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Dependence evolution of hydrological characteristics, applied to floods in a climate change context in Quebec

M.-A. Ben Aissia [a,*], F. Chebana [a], T.B.M.J. Ouarda [b,a], L. Roy [c], P. Bruneau [c], M. Barbet [c]

[a] Canada Research Chair on the Estimation of Hydro-meteorological Variables, INRS-ETE, 490, de la Couronne, Québec, Québec G1K 9A9, Canada
[b] Masdar Institute of Science and Technology, Abu Dhabi, United Arab Emirates
[c] Hydro-Québec Équipement, 855, Ste-Catherine East, 19th Floor, Montreal, Quebec H2L 4P5, Canada

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SUMMARY

Generally, hydrological event such as floods, storms and droughts can be described as a multivariate event with mutually dependent characteristics. In the literature, two types of studies are performed focusing either on the evolution of one variable or more but separately, or on the joint distribution of two or more variables on a fixed window period. The main aspect in multivariate analysis is the dependence between the studied variables. It is important to study the evolution of this dependence over a long period especially in studies dealing with climate change (CC). The aim of the present study is to evaluate and analyze the dependence evolution between hydrological variables with an emphasis on the following flood characteristics, peak (Q), volume (V) and duration (D). This analysis includes confidence interval determination, stationarity analysis and change-point detection over a moving window series of three dependence measures. Two watersheds are considered along with observed and simulated flow data, obtained from two hydrological models. Results show that the dependence between the main flood characteristics over time is not constant and not monotonic. The corresponding behavior is sensitive to the choice of hydrological model, to climate scenarios and to the global climate model being used. The dependence of (Q,V) decreases when that of (V,D) increases. Moreover, the two considered hydrological models generally overestimate the dependence of (Q,V) and underestimate the dependence of (V,D) and (Q,D). All simulated dependence series are stationary over the whole period and present several break-points corresponding to short trends. This study allows also to check the ability of hydrological models, and if necessary, to recalibrate them to correctly simulate the dependence historically and in the future.

1. Introduction

A number of engineering design planning, design, and management activities require a detailed knowledge of hydrological variables through their characteristics, which are mutually correlated. Various studies showed the importance of considering the dependence structure between these characteristics. For instance, Cordova and Rodriguez-Iturbe (1985) showed that the correlation between rainfall duration and average intensity had a non-negligible effect on the storm surface runoff. Kao and Govindaraju (2007) quantified the effect of dependence between rainfall duration and average intensity on surface runoff. Therefore, dependence between hydrological variables can influence flood flow quantiles (Goel et al. 2000).

In earlier studies (e.g. Wood (1976) and Chan and Bras (1979)) the use of joint distribution was often accompanied with the assumption of independence between different variables. This assumption was fairly inconvenient, and is frequently not supported by the data (Kao and Govindaraju, 2007). Recently, increasing attention has been given to multivariate analysis in which, the main component is the dependence between variables.

A number of hydrological studies considered either one or more variables and studied their future evolution (e.g. Reynard et al., 2001; Bronstert, 2003). Recently, Ben Aissia et al. (2011) compared, in a climate change (CC) context, eight spring flood characteristics on two different periods of 30 years: observed (1971–2000) and future simulated (2041–2070). In previous studies, attention was often given to modeling the joint distribution of two or more variables on a fixed window period, usually historical period, by evaluating one value of the corresponding correlation coefficient or the copula parameter (e.g. Shiau, 2003; Zhang and Singh, 2006; Chebana and Ouarda, 2011). However, the evolution of dependence between hydrological characteristics, over a long period has not been considered in the literature.

* Corresponding author. Tel.: +1 (418)654 2530x4469.
E-mail address: mohamed.ben.aissia@ete.inrs.ca (M.-A. Ben Aissia).

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Nomenclature

α	significance level
$\alpha_1, \alpha_2, \alpha'_1$ and α'_2	parameters to be estimated in break point detection test
θ	dependence measure of interest
$\hat{\theta}$	an estimate of θ based on the observed data
$\hat{\theta}^*$	bootstrap replication of $\hat{\theta}$ obtained by resampling
γ	break-point time
$v_{x_k^* y_k^*}$	covariance between x_k^* and y_k^*
$\sigma_{x_k^*}$, $\sigma_{y_k^*}$	standard deviations of x_k^* and y_k^* respectively
ε or ε'	test errors
Φ	standard normal cumulative distribution function
a	acceleration coefficients in BCa method
A2 and B2	climate change scenarios
ABC	approximate bootstrap confidence method
B	the number of bootstrap samples
BB	block-bootstrap test
BCa	bias-corrected and accelerated method
CC	climate change
CF	correction factor in VC1 and VC2 tests
CGCM3	Coupled Global Climate Model
CI	confidence interval
CRCM	Canadian Regional Climate Model
D	duration
ECHAM5	Coupled Global Climate Model
ERA-40	re-analysis results of the global atmosphere and surface conditions
HADCM3	Coupled Global Climate Model
MK	Mann–Kendall test
m	number of blocks in BB method
l	length of blocks in BB method
N	length of the multivariate dataset
n	number of components of the multivariate series
P	Spearman's rho
p	p-value of the BB test
PW	pre-whitening test
Q	peak
q	length of the moving windows
ql and qu	upper and lower bounds of confidence interval
R	Pearson's correlation
r_1	lag-1 serial correlation coefficient
r'_1	lag-1 serial correlation coefficient from the de-trended series
r_k	lag-k serial correlation coefficient
r_k^R	ranks of the data
S	Mann–Kendall test statistic
T	Kendall's tau
t	time in years
TFPW	trend-free pre-whitening test
x, y	two Multivariate datasets of interest
x_i^* or y_i^*	the ith moving window of x or y
U	a vector used in BCa method
V	volume
VC1 and VC2	variance correction tests
Z	standardized Mann–Kendall test statistic
Z^*	standardized Mann–Kendall test statistic from BB method
z_0	bias-correction in BCa method
z_i	the ith block of θ in BB method

In the present study, we are interested in the temporal evolution of the dependence of the characteristics of hydrological variables in a multivariate framework. Three dependence measures are considered, namely: the Pearson's correlation (r), Kendall's tau (τ) and Spearman's rho (ρ). Based on these measures, moving window series are analyzed. The methodology includes descriptive statistical analysis, confidence interval (CI) determination, stationarity analysis and change-point detection. An application of the proposed procedure, to a case-study from the province of Quebec (Canada), is performed. In this study we focus on the main flood characteristics: peak Q, volume V, and duration D. The main difference between the present study and the study of Ben Aissia et al. (2011) is that the aim of the latter is to compare eight flood characteristics in two fixed periods: historical period (1971–2000) and future period (2041–2070). However, in the present paper, the aim is to study the dependence evolution of the main flood characteristics (i.e. Q, V and D) over the whole period (1961–1970 for simulated data) based on moving averages. In summary, the differences between the two studies are in terms of the series (flood characteristics vs dependences evolution; two short and distinct periods vs one long and continues period; two watersheds vs one).

The paper is organized as follows. The methodology is presented in the second section. The third section contains a description of the study area and the available data. Results and discussions are reported in the fourth section and the conclusions are presented in the last session.

2. Methodology

In the present section we describe the proposed methodology in its general form applied on hydrological variables. This section contains the evaluation of variable dependence characteristics, CI determination, stationarity testing and break-point detection.

2.1. Determination of the dependence

From a physical point of view, and supported by the hydrological literature, the dependence is generally significant between Q & V and less significant between V & D, but not significant between Q & D (e.g. Yue et al., 1999). This dependence varies from one site to another. The most commonly used dependence measure coefficients are the Pearson's correlation (Hollander and Wolfe, 1973), Kendall's tau (Kendall, 1975) and Spearman's rho (Best and Roberts, 1975). These dependence measures are considered in the present study. Let $x = (x_1,\ldots,x_N)$ and $y = (y_1,\ldots,y_N)$ be the two datasets of interest (e.g. V and Q) where N is the length of the dataset. Let $(x_1^*, x_2^*, \ldots, x_n^*)$ and $(y_1^*, y_2^*, \ldots, y_n^*)$ be the n series for each variable derived by using a moving windows of length q (e.g. q = 30 years in the application below) where $n = N - q + 1$ and $x_1^* = (x_1, x_2, \ldots, x_q)$, $x_2^* = (x_2, x_3, \ldots, x_{q+1}), \ldots, x_n^* = (x_{N-q+1}, x_{N-q+2}, \ldots, x_N)$. The three dependence measures are then computed for the n series.

The Pearson's correlation coefficient (r) is defined by:

$$r_k = \frac{v_{x_k^* y_k^*}}{\sigma_{x_k^*}, \sigma_{y_k^*}}; \quad k = 1, \ldots, n \tag{1}$$

where $v_{x_k^* y_k^*}$ is the covariance between x_k^* and y_k^* and $\sigma_{x_k^*}$, $\sigma_{y_k^*}$ are the standard deviations of x_k^* and y_k^* respectively.

The Kendall' tau (τ) coefficient is given by:

$$\tau_k = \frac{(\text{number of concordant pairs}) - (\text{number of discordant pairs})}{n(n-1)/2}, \quad k = 1, \ldots, n \tag{2}$$

For $i, j = 1, \ldots, q$, $(x_k^*(i), y_k^*(i))$ and $(x_k^*(j), y_k^*(j))$ are said to be concordant if $x_k^*(i) > x_k^*(j)$ and $y_k^*(i) > y_k^*(j)$ or if $x_k^*(i) < x_k^*(j)$ and $y_k^*(i) < y_k^*(j)$. They are said to be discordant, if $x_k^*(i) > x_k^*(j)$ and