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Estimating the flood frequency distribution at seasonal and annual time scale

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Abstract

We propose an original approach to infer the flood frequency distribution at seasonal and annual time scale. Our purpose is to estimate the peak flow that is expected for an assigned return period T, independently of the season in which it occurs (i.e. annual flood frequency regime), as well as in different selected sub-yearly periods (i.e. seasonal flood frequency regime). While a huge literature exists on annual flood frequency analysis, few studies have focused on the estimation of seasonal flood frequencies despite the relevance of the issue, for instance when scheduling along the months of the year the construction phases of river engineering works directly interacting with the active river bed, like for instance dams. An approximate method for joint frequency analysis is presented here that guarantees consistency between fitted annual and seasonal distributions, i.e. the annual cumulative distribution is the product of the seasonal cumulative distribution functions, under the assumption of independence among floods in different seasons. In our method the parameters of the seasonal frequency distributions are fitted by maximising an objective function that accounts for the likelihoods of both seasonal and annual peaks. Differently from previous studies, our procedure is conceived to allow the users to introduce subjective weights to the components of the objective function in order to emphasize the fitting of specific seasons or of the annual peak flow distribution. An application to the time series of the Blue Nile daily flows at Sudan-Ethiopia border is presented.

1 Introduction

Flood frequency analysis is often used by practitioners to support the design of river engineering works, flood mitigation procedures and civil protection strategies. It is generally carried out by fitting peak flow observations by using a suitable probability distribution. Two approaches are mainly applied. Using an annual maximum series (AM), one considers the largest event in each year. Conversely, using a partial duration series, or peak-over-threshold method (POT), the analysis considers all peaks above a given threshold level (e.g. Madsen et al., 1997a,b).

In many practical cases one is also interested in inferring the flood frequency distribution for given intra–annual periods, for instance when one needs to estimate the risk of flood in different seasons. Such information is needed when planning the construction phases of river engineering works whose building area is in close proximity to the active river bed for various months or years.

There are several problems encountered when fitting seasonal and annual frequency curves independently and a key issue is to ensure the compatibility between intra–annual and annual flood probability distributions. One example is the problem of crossing over: in the probability plot, the annual distribution must always lie on or above the highest seasonal distribution (Durrans et al., 2003), i.e. the probability of one peak value of being exceeded in the entire year must be higher than the probability of the same value of being exceeded in one season. The issue of seasonal flood frequency analysis was considered by Creager et al. already in 1951. However, literature dedicated little attention to this problem in comparison with the estimation of annual extremes. In fact, several contributions dealt with intra-annual flood assessment but in many cases the purpose was to support with seasonal information the estimation of the annual peak flow. For instance, Stedinger et al. (1992) discussed the advantages and drawbacks related to using seasonal flow data to estimate the annual peak flow distribution but did not explicitly focus on flood estimation in sub-yearly periods. Similarly, Kochanek et al. (2012) and Strupczewski et al. (2012) focused on the upper quantiles of the annual peak flows by fitting data collected in two seasons. Other analogous contributions were provided by Buishand and Demarè (1990), who refer to rainfall depths, and Singh et al. (2005). Among the contributions that are explicitly dedicated to inferring flood occurrence in different seasons, it is worth mentioning McCuen and Beighley (2003), who focused on filling the gaps of seasonal data records, and in particular Durrans et al. (2003), who first considered alternative approaches to jointly estimate seasonal and annual flood frequency distributions. However, their methods are based on adapting the skewness coefficient of seasonal distributions to ensure a satisfactory fit of the annual peak flows, thereby putting more emphasis on the annual distribution. Allamano et al. (2011) analyze the magnitude of under- (or over-) estimation of design events in the presence of seasonality by using the POT or AM approach. Bowers et al. (2012) presents a statistical procedure to partition river flow data into three seasons and focuses on two particular distributions to describe the constructed seasonal river flows: power law and lognormal. Fang et al. (2007) proposed an approach based on the peaks-over-threshold sampling method and a non-identical Poisson distribution to model the flood occurrence within each season. Another relevant contribution was recently given by Chen et al. (2010) who proposed the use of a copula function to jointly model the distributions of flood magnitude and date of occurrence. We propose a practical and useful alternative approach for jointly estimating seasonal and annual flood frequency distributions, which has the relevant feature that, under the assumption of mutual independence of seasonal peaks, the number of seasons and their distribution along the year can be defined with great flexibility. In detail, we analyse yearly maxima collected at seasonal and annual time scale and develop an objective function for parameter estimation, which consists in the weighted sum of seasonal and annual log-likelihoods for the peaks of being observed. Parameters of the seasonal distributions are optimised while, under the assumption of independence of the flood generating process among seasons, the annual distribution is computed as the product of the seasonal ones. Likelihood weights can be used to put more emphasis on one or more distributions, whether sub-yearly or annual. It is worth noting that the optimisation procedure is similar to a maximum likelihood estimation, but our objective function is not a likelihood function since combines seasonal and annual likelihoods and allow the user to assign weights to them. The method represents an approximate solution to the problem of the seasonal and annual flood frequency analysis, providing however results wholly comparable with respect to those that would be obtained through the classic method of annual, or seasonal, peak discharge and overcoming consistency problems such as the crossing over problem.

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With respect to the approach proposed by Chen et al. (2010) our method ensures more flexibility in the choice of the seasons which can eventually be very different in terms of their impact on the annual flood distribution. For illustration purposes, the proposed approach is applied to infer seasonal and annual flood frequency distributions for the Nile River at the Sudan-Ethiopia border.

2 Parameterisation of seasonal and annual flood frequency distributions

Let us define a season as a contiguous period of the year with its own river flow regime and seasonal flood frequency distribution. Assuming that the year is divided into N seasons in which flood distributions are independent of each other, the cumulative probability distribution function (CDF) of the annual maximum flood F_{Q_Y} is given by (e.g. Waylen and Woo, 1982; Durrans et al., 2003)

$$F_{Q_Y}(q|(\boldsymbol{\theta}_1,...,\boldsymbol{\theta}_N)) = \prod_{i=1}^{N} F_{Q_i}(q|\boldsymbol{\theta}_i), \quad i = 1,...,N \tag{1}$$

where F_{Q_i} and $\boldsymbol{\theta}_i$ are the CDF and the vector of the parameters for season i, respectively. This relationship clearly shows that seasonal and annual probability distributions are strictly related, meaning that the estimation of their parameters should be conditioned by Eq. (1). The literature has proposed several methods to impose the aforementioned condition. For instance, Durrans et al. (2003) conditioned the skewness coefficients of seasonal distributions to fit the annual flood frequency behaviors.

One should note that the dependency among seasonal and annual peak flow distributions implies that the yearly peak flow estimated by seasonal maxima discharge is generally different with respect to the result of traditional procedures that are based on the analysis of peak flows only. This is the consequence of the presence of uncertainty, mainly induced by the limited sample size of the observed data, which originates possible discrepancy, especially for high return periods.

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Under the assumption of independence among seasonal peak flows, we propose an estimation technique for seasonal and annual flood frequency distributions which enables the user to (a) select the seasons independently of their significance in the formation of the overall flood regime, (b) assign different weights to the fitting of seasonal and annual distributions and (c) overcome the problem of the crossing over among seasonals and annual distributions.

The method makes use of the annual maxima sampling method to select relevant floods at seasonal and annual time scale and is articulated in the following steps.

1. From the observed data series, select the sample of the annual maximum peak flows (AM), as well as the samples collecting the annual maxima in each season (SM_i).

2. For the above seasonal samples, identify a suitable probability distribution and estimate its parameters, for instance by using the L-moments method (e.g. Hosking and Wallis, 1997) (i.e. initial parameter set).

3. Compute the objective function $\xi(\boldsymbol{\theta}_1,...,\boldsymbol{\theta}_N)$ for the joint-estimation of seasonal and annual distributions parameters through the relationship

$$\xi(\boldsymbol{\theta}_1,...,\boldsymbol{\theta}_N) = \sum_{i=1}^{N}\left\{ w_i \sum_{j=1}^{M_{S_i}} \ln\left[f_{Q_i}(q_{S_{i,j}}|\boldsymbol{\theta}_i)\right]\right\} + w_Y \sum_{k=1}^{M_Y} \ln\left[f_{Q_Y}(q_{Y,k}|(\boldsymbol{\theta}_1,...,\boldsymbol{\theta}_N))\right] \tag{2}$$

where M_{S_i} and M_Y are the samples sizes of SM_i and AM, respectively, which may be different (e.g. the case of seasons affected by missing data); $q_{S_{i,j}}$ and $q_{Y,k}$ are the observations in SM_i and AM, respectively; $f_{Q_i}(q_{S_{i,j}}|\boldsymbol{\theta}_i)$ and $f_{Q_Y}(q_{Y,k}|\boldsymbol{\theta}_1,...\boldsymbol{\theta}_N)$ are the seasonal and annual probability density functions; w_i and w_Y, with $w_Y + \sum_{i=1}^{N} w_i = 1$ are weights, for the seasonal and annual distributions, respectively. Note that Eq. (2) is based on the log-likelihood function of the seasonal and annual

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distributions given the observed intra–annual and annual peak discharges. In view of Eq. (1), the annual log-likelihood, presents in the second term at the right hand side of Eq. (2), can be computed by

$$\ln\left[f_{Q_Y}(q_{Y,k}|(\boldsymbol{\theta}_1,\ldots,\boldsymbol{\theta}_N))\right] = \ln\left[\sum_{i=1}^{N} f_{Q_i}(q_{Y,k}|\boldsymbol{\theta}_i)\left(\prod_{\substack{j=1\\ j\neq i}}^{N} F_{Q_J}(q_{Y,k}|\boldsymbol{\theta}_j)\right)\right]. \quad (3)$$

Since Eq. (2) depends only by seasonal parameters $\boldsymbol{\theta}_1,\ldots,\boldsymbol{\theta}_N$.

4. Through an optimization algorithm maximize the objective function given by Eq. (2) therefore identifying the best parameter set (i.e. optimal parameter set).

Weights in Eq. (2) are introduced to control the relevance of the fit of each single frequency distribution in the overall procedure. Weights are necessary because Eq. (2) is a fit-for-purpose procedure that makes a redundant use of the annual maximum peak flow, whose frequency distribution is used twice to assign a priority, if needed, to the fit of the annual distribution with respect to the related seasonal ones. With a proper choice of weights, the proposed procedure may converge to the traditional procedure that is based on the analysis of annual maxima only. One application of the proposed approach is presented in the following section.

3 Application to the Blue Nile River at Sudan-Ethiopia Border

The proposed method was used to estimate the flood frequency distribution, by referring to different yearly subperiods, for the Blue Nile River at Sudan-Ethiopia Border. The Blue Nile originates from Lake Tana, in Ethiopia. Together with the White Nile, it is one of the major tributaries of the Nile River. The main stream length at Sudan Border is about 900 km and the contributing area is 175 000 km^2. The Blue Nile is vital to the livelihood of Egypt. In fact, about 59 % of the water that reaches Egypt is due to

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the Blue Nile contribution. Figure 1 shows a schematic representation of the Blue Nile watershed.

Daily river flow observations that were collected by the Ethiopian Ministry of Irrigation and Water Resources (MoWR) between 1961 and 2005 (i.e. 45 yr) are available at Sudan Border. Nevertheless, the series is affected by several missing data, mainly from January to June/July, therefore the number of usable years is less than 45. In particular, we retained in the annual maximum series of flood flows only the 25 yr for which daily observations are available during the whole wet season (i.e. from June to September, see Rientjes et al., 2011). Concerning seasonal sub-samples, we included the seasonal maximum daily discharge in the seasonal database only when observations are available for at least 70 % of the i-th season.

The maximum annual flood of the Blue Nile exhibits a very strong seasonality and is characterized by one peak season, as it is common in monsoon–dominated climates. Indications reported in the literature (e.g. Rientjes et al., 2011) distinguishes two main climatic seasons for the study area, namely: a wet (i.e. from June to September) and a dry (i.e. from October to May) season, while in the easternmost part of the study area a subdivision into three climatic seasons is suggested by some authors (e.g. Seleshi and Camberlin, 2006): Kiremt ("main rains", heavy rainy season, June–September), Belg ("small rains", light rainy season, February–May), and the dry season Bega (October–January). During the wet season the contribution of the Blue Nile is about two thirds of the flow of the receiving Nile.

3.1 Season identification

In order to identify the optimal number of seasons, climatic behaviours were considered along with the practical need to estimate peak flows in assigned periods for water resources management purposes. To obtain a first picture of climatic behaviours, Fig. 2 shows the progress of the mean daily streamflows along the year (black thin dotted line) together with a 30-day running mean (black thick line). The standard deviation of daily streamflows is also reported (red thin dotted line) together with a 30-day running mean (red thick line), while annual maximum peak flows are indicated as blue dots. It can be seen that seasonality is very pronounced with one flood season only.

Directional statistics were used to quantify seasonality of flood events (Mardia, 1972) on the basis of the timing of annual maximum flood flows. After Bayliss and Jones (1993), the date of occurrence of the event i can be written as a directional statistic by converting the Julian date, Jd, of occurrence into an angular measure given by

$$\varphi_i = \mathrm{Jd}_i \left(\frac{2\pi}{365} \right). \tag{4}$$

Therefore, each date of occurrence can be represented in polar coordinates as a vector with a unit magnitude and a direction given by Eq. (4). This allows the determination of the x and y coordinates of the mean of a sample of Z dates of occurrence as

$$x = \frac{1}{Z} \sum_{i=1}^{Z} \cos(\varphi_i); \; y = \frac{1}{Z} \sum_{i=1}^{Z} \sin(\varphi_i)\;. \tag{5}$$

Therefore, the direction $\overline{\varphi}$, along with the magnitude, r, of the vector representing this point in polar coordinates, can be obtained by

$$\overline{\varphi} = \arctan \left(\frac{y}{x} \right), \tag{6}$$

$$r = \sqrt{x^2 + y^2}. \tag{7}$$

Equation (6) represents a measure of the mean timing for the sample of Z dates, such as the days of occurrence in an annual maximum series, and can be converted back to a mean date, MD, through

$$\mathrm{MD} = \overline{\varphi} \left(\frac{365}{2\varphi} \right). \tag{8}$$

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Equation (7) gives a measure of the regularity of the phenomenon: values of r close to one imply a strong seasonality, or regularity, in the dates of occurrence of the events, values close to zero are symptomatic of a great dispersion throughout the year.

Through directional statistics the limits of the flood season, φ_1 and φ_2, are quantitatively identified through the relationship

$$\varphi_{1,2} = \overline{\varphi} \pm \sigma, \tag{9}$$

where the negative and positive signs correspond to the beginning and the end of the season, respectively, and σ is the standard deviation in radiants given by $\sigma = \sqrt{-2\ln(r)}$ (Mardia, 1972). The computed mean angular measures are converted back to calendar dates by using Eq. (8).

Directional statistics were applied to annual maximum series (AM) of daily streamflows of the Blue Nile at Sudan-Ethiopia Border. The results show that the annual maximum flood is extremely regular, with measure of regularity equal to $r = 0.977$ (it is relevant to note that $r = 1$ would correspond to observed annual maxima happening on the same day of the year). Most of the observed flood dates falls within the 3-week time period from 31 July to 25 August. We identify this period as the flood season. Furthermore, we identify three additional seasons to fully characterize the high streamflow regime (see Fig. 2), by also taking practical need of water resources management into account: a dry season from 1 November to 31 May; a pre-flood season from 1 June to 30 July, and a post flood season from 26 August to 31 October. For each of the above periods, the seasonal maximum daily discharge was extracted. Table 1 presents the record length in years of each seasonal sample as well as the unique sample composed by the annual peak discharge. The matrix of the Pearson's correlation coefficients between the different samples is also shown in Table 1.

It can be seen that the null hypothesis of statistical mutual independence of seasonal peaks cannot be rejected at the 5 % significance level, with the exception of the post-flood season that is positively correlated to the flood season.

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It is relevant to point out that, in principle, the number of seasons and their calendar limits can be defined arbitrarily. However, for increasing number of seasons one experiences a higher chance of detecting correlation among them. It is also significant to note that season identification based on climatic behaviours, rather than an arbitrary selection, leads to yearly subperiods that are well distinguished from a climatic point of view and therefore are more likely to be independent (e.g. Waylen and Woo, 1982; Durrans et al., 2003; Strupczewski et al., 2012; Kochanek et al., 2012).

3.2 Estimation of seasonal and annual flood frequency distributions

Table 1 reports the results of the Plotting Position Correlation-Coefficient (PPCC) test (e.g. Vogel, 1986; Castellarin et al., 2004) that was carried out to test the suitability of the Gumbel distribution (also called EV1 distribution) to simulate the flood frequency behaviours in each season. For all seasons the linear correlation coefficient is reported between seasonal flood flows and their sample non-exceedance probability expressed through the Gumbel reduced variate (i.e. $y = -\ln(-\ln(F))$, where F indicates the nonexceedance probability). The test value for a 5 % significance level is also given. It can be seen that the Gumbel distribution can never be rejected at the 5 % significance level for all the seasons. Therefore, initial values for the distribution parameters were estimated through the L-moments method (Hosking and Wallis, 1997) (see Table 2).

Through a genetic algorithm (Mebane and Sekhon, 2011), the seasonal distribution parameters were obtained by maximizing Eq. (2). Figure 3 shows in a Gumbel probability plot the initially fitted seasonal distributions (dotted lines) along with the sample frequency of the observed data (dots) and the final seasonal distributions resulting from the proposed approach (continuous lines) by adopting uniform weights. The annual CDF obtained from individual fitting of annual maxima and joint estimation technique are also shown (blue dashed-dotted and continuous lines, respectively). The figure also evidences the problem of crossing over: for a return period approximately equal to 7–15 yr, the independently fitted flood season distribution (pink dotted line)

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cross the independently fitted annual distribution (blue dashed-dotted line). The seasonal distribution parameters, given by initial fitting and jointly fitting, are summarised in Table 2.

Figure 3 shows a fair-to-good agreement between sample, individually fitted and joint estimated distributions, although some slight discrepancy is detected, as expected. In particular, the individually (independently) fitted seasonal distributions are overestimated while the contrary holds for the individually fitted annual distribution.

It can be also seen that the effect of dependence on the fitting of the post flood and the flood season, namely, the difference between independent and joint estimates, is indeed negligible. As it was expected for the given climate, it can be seen that the annual distribution is similar to that of the dominant flood season (Strupczewski et al., 2012; Kochanek et al., 2012).

In Fig. 4 the sensitivity of the method to the choice of weights is characterised by showing the differences in percentage between the 100-yr peak flows estimated jointly with the proposed technique and the ones estimated by maximum likelihood independently on each season and on the maximum annual values.

The effect of attributing a prevailing weight (95 %) to one given season or to the annual distribution is shown in Fig. 4a. The estimated 100-yr quantile for the season (or annual distribution) with the high weight is very close to the corresponding independent estimate. This result is expected because the objective function is very close to the individual log-likelihood function for the season (or annual distribution). On the other hand, Fig. 4b shows the effect of attributing a small weight (5 %) to one distribution only. For instance, if the small weight is assigned to the annual distribution (light-green weighs combination), the seasonal estimates lie close to the individual maximum likelihood estimates, since the objective function is almost coincident with the sum of the log-likelihoods of observing the seasonal peaks independently.

In summary, Fig. 4 demonstrates that the annual distribution, as well as the flood and post flood seasons, are sensitive to the value of the weights, while the pre-flood and dry seasons display little or no sensitivity. This is because our method accounts for

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the dependence between seasonal and annual maxima (and not among the seasons themselves) and the peaks in the pre-flood and dry season almost never are maximum annual peaks.

4 Conclusions

We propose an estimation procedure for the joint fitting of seasonal and annual flood frequency distributions that ensures their consistency, i.e. the fact that the probability of one peak value of being exceeded in the entire year is higher than the probability of the same value of being exceeded in one season. Differently from previous studies, our method allows the user to attribute weights to the estimation of seasonal and/or annual flood frequency distributions. A relevant feature of the approach is that the number of seasons and their calendar limits can be defined with great flexibility. However, this characteristic is limited by the assumption of independence among the peak flow seasonal distributions, which conditions season selection. Further research work is currently under development to remove the above assumption therefore ensuring full flexibility in practical applications.

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Table 1. Matrix of Pearson's seasonal correlation coefficients for the Blue Nile River at Sudan Border. The second last column reports the linear correlation coefficient between seasonal flood flows and the associated Gumbel reduced variate; the last shows the PPCC test value for assessing the goodness of the fit of the Gumbel (i.e. EV1) distribution for a significance level of 5 %.

Season	Record length (years)	Pearson's Corr. Coeff.				PPCC	
		Dry Season	Pre flood Season	Flood Season	Post flood Season	Corr. coeff.	Test value $\alpha_{5\%}$
Dry	18	1	−0.018	0.000	0.355	0.972	0.933
Pre flood	21	–	1	0.008	0.158	0.977	0.940
Flood	25	–	–	1	0.526	0.985	0.946
Post flood	24	–	–	–	1	0.982	0.944
AMS	25					0.977	0.946

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Table 2. Seasonals distribution parameters [$m^3 s^{-1}$]: independent fitting (L-moments method) and joint estimation by adopting uniform weights (proposed method).

Season	Independent Estimation (L-moments)		Joint Estimation (Proposed method)	
	Location	Scale	Location	Scale
Dry season	1182	533	1195	492
Pre flood season	4433	1061	4432	1056
Flood season	6666	1372	6600	1267
Post flood season	5660	1226	5622	1208

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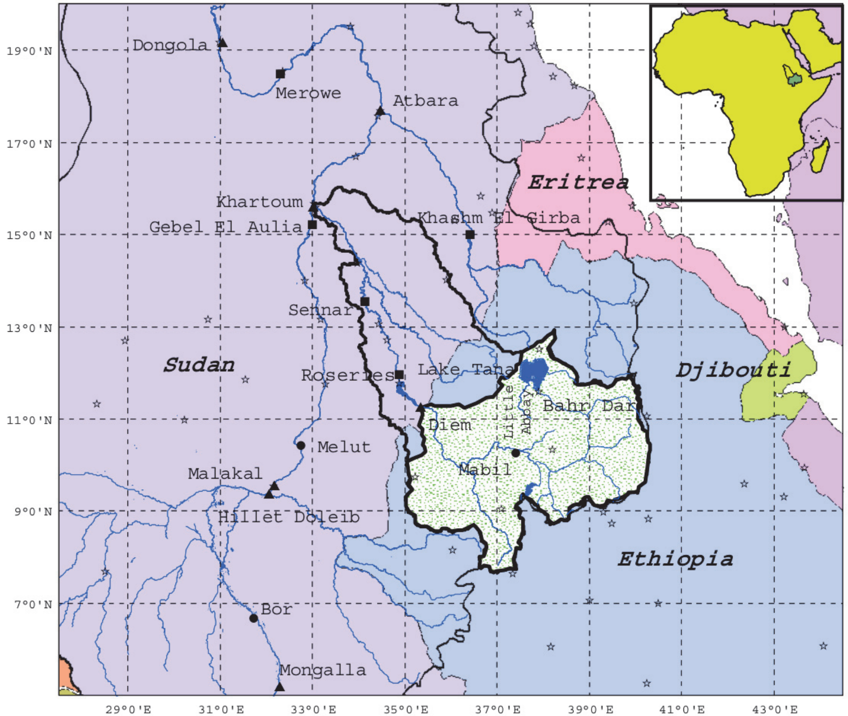

Fig. 1. Schematic representation of the upper Blue Nile Basin (hatched) within Blue Nile River basin (outlined). Source: Fig. 1 in Elshamy et al. (2009).

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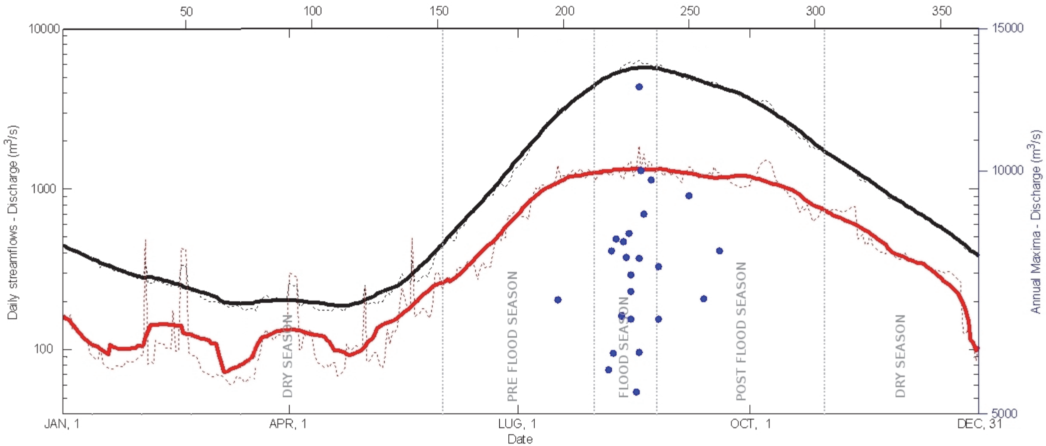

Fig. 2. Mean daily streamflow (black thin dotted line) and 30-day running mean (black thick line); standard deviation of daily streamflows (red thin dotted line) and a 30-day running mean (red thick line) as a function of the day of the year; annual maximum series are also reported (left y axis) as blue dots.

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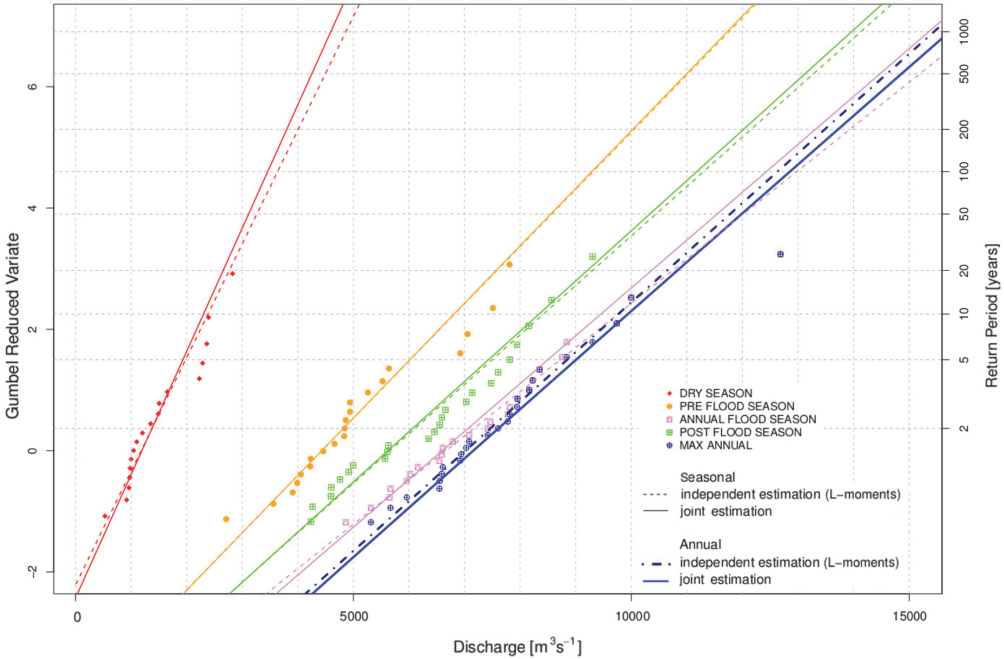

Fig. 3. Empirical (dots) and theoretical CDFs of the seasonal (dotted lines) and annual (blue dashed-dotted lines) maxima estimated using the L-moments method; CDFs estimated by maximizing the proposed objective function of the observed seasonal samples (thin lines) and annual flood CDF obtained as the product of the seasonal CDFs (thick blue line) by adopting uniform weights.

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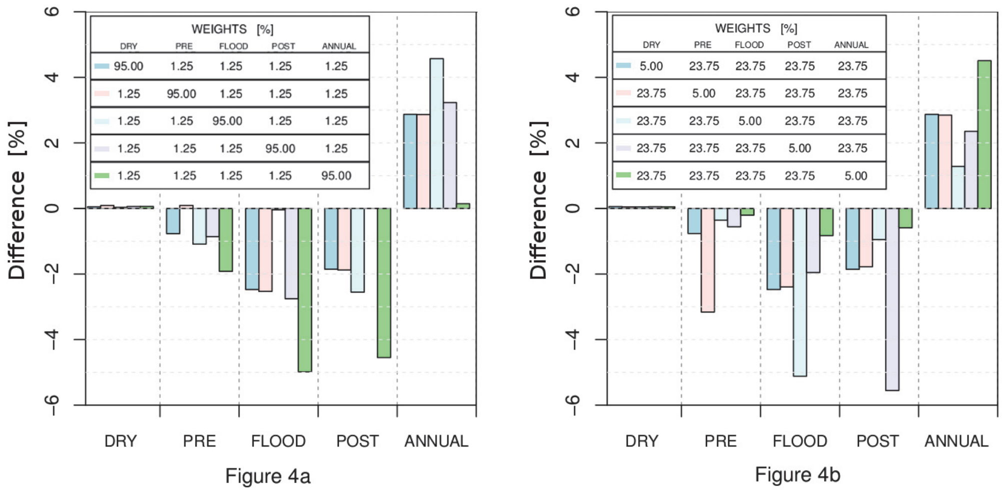

Fig. 4. Differences in percentage between the 100-yr peak flows estimated jointly (proposed technique) and the ones estimated by maximum likelihood independently on each season and on the maximum annual values. **(a)** prevailing weight (95 %) to one given period and 1.15 % to the other distributions; **(b)** small weight (5 %) to one given period and 23.75 % to the other distributions.

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