Long-Term Dependence of Annual Peak Flows of Canadian Rivers: Two Decades Later

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Long-Term Dependence of Annual Peak Flows of Canadian Rivers: Two Decades Later

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Abstract

Both short- and long-term dependence of the peak flow series of 90 Canadian rivers were analyzed two decades ago. It showed that although short-term dependence was practically absent for most of the flow series, significant long-term dependence was present for a large number of rivers tested. With 20 or more years of additional data available today, the authors analyzed 57 rivers (only 57/90 were suitable for analysis) for: a) short-term dependence using several parametric and non-parametric tests; b) long-term dependence using a resampling-based Hurst's K; and c) trend using Mann-Kendall's test. Results showed that as expected, short-term dependence is practically absent in all rivers before or after the additional data. However, the percentage of rivers showing long-term dependence remains high. The trend test showed that most of the rivers showed no trends before or after the additional records were added. However, several rivers showed a downward trend, and a few showed an upward trend before and after the additional records were added. This study showed that sample statistics and the associated statistical significance tests can change unpredictably over time. Hence engineering decisions made in the past need to be re-visited and cannot assumed to remain unchanged especially when dealing with natural phenomenon such as annual peak flows.

Keywords: annual peak flows, engineering decisions, risk analysis, short and long-term dependence.

Introduction

In flood frequency analysis, it is normally assumed that the flood peak data to be analyzed is a set of independent random events from a stationary population. To verify this assumption, statistical tests of independence are carried out. However, most statistical tests of independence are designed to illustrate only short-term dependence and are insensitive to the presence of long-term dependence, which can lead to dramatically greater uncertainty in estimated flood quantile estimates (Booy and Lye, 1989; Burn and Goel, 2001).

Lye and Lin (1994) investigated the annual peak flows of 90 Canadian rivers for both short- and long-term dependence with at least 40 years of data. They showed that although short-term dependence was practically absent for most of the peak flow series, significant long-term dependence was present for a large number of rivers tested. Records at that time were available until 1988. More than 20 years of additional flow data should now be available for the rivers analyzed. It would be interesting to investigate whether the same conclusion holds true with the additional data.

In this paper, the records of the 90 rivers analyzed by Lye and Lin (1994) will be reexamined. The peak flow data will be analyzed for: a) short-term dependence using several parametric and non-parametric tests; b) long-term dependence using a resampling-based Hurst's K; and c) trend using Mann-Kendall's test. The statistical tests were conducted for data up to 1988 and for the extended data. No trend analysis was done in Lye and Lin (1994).

In the next section, the historical records of the 90 rivers investigated by Lye and Lin (1994) are reexamined. This will be followed by brief descriptions of the parametric and nonparametric tests for short- and long-term dependence, and trend. Finally, the results and conclusions will be presented.

Reexamining the historical data

Lye and Lin (1994) used flood peak data that were available until 1988. Of the 90 rivers analyzed, 12 were from Alberta, 13 from the Atlantic Provinces, 32 were from British Columbia, 6 from Manitoba, 17 from Ontario, 5 from Quebec, 4 from Saskatchewan, and 1 from the Yukon. They range in length from 40 to 80 years. More than 20 years of additional flow data should now be available for re-analysis. However, on reexamining the records of the 90 rivers, it was found that only 57 (about 2/3) of them have additional data that are useable for analysis. Of these 57 rivers, only 5 are from Alberta, all 13 from the Atlantic Provinces, 21 from British Columbia, 3 from Manitoba, 12 from Ontario, and 2 from Quebec. Some rivers have only a few additional years while some have up to 24 years of additional flow data. On average 21 years of additional data were available. Of the 33 rivers with no additional useable data, a majority of the stations have been discontinued, some have many years of missing data, and for several rivers the flow data were not retrievable from the Water Survey of Canada database. The list of the 57 rivers and some relevant statistics is shown in Table 1.

Statistical tests for dependence

In Lye and Lin (1994), 11 tests of short-term dependence and one test for long-term dependence were used. Nine of the short-term dependence tests used were non-parametric and two were parametric. The long-term dependence test used was the Hurst's K test (Hurst, 1951). They declared that for a particular flow series to exhibit short-term dependence, four out of 11 tests should indicate dependence. Others have used slightly different criterion. For example, Wall and Englot (1985) suggested that two out of five tests should show dependence whereas Srikanthan et al (1983) used two out of six tests. For long-term dependence, judgment was made on the results of the Hurst's K test. For the parametric tests, the flood peak data were transformed using the Box-Cox transformation (Box and Cox, 1964) to give approximately normally distributed data. The Box-Cox transformation is

$$Y_t = \left(X_t^{\lambda} - 1\right)/\lambda \quad if\ \lambda > 0$$
$$Y_t = \ln\left(X_t\right) \quad if\ \lambda = 0 \qquad (1)$$

where Y_t are the transformed values and the value of λ is obtained using a simple technique described in Lye (1993).

Table 1: Canadian rivers reexamined

River	Province	n_1	n_2	K_1	K_2	r_1	r_2	T_1	T_2
Athabasca (07BE001)	Alb	47	70	0.579	0.598	-0.198	-0.091	no	no
Bow (05BB001)	Alb	80	103	0.649	0.674	-0.136	-0.014	no	D
Castle (05AA022)[a]	Alb	44	67	0.717	0.704	0.053	-0.021	d	no
Elbow (05BJ004)	Alb	54	77	0.677	0.621	0.042	0.024	no	no
Waterton (05AD003)	Alb	41	64	0.711	0.699	0.103	0.054	d	d
U. Humber (02YL001)	Atlantic	60	83	0.645	0.623	0.204	0.082	no	no
Lepreau (01AQ001)	Atlantic	72	95	0.586	0.679	0.000	0.012	no	no
Saint John (01AD002)[c]	Atlantic	62	85	0.724	0.688	0.150	0.133	no	no
Shogomoc (01AK001)	Atlantic	45	69	0.630	0.608	0.046	0.032	no	no
Upsalguith (01BE001)	Atlantic	45	67	0.643	0.581	0.031	0.067	no	no
Beaverbank (01DG003)	Atlantic	67	90	0.717	0.660	-0.084	-0.017	no	no
East (01EH003)	Atlantic	63	70	0.657	0.665	-0.094	-0.094	no	no
Grand (01FH001)	Atlantic	68	74	0.705	0.688	-0.048	-0.051	D	D
La Have (01EF003)[c]	Atlantic	73	95	0.710	0.654	-0.016	0.146	no	no
NE Margaree (01FB001)[b,d]	Atlantic	72	95	0.753	0.734	0.143	0.083	no	no
Roseway (01EC001)[a]	Atlantic	71	93	0.736	0.701	0.074	0.086	no	no
SW Margaree (01FB003)	Atlantic	70	93	0.757	0.690	0.136	0.111	no	no
St. Mary's (01EO001)	Atlantic	73	96	0.664	0.604	0.005	0.026	no	no
Adams (08LD001)[d]	B.C.	42	63	0.632	0.722	0.171	0.169	no	D
Ashnola (08NL004)	B.C.	42	65	0.592	0.684	-0.340	-0.171	no	D
Boundary Cr. (08NH032)[b,d]	B.C.	61	84	0.756	0.723	0.174	0.143	U	U
Chilko-Out (08MA002)	B.C.	60	84	0.744	0.656	-0.033	0.004	no	no
Chilko-Red (08MA001)	B.C.	62	85	0.603	0.630	-0.127	-0.062	no	no
Columbia-N (08NA002)	B.C.	77	101	0.657	0.684	-0.077	-0.048	no	no
Columbia-D (08NB005)[a]	B.C.	44	68	0.708	0.716	-0.277	-0.084	no	D
Columbia-F (08NA045)[c]	B.C.	43	51	0.691	0.716	-0.262	-0.145	D	D
Flathead (08NP001)[b]	B.C.	60	75	0.783	0.750	0.201	0.065	no	no
Kettle (08NN013)[a]	B.C.	60	84	0.738	0.704	0.133	0.054	U	no
Kootenay (08NF001)	B.C.	41	65	0.564	0.590	-0.093	-0.005	no	no
Liard (10BE001)	B.C.	42	66	0.663	0.575	0.196	0.102	no	no
Lillooet (08MG005)	B.C.	63	85	0.577	0.562	0.092	0.102	no	no
Moyie (08NH006)[b]	B.C.	59	83	0.848	0.777	0.132	0.072	no	no
Quesnel (08KH001)	B.C.	64	86	0.701	0.687	0.130	0.099	no	no
Salmo (08NE074)	B.C.	40	64	0.593	0.548	0.075	-0.010	no	no
Sikanni (10CB001)	B.C.	44	68	0.582	0.603	-0.016	-0.027	no	no
Similkameen (08NL007)[b]	B.C.	44	68	0.699	0.749	0.079	0.102	no	D
Skeena (08JE001)[c]	B.C.	41	64	0.617	0.626	-0.247	-0.183	no	no
Slocan (08NJ013)	B.C.	64	88	0.728	0.696	0.131	0.124	u	no
St. Mary (08NG046)	B.C.	41	47	0.612	0.690	-0.077	0.006	no	D
Stuart (08JE001)	B.C.	56	79	0.751	0.646	0.218	0.127	no	no
Brokenhead (05SA002)	Man	46	69	0.691	0.657	0.097	0.105	no	no
Roseau (05OD030)[f]	Man	67	76	0.663	0.657	0.199	0.246	no	no
Whitemouth (05PH003)	Man	42	66	0.679	0.691	-0.037	0.065	no	no

Table 1: Canadian rivers reexamined (continued)

River	Province	n_1	n_2	K_1	K_2	r_1	r_2	T_1	T_2
Ausable (02FF002)	Ont.	43	66	0.488	0.598	-0.131	-0.011	no	no
Black (02FF002)[c]	Ont.	73	97	0.731	0.631	0.112	0.113	no	no
English (05QA002)	Ont.	67	91	0.727	0.665	-0.006	-0.024	no	no
Missinabi (04LJ001)[b]	Ont.	69	93	0.729	0.731	0.106	0.074	no	no
Nith (02GA010)	Ont.	42	63	0.682	0.642	-0.044	0.092	no	no
NMagnetawan (02EA005)	Ont.	73	97	0.615	0.538	-0.012	-0.094	no	no
Nottawasaga (02ED003)	Ont.	40	62	0.647	0.642	0.109	0.079	no	no
Pigeon (02AA001)	Ont.	65	75	0.682	0.698	0.015	0.030	no	D
Saugeen (02FC002)[c]	Ont.	74	98	0.645	0.645	0.140	0.141	no	no
Sydenham-A (02FC002)	Ont.	40	64	0.672	0.640	-0.055	0.043	no	no
Sydenham-O (02FB007)	Ont.	43	62	0.592	0.625	0.020	0.024	no	no
Turtle (05PB014)	Ont.	58	90	0.670	0.636	-0.034	-0.065	no	no
Hall (02OE018)[b]	Quebec	40	46	0.712	0.758	-0.104	-0.090	D	no
Richelieu (02OJ007)	Quebec	51	75	0.632	0.554	0.176	-0.050	no	no
Mean		56	77	0.673	0.660	0.020	0.029		
Standard deviation		13	14	0.065	0.056	0.133	0.089		

Subscript 1 indicates data up to 1988 and subscript 2 indicates all available data.
K = Hurst's K, r = first order correlation coefficient, T = Trend indicator
[a]Short-term independent but Hurst's K significant at 10%
[b]Short-term independent but Hurst's K significant at 5%
[c]Short-term dependent at 10% and Hurst's K significant at 5%
[d]Short-term dependent at 10% and Hurst's K significant at 10%
[e]Short-term dependent only at 10%
[f]Short-term dependent only at 5%
U or D = significant upward or downward trend at 5%
u or d = significant upward or downward trend at 10%

Tests for short-term dependence

In this paper, only five tests (three non-parametric and two parametric) for short-term dependence will be used. These tests are chosen because they have been shown to have reasonable power, are widely available in popular statistical packages such as Minitab®, or are easily programmed as a macro in Minitab®. The theories behind the tests are described in Madansky (1988), Lye and Lin (1994) and more recently in Rai et al (2013).

Non-parametric tests

a. Rank difference (RD)
b. Runs above and below the median (RUNAB)
c. Rank Von Neuman ratio (RVNR)

Parametric tests

d. Von Neuman ratio (VNR)

e. Autocorrelation (AUTO)

Test for long-term dependence

The most well known test for long-term dependence is based on the Hurst coefficient h first proposed in Hurst (1951). Several methods have been proposed to estimate the Hurst coefficient but the method based on Hurst's K has been shown to provide lower variance and is straightforward to calculate compared to other methods. However, it has been also shown to have a substantial bias in that it overestimates h for values below 0.7 and underestimates h for values over 0.70 (Wallis and Matalas, 1970). Hurst's K is given by

$$K = \frac{\log\left(R/s\right)}{\log\left(n/2\right)} \qquad (2)$$

where R is the range of cumulative departures from the mean, s is the standard deviation, and n is the sample length. Hurst's K is theoretically 0.5 for an independent series and it increases when there is a greater degree of dependence. Hurst's K values of less than 0.5 indicate negatively autocorrelated series. Due to the bias, independent series would normally show a K value between 0.5 and 0.7.

To test for statistical significance of the calculated Hurst's K, Lye and Lin (1994) developed statistical tables for testing the significance Hurst's K using Monte Carlo simulations. They assumed that the null hypothesis is that the flood peak series is normally distributed and serially independent. The alternate hypothesis is long-term dependence. The empirical percentage points for sample length ranging from 20 – 200 are given in Lye and Lin (1994).

A non-parametric approach based on the bootstrap method (Efron, 1982) was also proposed by Lye and Lin (1994) as a check for tables developed. The advantage of the bootstrap method is that the data need not be transformed to the normal before applying the test. The disadvantage is that it would require some computational time to do the bootstrapping. The final results showed that both approaches gave similar conclusions.

In this paper, a resampling approach will be used. This approach is a non-parametric approach and gives basically the same results as the bootstrap method but the distribution of the data remains unchanged from resample to resample. In this approach, it is assumed that the observed peak flow series is only one possible sequence out of many possible and the observed correlation structure could have occurred just by chance. If the series were rearranged in a different sequence, a different result would be observed. The steps needed to estimate the p-value for the calculated Hurst's K then is as follows:

(1) Assume that the annual peak flow series $x_1, x_2, x_3, \ldots, x_n$ are independent observations
(2) Resample or rearrange the series in a different sequence
(3) Calculate the Hurst's K for the rearranged series (resampled series)
(4) Repeat Steps 2 and 3 a large number of times (2,000 used in this study)
(5) Count the number of times the observed K of the sample is exceeded by the 2,000 resampled K values

(6) Calculate the p-value given by

$$p\text{-}value = \frac{\#\, of\, K > K_{obs}}{2{,}000} \tag{3}$$

If the p-value is less than the specified significance level (e.g. 5% and 10%), it is concluded that the sample exhibits long-term dependence at the specified level; otherwise it has no long-term dependence. One must be careful in interpreting the results of this test, as it is known that series exhibiting short-term dependence tends to inflate the Hurst's K value. The test proposed is valid only for series that are serially independent, which is the standard assumption used for annual peak flows.

Test for Trend

In a standard flood frequency analysis, the flood peak data are assumed to be an independent series from a stationary population i.e. no trends. The presence of trends will also affect the estimation of both short-term and long-term dependence. Positive or upward trends will tend increase the magnitude of the autocorrelation and Hurst's K. Testing for trend was not reported in Lye and Lin (1994).

In this paper, the Mann-Kendall test for monotonic trend will be used. This test described in detail in Helsel and Hirsh (1992). It is one of the most widely used tests for trend in hydrology. The test is non-parametric and based only on the relative ranking of the data. The null hypothesis is that the time series values are independent and identically distributed. The alternate hypothesis is that there is a monotonic (not necessarily linear) trend. The test statistic is given by

$$S = \sum_{i<k} sign(x_k - x_i) \quad \text{with sign (x) = 1 if x>0, = 0 if x=0, and = -1 if x <0.} \tag{4}$$

For sample sizes greater than 8, S is normally distributed with

$$E(S) = 0, \qquad Var(S) = \frac{n(2n+5)(n-1)}{18} \tag{5}$$

In this study, the p-values for the Mann-Kendall test will be obtained using the resampling approach similar to that used for Hurst's K. That is:

(1) Assume that the annual peak flow series $x_1, x_2, x_3, \ldots, x_n$ are independent observations
(2) Resample or rearrange the series in a different sequence
(3) Calculate S for the rearranged series (resampled series)
(4) Repeat Steps 2 and 3 a large number of times (2,000 used in this study)
(5) Count the number of times the observed S of the sample is exceeded by the 2,000 resampled S values
(6) Calculate the p-value given by

$$p-value = \frac{\# \, of \, S > S_{obs}}{2{,}000} \tag{6}$$

If the p-value is less than the specified significance level, it is concluded that the sample exhibits monotonic trend at the specified level; otherwise it has no trend.

Results

All tests (5 short-term dependence, 1 long-term dependence, and 1 trend) are carried out one after another within a Minitab macro. Their significance were tested at both the 5% and 10% levels and compared. Table 2 summarizes the percentage and numbers of rivers indicating statistical significance with respect to the statistical tests for data before and after the additional data were added. Table 3 shows the percentage and numbers of rivers indicating short-term dependence at the 5% and 10% levels.

Table 2: Statistical significance as a function of test

Test	% (no.) of rivers indicating significance at the 5% level		% (no.) of rivers indicating significance at the 10% level	
	Before	After	Before	After
RD	10.53(6)	3.51(2)	28.07(16)	14.04(8)
RUNAB	1.75(1)	0.00(0)	7.02(4)	3.51(2)
RVNR	5.26(3)	5.26(3)	28.07(16)	17.54(10)
VNR	12.28(7)	3.51(2)	26.32(15)	15.79(9)
AUTO	10.53(6)	1.75(1)	28.07(16)	15.79(9)
Hurst's K	21.05(12)	12.28(7)	31.58(18)	22.80(13)
Mann-Kendall	8.77(5)	17.54(10)	14.04(8)	19.30(11)

Table 3: Percentage and number of rivers indicating short-term dependence

No. of tests indicating dependence	Percentage (no.) of rivers 5% level		10% level	
	Before	After	Before	After
5	0.00(0)	0.00(0)	5.26(3)	0.00(0)
4	1.75(1)	1.75(1)	12.28(7)	7.02(4)
3	5.26(3)	0.00(0)	1.75(1)	1.75(1)
2	7.02(4)	0.00(0)	14.03(8)	10.53(6)
1	3.51(2)	7.02(4)	8.77(5)	12.28(7)
0	82.46(47)	91.22(52)	57.89(33)	68.42(39)

From the results presented in Tables 2 and 3, short- and long-term dependence can be summarized in Table 4. The particular rivers exhibiting short-term dependence, long-term dependence, both short- and long-term dependence or trend are also indicated in Table 1 for the extended data set since this is the most recent data available.

Table 4: Comparison of short-term and long-term dependence

	Percentage (no.) of rivers			
	5%		10%	
	Before	After	Before	After
[1]short-term dependence	14.04(8)	1.75(1)	33.33(19)	19.30(11)
long-term dependence	21.05(12)	12.28(7)	31.58(18)	22.80(13)
only short-term dependence	8.77(5)	1.75(1)	17.54(10)	12.28(7)
only long-term dependence	15.78(9)	12.28(7)	17.54(10)	15.78(9)
both short-and long-term dependence	5.26(3)	0.00(0)	12.28(7)	7.02(4)

[1]Failed 2 or more short-term dependence tests.

From the preceding tables, it can be observed that:

(1) The extended data set has on average about 21 extra years of data. These additional data caused various statistics calculated and tested two decades ago to change in unpredictable ways as can be seen from Tables 1 to 4.
(2) A vast majority of the rivers tested do not exhibit any serial dependence and do not show any trends. For these rivers standard flood frequency analysis techniques apply.
(3) In nearly all cases, the percentage of rivers exhibiting long-term dependence is more than those exhibiting short-term dependence. For the extended data set, only 1 river or 1.75% exhibits short-term dependence while 7 or 12.28% show long-term dependence, at the 5% significance level. This confirms that the short-term dependence tests are insensitive to long-term serial correlation structure in the data as pointed out by Lye and Lin (1994). This means that series that show short-term independence, may still exhibit significant long-term dependence.
(4) For the 57 rivers tested, the conditional probabilities of the existence of long-term dependence when the series is found to have no short-term dependence are as follows for the extended data set:
    a. At the 5% level:
    P(long-term dependence|short-term independence) = 7/56*100% = 12.50%

    b. At the 10% level:
    P(long-term dependence|short-term independence) = 9/46*100% = 19.56%

These probabilities are quite high and should not be ignored. That is, rivers that show short-term independence should be further investigated for long-term dependence. There could be significant underestimation of the flood risk if long-term dependence is ignored. A technique for incorporating long-term dependence in flood risk estimation is shown in Booy and Lye (1989).

(5) The current study included trend analysis before and after the addition of recent data. It can be seen from Tables 1 and 2 that some rivers exhibit statistically significant upward or downward trends. In some cases, the trend became statistically insignificant after the additional data but some showed a significant trend after the additional data. There seem to be more downward trends than upward trends.

(6) Trends, upward or downward, affect the calculation of and tests for short- and long-term dependence. Trends also affect the estimation of flood frequencies. The reverse is also true. Autocorrelation also has an effect on the estimation of trends. It is hard to tell which is the cause and which is the effect.

Conclusions

Results showed that as expected, short-term dependence is practically absent in all rivers before or after the additional data were available. Long-term dependence, however, is statistically significant at the 10% level for about 22.80% of the rivers and 12.28% showed statistical significance at the 5% level. There were no rivers that exhibited both short-and long-term dependence at the 5% level, but there were 7.02% exhibiting both phenomena at the 10% level. The trend tests showed that about 80% of the rivers showed no trends before or after the additional records were added. However, several rivers showed a downward trend, and a few rivers showed an upward trend, before and after the additional records were added.

Although there is a reduction in the number of rivers indicating long-term persistence with additional data, there are still a fairly large number of rivers remaining that has significant long-term dependence. This long-term dependence should not be ignored as in traditional flood frequency analysis; it should be taken into account as it has been shown to increase the risk associated with future peak flows.

The study showed that sample statistics and the associated statistical significance tests change over time in an unpredictable manner as we obtain more data. Hence engineering decisions made in the past need to be re-visited and cannot assumed to remain correct and unchanging especially when dealing with natural phenomenon such as annual peak flows. Furthermore, one also cannot conclude anything about those rivers where the records have been unfortunately discontinued or have lots of missing information.

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