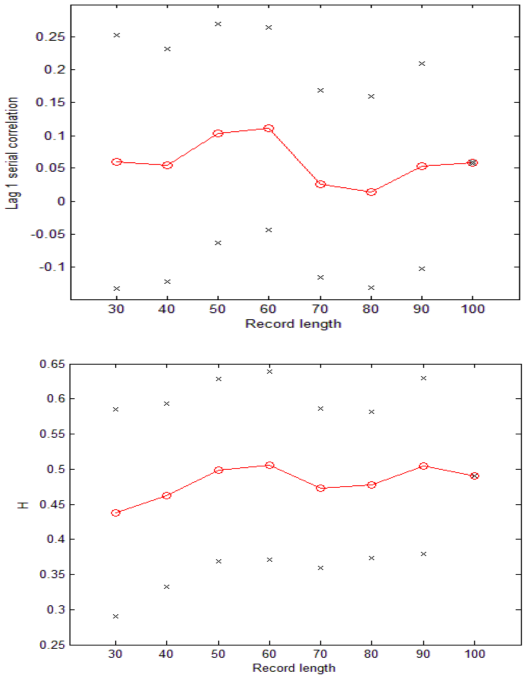


Figure 3. Average of ρ_1 values (top) and H values (bottom) (both shown by curve in red) for different record length classes for Canadian RHBN stations. Upper and lower x-marks for each record length class shows average ρ_1/H value ± 1 standard deviation

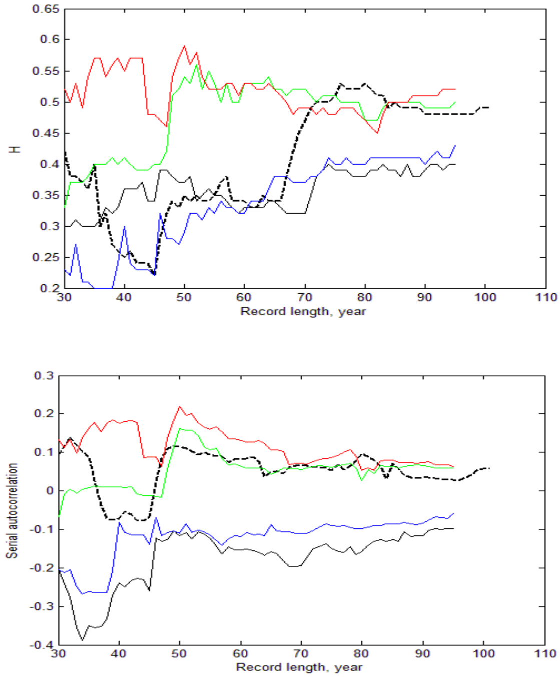


Figure 4. Variation of Hurst exponent (top) and lag 1 serial autocorrelation (bottom) for annual runoff data of five RHBN Canadian dataset (05BB001, dotted black; 01EF001, black; 01EO001, blue; 02EA005, green; 02EC002, red) to variable record lengths ending 2010/2011.

Hurst exponent, as a measure for long-term memory of a hydrologic process, was computed based on “equivalent Normal deviate” concept of Hamed [5]. The average (median) of *H* values was 0.47 (0.48). Thus, about half of the data sets are anti-persistent (H<0.5), while the other 41% of the data sets, were greater than 0.5 with an average of 0.60. This average value is partially supported by Hurst [43], who found that *H* was greater than 0.5 for many geophysical time series, with values typically around 0.7. The minimum and maximum value of *H* was 0.20 and 0.87, respectively. The frequency distribution of *H* was slightly right-skewed (Figure 5). Our results can be supported by the literature. From monthly data for 30 catchments with at least 30 years of record in UK, Arnell et al. [40] reported that calculated Hurst coefficients ranged from 0.54 to 0.75 with a mean of 0.65. Hamed [5] analyzed total annual river flow series for 35 stations from different parts of the world with minimum (maximum) length of records was 37 (179) with an average of around 75 years. About two thirds of the stations showed persistence behaviour, while the other one third was anti-persistent with as low as 0.33. Average and maximum of persistent *H* values were 0.63 and 0.83, respectively, which are completely supported by our results. Another support is due to Villarini et al. [30] who studied the stationarity of flood peaks for 50 stations with minimum record length of 100 years in the continental USA. Their reported *H* values were nearly normally distributed with a mean of about 0.55. Nineteen stations (38%) showed anti-persistence with a minimum and average of 0.21 and 0.43, respectively. While the other 28 stations (56%) were persistent with a mean and maximum of 0.63 and 0.85, respectively. However, all these findings are quite similar to ours. On the other hand, Ehsanzadeh and Adamowski [14], reported much higher values for Hurst exponent for the timing of summer and winter low stream flows in Canada. They used only those stations with record length of at least 50 years, which was 44 and 46 for summer and winter stream flows, respectively. For summer time, 40 stations showed LTP, from which *H* values for 30 stations (75%) were higher than 0.9. On the other hand, all winter stations followed LTP and were higher than 0.9. We could not justify such high values in literature, however.

There were no spatial pattern for persistent (H>0.5) and anti-persistent (H<0.5) stations across the Canada (Figure 2). The pattern is very similar to that of lag 1 serial correlation considering the two classes of negative and positive correlation, which admits for high correlation between these two parameters (Figure 6). Over the continental of Canada, *H* showed a rather weak correlation (r=0.6) with record length, which was computed based on average *H* values corresponding to different classes of record length, in the form of $\overline{H} = 0.444 + 5.69e^{-4}N$ (Figure 3), which is supported by low correlation (r=0.13) for data of Villarini et al. [30]. One may expect for unstable hydrologic parameters under short record length. So, how Hurst exponent stabilizes for increasingly record length, is shown in Figures 4 for 5 stations with highest record length. As was shown for lag 1 serial correlation, after about 50 years, roughly speaking, *H* values are being stabilized. Hurst exponent, computed based on equivalent Normal variate concept showed a high correlation (r=0.86) with serial autocorrelation in the form of $H = 0.4239 + 0.6565\rho$ (Figure 6). Just as a comparison, we computed Hurst exponent from the original data. These *H* values was rather Normally distributed (Figure 5) and showed a higher correlation (r=0.92) and narrower spread with serial autocorrelation, as was compared to equivalent Normal deviate case, in the form of $H = 0.4714 + 0.6947\rho$ (Figure 6). On the overall, *H* from eNd were smaller than *H* from original data by around 10% (Figure 7), around 16% of the data were failed to be such. *H* data sets for the two approaches were highly correlated (r=0.87) and are in good agreement with those reported by Hamed ([5], Table 7). On the contrast of high correlation between *H* and serial autocorrelation, there was not a sound correlation between *H* and p-value of the classic Mann-Kendall trend test (data not shown).

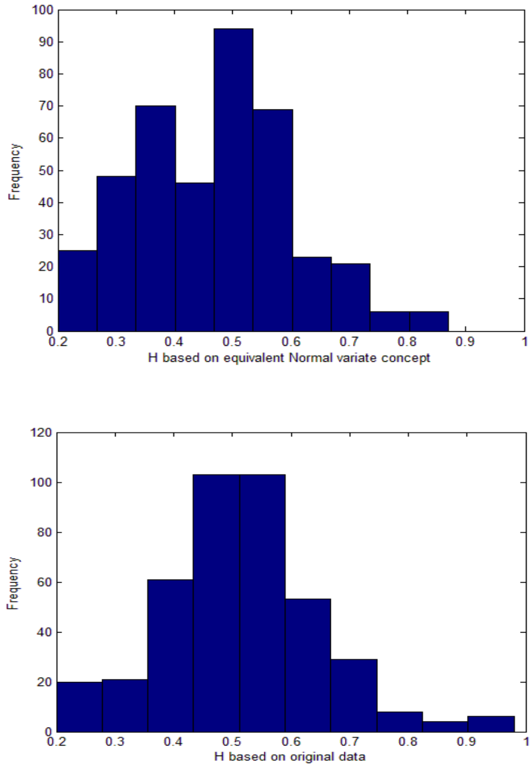


Figure 5. Frequency distribution of *H* based on equivalent Normal variate concept (top) and based on original data (bottom) of Canadian RHBN stations.

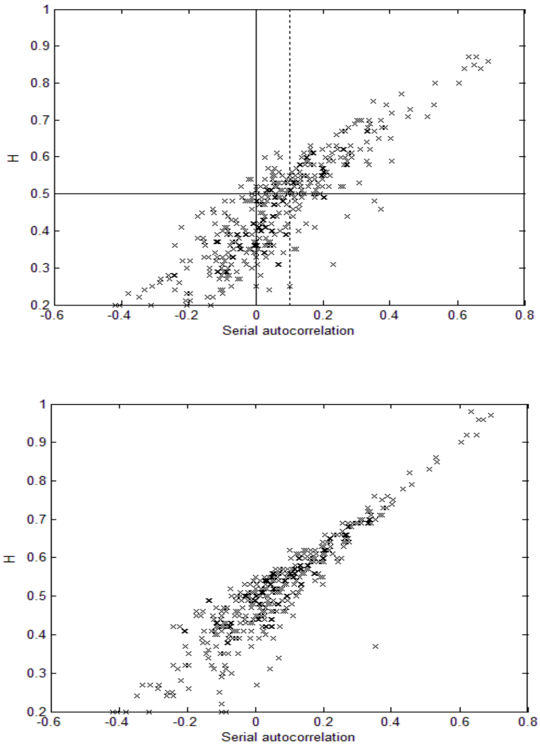


Figure 6. Relationship between Hurst exponent (computed based on equivalent Normal variate concept, top; original data sets, bottom) and lag 1 serial autocorrelation for Canadian annual runoff data (RHBN dataset).

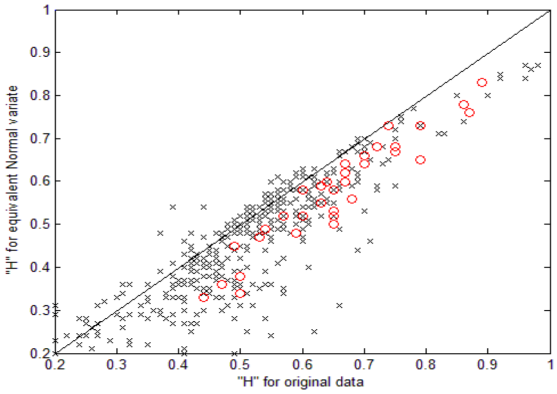


Figure 7. Relationship between Hurst exponent derived from original data sets and "equivalent Normal variate" concept for Canadian annual runoff data of RHBN (black ×-marks) and those of Hamed (2008, Table 7) (red O-marks).

4. 2. Trend under Classic Mann-Kendall Test

Different time periods of different stations showed different trend direction and significancy (Table 3), which shows that trend direction and significancy may change abruptly for different time periods (e.g. [28, 44-45]). On overall, the majority of the stations (64%) are experiencing insignificant trends (p-value>0.1). On the other hand, the number of positive and negative trends are nearly the same, though fluctuating for different time spans.

4. 3. Effect of Short-term Memory on Trend

One problem associated with the Mann-Kendall test is that the result is affected by serial correlation of the time series. Specifically, Kulkarni and von Storch [38] showed that if there is a positive serial correlation (persistence) in the time series, the test will suggest significant trend in a time series which is actually random more often than specified by the significance level. Therefore, one plausible solution is that the time series to be "pre-whitened" before conducting the Mann-Kendall test. Among different methods of pre-whitening, we adopted the simple method of Kulkarni and von Storch [38] as was done also by Zhang et al. [28]. The negative serial correlations were not so high, its mean and median values were -0.11 and -0.09, respectively. The greatest negative lag 1 serial correlation was -0.4. Nearly half of the cases with positive autocorrelation (122 out of 273) showed a negligible serial correlation of less than 0.1, as limit of pronounced effect on power of the Mann-Kendall trend test. Thus, there were only 151 cases with r>0.1 in our data set. The mean and median of these cases were 0.24 and 0.21, respectively, with the maximum amount of around 0.69. Not all of the 151 cases are useful here, because p-values of original Mann-Kendall for some of them are larger than 0.1. Only 68 cases were statistically significant (p-value ≤ 0.1) and needs pre-whitening. The effect of pre-whitening was not similar for these cases, but Figure 8 shows that p-value after pre-whitening was highly correlated with those of before pre-whitening, though different for negative and positive trends (to distinguish negative trends, we multiplied their corresponding p-values by minus one). Out of the 68 cases, there were 11 cases (16%) that pre-whitening decreased the p-values of the Mann-Kendall trend test. Ignoring one odd point, all of such cases are due to negative trend in data sets (Figure 8). In general, one should expect that the p-value increases by pre-whitening. If there is serial correlation, this means that the 'effective sample size' decreases. It should lead to larger variance which in turn would imply a higher p-value. The lag 1 serial correlations for these cases were between 0.11 and 0.53 with a mean of 0.28 which were nearly uniformly distributed (data not shown). The above facts are 'in general', so it is possible that the pre-whitened series actually can be more correlated that the original series – simply by chance. On general, we could not find any sound relationship between percentage change in p-value, either increase or decrease and either for negative trends or for positive trend cases, with the amount of lag 1 serial correlation.

TABLE 3. Trend analysis results for Canadian mean annual runoff and for different record lengths (up to 2011) based on different approaches to Mann-Kendall trend test.

Significancy level	Test type	Trend direction	30 [114]+	40 [90]	50 [44]	60 [28]	70 [12]	80 [12]	90 [9]	100 [1]
		Upward	62 (54)++	29 (32)	22 (50)	10 (36)	7 (58)	9 (75)	7 (78)	0 (0)
		Downward	52 (46)	61 (68)	22 (50)	18 (64)	5 (42)	3 (25)	2 (22)	1 (100)
p-value>0.1	classic	Total	77 (68)	64 (71)	26 (59)	16 (57)	8 (67)	6 (50)	3 (33)	0 (0)
		Upward	38	22	17	5	5	5	3	0
		Downward	39	42	9	11	3	1	0	0
	STP	Total	80 (70)	67 (74)	26 (59)	16 (57)	8 (67)	6 (50)	5 (56)	0 (0)
		Upward	43	25	18	5	5	5	4	0
		Downward	37	42	8	11	3	1	1	0
	LTP	Total	87 (76)	68 (76)	32 (73)	18 (64)	8 (67)	6 (50)	5 (56)	0 (0)
		Upward	46	23	19	7	5	5	4	0
		Downward	41	45	13	11	3	1	1	0
α=0.1	classic	Total	37 (32)	26 (29)	18 (41)	12 (43)	4 (33)	6 (50)	6 (67)	1 (100)
		Upward	24	7	5	5	2	4	4	0
		Downward	13	19	13	7	2	2	2	1
	STP	Total	34 (30)	23 (26)	18 (41)	12 (43)	4 (33)	6 (50)	4 (44)	1 (100)
		Upward	19	4	4	5	2	4	3	0
		Downward	15	19	14	7	2	2	1	1
	LTP	Total	27 (24)	22 (24)	12 (27)	10 (36)	4 (33)	6 (50)	4 (44)	1 (100)
		Upward	16	9	3	3	2	4	3	0
		Downward	11	16	9	7	2	2	1	1
α=0.05	classic	Total	18 (16)	15 (17)	12 (27)	10 (36)	3 (25)	5 (42)	3 (33)	1 (100)
		Upward	12	6	3	4	1	3	2	0
		Downward	6	9	9	6	2	2	1	1
	STP	Total	13 (11)	11 (12)	9 (20)	6 (21)	3 (25)	5 (42)	2 (22)	1 (100)
		Upward	7	3	1	0	1	3	1	0
		Downward	6	8	8	6	2	2	1	1
	LTP	Total	12 (11)	11 (12)	7 (16)	7 (25)	3 (25)	5 (42)	2 (22)	1 (100)
		Upward	6	4	2	2	1	3	1	0
		Downward	6	7	5	5	2	2	1	1
α=0.025	classic	Total	11 (10)	11 (12)	9 (20)	6 (21)	1 (8)	1 (8)	2 (22)	1 (100)
		Upward	9	3	2	0	0	0	1	0
		Downward	2	8	7	6	1	1	1	1
	STP	Total	7 (6)	8 (9)	8 (18)	6 (21)	1 (8)	1 (8)	2 (22)	1 (100)
		Upward	5	0	1	0	0	0	1	0
		Downward	2	8	7	6	1	1	1	1
	LTP	Total	7 (6)	8 (9)	4 (9)	5 (18)	1 (8)	1 (8)	2 (22)	1 (100)
		Upward	5	1	1	0	0	0	1	0
		Downward	2	7	3	5	1	1	1	1

+ Total number of stations with corresponding record length.

++ Percentage of the corresponding total stations

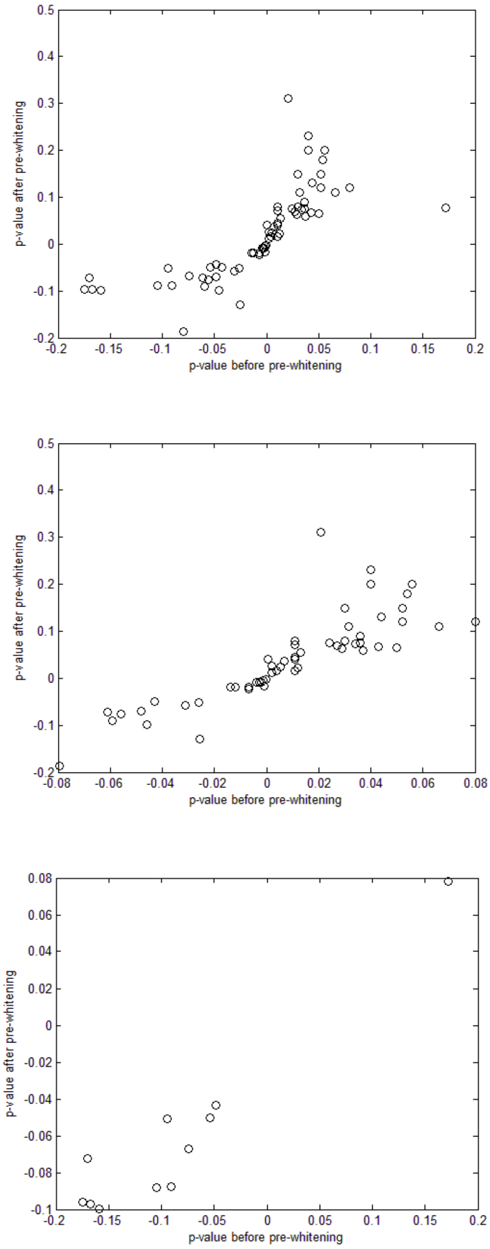
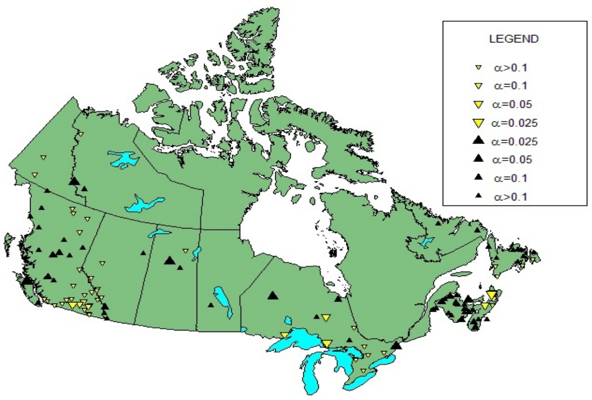


Figure 8. Change in p-value of Mann-Kendall trend test for mean annual flow of Canadian RHBN stations due to pre-whitening for all cases corresponding to $\rho_1>0.1$ (top), for cases with increase (middle) and decrease (bottom) in p-value after pre-whitening. Negative trends are denoted by negative p-values.

The results of Mann-Kendall trend test considering the STP of the data sets, is summarized in Table 3. Number of cases corresponding to different significancy levels and corresponding to different record lengths, are decreased as compared with classic approach of Mann-Kendall trend test.

4. 4. Effect of Long-term Memory on Trend The effect of LTP on Mann-Kendall trend test should be investigated when both criteria of (a) significant trend test in the classic test, and (b) significant Hurst exponent are met. Most of the cases that H was significantly (α=0.05) greater than 0.5 were no significant trend in the original data sets. There were only 17 cases with concurrent significant trend (p-value $\leq$ 0.1) and LTP. For all of these case, the p-values were increased, which means that the significancy of trend is decreasing. For 5 out of 12 cases the trend remained significant but for the other cases the significant trend shifted to insignificancy. Spatial patterns of upward and downward trends in mean annual flows of Canadian RHBN stations for some selected record lengths are shown in Figure 9, while a statistical vision of the trend situation is summarized in Table 3. For recent 30 years length of record (1982-2011), British Columbia is experiencing positive trends in the west and negative trend in the east. The trend in annual mean streamflow reflects changes in precipitation and temperature observed over the same periods. However, there is no study compatible directly to the periods taken here. So, comparison with literature seems to some extent uncertain. The result is partially supported by Zhang et al. [28], considering about 15 year difference. Most parts of the New Brunswick are experiencing the positive trend, while negative trend is due to South East of Ontario. For the longer duration of 40 years, trend statistics and geographical pattern are changed (Table 3, Figure 9). While the significant trends are decreased, more significant negative trends are governed over New Brunswick. There is no positive trend in British Colombia in the past 50 years (1962-2011), while there are both negative and positive trends in New Brunswick and negative trends are switched to positive trends in south east of Ontario. For long duration of > 70 years, there are only positive trends in South East of Canada (South New Brunswick and South East of Ontario) while central and east of Canada have experienced a negative trend.



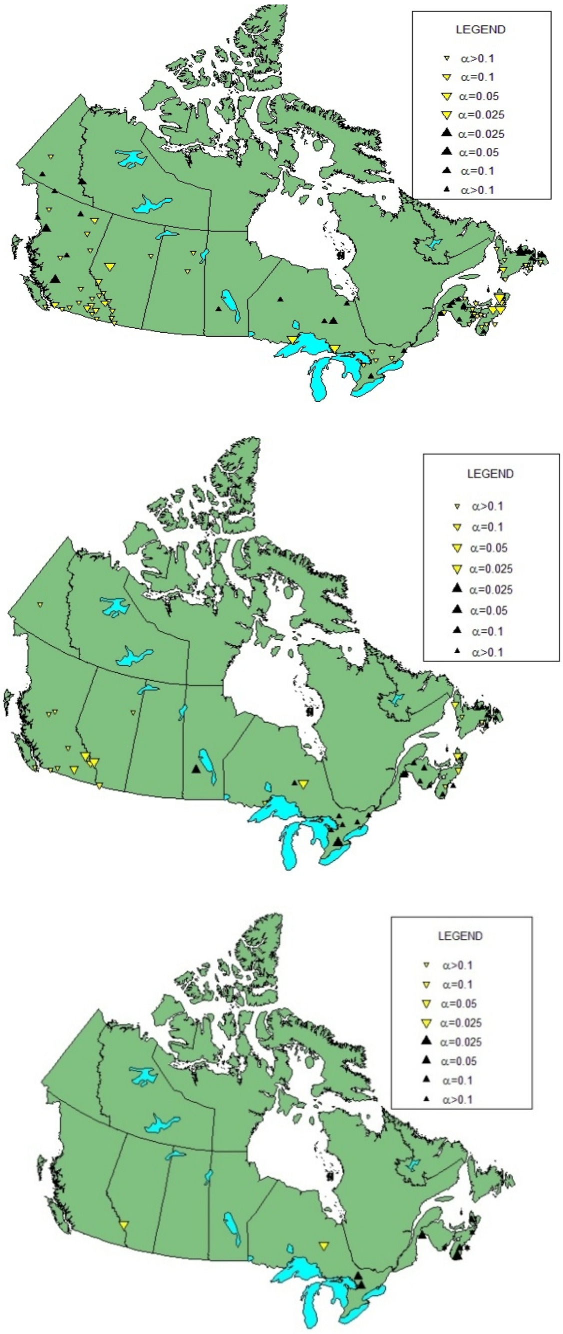


Figure 9. Spatial patterns of upward and downward trends in mean annual flows of Canadian RHBN stations for (a) 30 years, (b) 40 years, (c) 50 years, and (d) more than 70 years record lengths. a to d are ordered from top to bottom.

Zhang et al. [46] showed that from 1900–1998, the annual mean temperature has increased, especially in the south. The greatest warming in minimum occurred in the west. Annual precipitation has also increased in southern Canada over the same period. Thus, decreasing the streamflow across the south should be postulated. For the shorter time horizon of 1950–1998, the pattern of temperature change was distinct: warming in the south and west and cooling in the north east, with similar magnitudes in both maximum and minimum temperatures. Across Canada, precipitation has increased by 5% to 35%, with significant negative trends found in southern regions during winter. These patterns of precipitation and temperature support our results for streamflow.

Zhang et al. [6] showed that for time period of 1950-2007 mean daily air temperature trends were dominated by significant increases that are observed over most regions of Canada. The annual mean temperature increased over the country as a whole. The strongest warming has occurred over western and north western Canada, with the lowest warming over eastern Canada. Temperature increases in Canada has been found to be influenced by increases in atmospheric concentrations of greenhouse gases from human activities [7]. So, precipitation also generally increased over Canada since 1950 with the majority of stations with significant trends showing increases [6]. The increasing trend was most coherent over northern Canada where many stations show significant increases. There was not much evidence of clear regional patterns in stations showing significant changes in seasonal precipitation except for significant decreases which tend to be concentrated in the winter season over south western and south eastern Canada. In addition, increasing precipitation over the Arctic appears to be occurring in all seasons except summer. Although the main source of precipitation changes in Canada is not well defined, it may be attributed to anthropogenic influences, especially observed over Northern Hemispheric land areas north of 55°N including Canada [47]. Increase in precipitation and high increase in temperature may explain to some extent the increase in streamflow for the past 50 years and earlier in Southeast of Canada (Figure 9).

5. CONCLUSION

The classic Mann-Kendall trend test and its modifications with respect to short- and long-term persistence (STP and LTP, respectively) were utilized for 114 Canadian Reference Hydrometric Basin Network (RHBN) with more than 30 years data up to 2011. There was no significant trend in most of the data sets. Incorporation serial autocorrelation, as a measure of short-term memory, causes original p-values to be either increases, or decreases. The last case is hardly, if ever, supported by literature. There were just minor modifications, toward the increasing p-values, to significant levels due to adopting the long-term memory in all data sets. Majority of the Canadian streamflow data showed anti-persistence. For recent 30 years length of record (1982-2011), British Columbia is experiencing positive trends in the west and negative trend in the east. Most parts of the New Brunswick are experiencing the positive trend, while negative trend is due to south east of Ontario. For the longer duration of 40 years, trend statistics and geographical pattern were changed. While the significant trends are decreased, more significant negative trends are governed over New Brunswick. There is no positive trend in British Colombia in the past 50 years (1962-2011) while there are both negative and positive trends in New Brunswick and negative trends are switched to positive trends in south east of Ontario. For long duration of > 70 years, there are only positive trends in South East of Canada (south of New Brunswick and south east of Ontario) while central and east of Canada have experienced a negative trend.

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Effect of Short- and Long-term Memory on Trend Significancy of Mean Annual Flow by Mann-Kendall Test

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چکیده

تغییرپذیری و تغییر اقلیم منابع آب در جهان را تهدید می‌کند. تعداد ۱۱٤ ایستگاه از شبکه‌ی مرجع آب‌سنجی حوضه (RHBN) در کانادا با دست‌کم ۳۰سال آمار پیوسته (تا سال ۲۰۱۱) برای بررسی روند متوسط روان‌آب سالانه متناظر با ۳۰ تا ۱۰۰ سال در بازه‌های ۱۰ سال با آزمون ناپامتری من–کندال درنظر گرفته شد. از ضریب خودهمبستگی با تاخیر ۱ (ρ_1) و نمایه‌ی هرست (H) به‌ترتیب برای بیان تاثیر پایداری کوتاه–مدت (STP) و بلند–مدت (LTP) بر روی این آزمون استفاده شد. ρ_1 برای حدود یک‌سوم حالات منفی بود. توزیع H، برمبنای "متغیر نرمال معادل" (eNv)، اندکی چوله به راست بود و کمینه و بیشینه‌ی آن به‌ترتیب ۰/۲۰ و ۰/۸۷ بود. تقریبا نیمی از حالات ضد–پایدار ($H<0.5$) بودند. نه ρ_1 و نه H از خود الگوی منظم مکانی نشان ندادند. برمبنای ۵ ایستگاه با حدود ۱۰۰ سال داده، ρ_1 و H برای سری‌هایی با طول کم‌تر از ۵۰ سال شدیدا ناپایدار بود. ρ_1 و H به‌خوبی ($r=0.86$) همبسته بودند. H برمبنای eNv حدود ۱۰٪ از H برمبنای داده‌های اصلی کوچک‌تر بوده و همبستگی آن‌ها با هم بالا ($r=0.87$) بود. برمبنای آزمون کلاسیک من–کندال جهت روند و معنی‌داری آن برای بازه‌های متفاوت ایستگاه‌ها کاملا متفاوت بود. در مجموع روند در بیش از ٦۰٪ از حالات معنی‌دار نبوده (p–مقدار بزرگ‌تر از ۰/۱) و تعداد روندهای مثبت و منفی تقریبا برابر بود. p–مقدار، هم برای روندهای مثبت و هم منفی، پس از پیش‌سفیدسازی با پس از آن شدیدا همبسته بود. در حدود ١٦٪ حالت‌ها، عمدتا برای روندهای منفی، پیش‌سفیدسازی p–مقدار آزمون روند را کاهش داد. به‌دلیل مقارن نبودن معنی دار بودن روند در حالت کلاسیک آزمون و معنی‌دار بودن H (بزرگ‌تر از ۰/۵)، تاثیر LTP بر روی آزمون روند من–کندال ناچیز بود. برمبنای ۳۰ سال اخیر (۱۹۸۲–۲۰۱۱۱)، روند در غرب و شرق بریتیش کلمبیا به‌ترتیب مثبت و منفی بود. روند در بیش‌ترین بخش‌های نیوبرانزویک مثبت ولی در جنوب انتاریو منفی بود. در دوره‌ی ٤۰ ساله، روندهای معنی‌دار کاهش یافت و بیش‌ترین معنی‌داری منفی در نیوبرانزویک بود. در دوره‌ی ۵۰ ساله (۱۹٦۲–۲۰۱۱) هیچ روند مثبت در بریتیش کلمبیا وجود نداشت درحالی‌که هر دو نوع روندهای مثبت و منفی در نیوبرانزویک حکم‌فرما بوده و روندهای منفی در جنوب‌شرق انتاریو به مثبت تبدیل شدند. در دوره‌ی طولانی‌تر (بیش‌تر از ۷۰ سال)، روند مثبت در جنوب‌شرق کانادا (جنوب نیوبرانزویک و جنوب‌شرق انتاریو) و روند منفی در نواحی مرکزی و شرق آن وجود داشت.

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