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Flood seasonality-based regionalization methods: a data-based comparison

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Abstract:

Improving techniques of flood frequency estimation at ungauged catchments is one of the major challenges for hydrologists, especially in arid and semi-arid regions with insufficient information. Recently, popularity of flood seasonality-based descriptors has increased among hydrologists for delineating of hydrologically homogenous regions.

This study presents a data-based comparison of three well-known flood seasonality-based regionalization methods in Halilrud basin in southeastern Iran. A Jack-knife procedure is used to assess the performance of the methods for flood quantile estimation at ungauged sites. The results of these three seasonality-based methods are compared to those results obtained from two alternative methods: a traditional regionalization method based on catchment's hydrogeomorphic characteristics similarity and a scenario that uses all available information without subdividing area.

The results indicate that although peak over threshold (POT) approach which uses all flood events during year leads to better performance than other methods, but applying POT data series in a specific season (critical season) based on POT-CS approach leads to better homogenous region and improves flood quantile estimation at ungauged sites. Copyright © 2011 John Wiley & Sons, Ltd.

KEY WORDS seasonality-based regional flood frequency; peak over threshold method; Jack-knife; critical season

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INTRODUCTION

Regional flood frequency analysis is a common method used for reliable estimation of flood quantiles in the required return period at the ungauged locations. This objective comprises two main steps: (i) delineation of homogenous region and (ii) estimation of the regional flood quantiles at different return periods for the region of interest. The identification of homogenous regions is a fundamental step in regional frequency analysis. Catchment grouping approaches based on geographic similarity and flood magnitude are common methods used for the delineation of homogenous region (Mosley, 1981; Wiltshire, 1985; Acreman and Sinclair, 1986; Chokmani and Ouarda, 2004). However, an approach based on similarity in flood seasonality has been recently gaining increased popularity among hydrologists. In this seasonal regional method, the delineation of homogenous regions is based on the seasonal behaviour of flood flows in different sites (Ouarda *et al*., 1993; Burn, 1997; Cunderlik and Burn, 2002; Cunderlik *et al*., 2004). The seasonal partitioning of flood events can help water resources manager to identify the flood risk associated with seasonal behaviour of floods. The results of flood seasonality that lead to the delineation of hydrologically homogenous regions can also be used for separating mixed-distribution floods generated by different mechanisms and in other applications in the field of water resources management such as reservoir management, flood forecasting and floodplain protection (Ouarda *et al*., 2006).

During the last decade, several directional statistic-based methods have been proposed for flood seasonality-based regionalization (Magilligan and Graber, 1996; Cunderlik and Burn, 2002). The main advantage of these approaches is that flood seasonality is based on date data which are particularly error-free and more robust than methods based on flood magnitude data. The use of directional statistical methods for flood seasonality can be found in Bayliss and Jones (1993), Burn (1997), Castellarin *et al*. (2001), Cunderlik and Burn (2002) and Cunderlik *et al*. (2004). Ouarda *et al*. (2006) presented a data-based comparison of three flood seasonality regionalization methods by using a set of catchments in the province of Quebec (Canada). They used Jack-knife procedure to assess the performance of the methods in regional quantile estimation. Comprising with the results of traditional regionalization methods, the seasonality method based on the peak over threshold (POT) approach was concluded to have the best results.

Although the increasing interest in the use of flood seasonality for identifying homogenous hydrological regions for regional flood frequency, there is no study focussing on flood seasonality approaches in arid and semi-arid regions. The insufficient data for flood frequency analysis, complex physiographic characteristics; including high mountainous area and low flat plains in arid regions

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in combination with irregular spatiotemporal pattern of intense rainfall make it difficult to address the exact flood generating mechanisms in arid regions, especially for flash floods. Regional flood frequency based on the seasonality approaches can help us to understand the role of different factors on flash floods in these areas.

The aim of this study is to present a data-based comparison of three main approaches for describing flood seasonality to find the best flood regionalization method in arid region with the problem of insufficient available data for better quantiles estimation at ungauged sites: the method based on the relative frequencies (RFs) of flood occurrence, the method based on directional statistics and the method based on discrete seasonal POT model (POT-DS).

In the first part of this study, part A, homogenous hydrological regions with similar flood regime are identified based on seasonality-based methods. In each region, flood quantiles are estimated at all sites (treated consecutively as ungauged sites) using a Jack-knife procedure. The performance results of quantile estimation at ungauged sites are then compared for all the three methods. The results are also compared with two alternative methods: a traditional regionalization method based on similarity of hydrogeomorphic catchment characteristics and the results of a scenario which assumes all regions as a single region and all available information is used in the regional analysis.

In the second part of this study, part B, better homogenous regions are tried to being identified and flood quantile estimation at ungauged sites based on ‘discrete critical season POT mode’ which uses only information of exceedances in a specific season are improved. Finally, the results of two part A and B are compared and the best regionalization method is introduced. Figure 1 shows a brief overview of the procedure of this study.

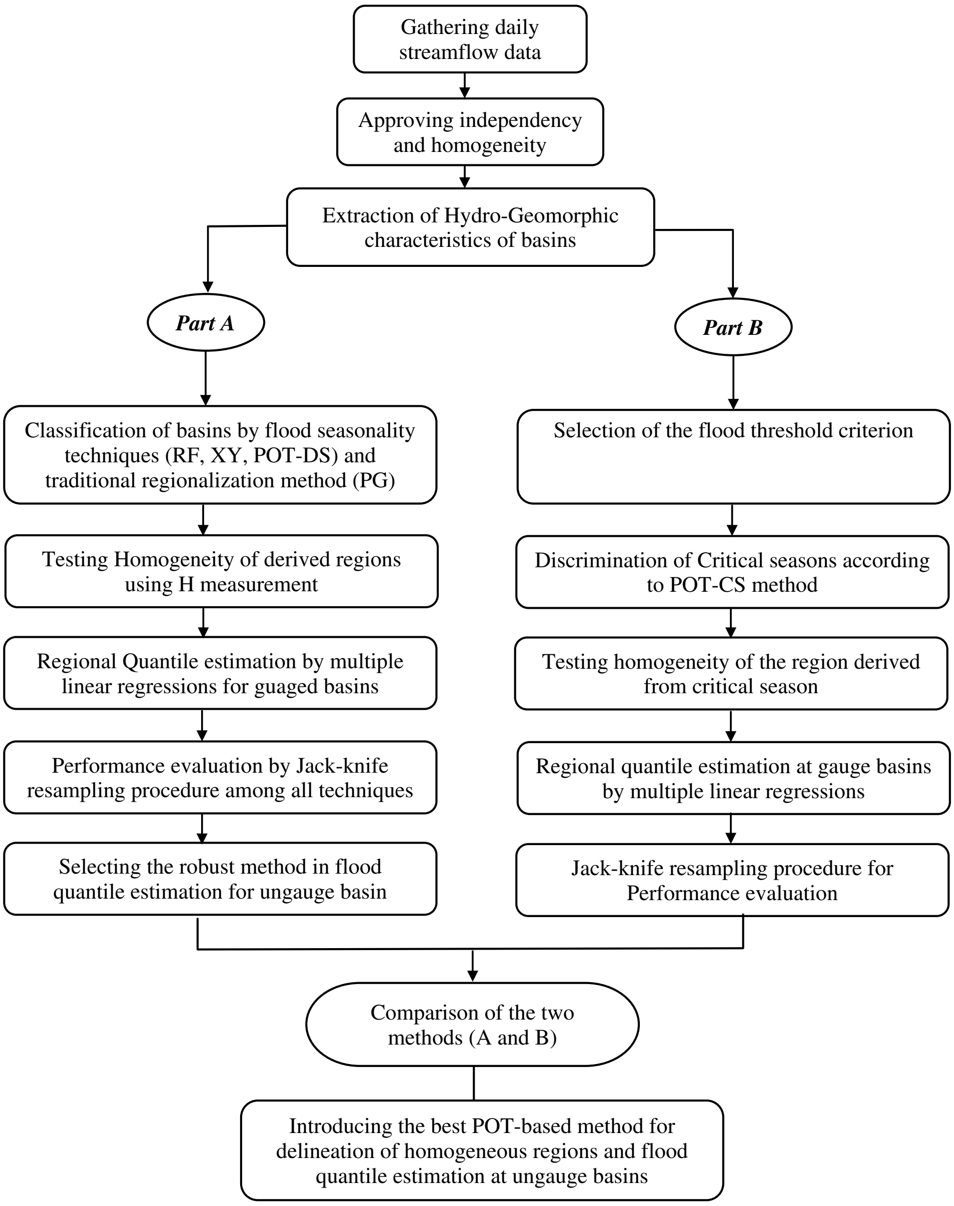

Figure 1. Flowchart of the methodology

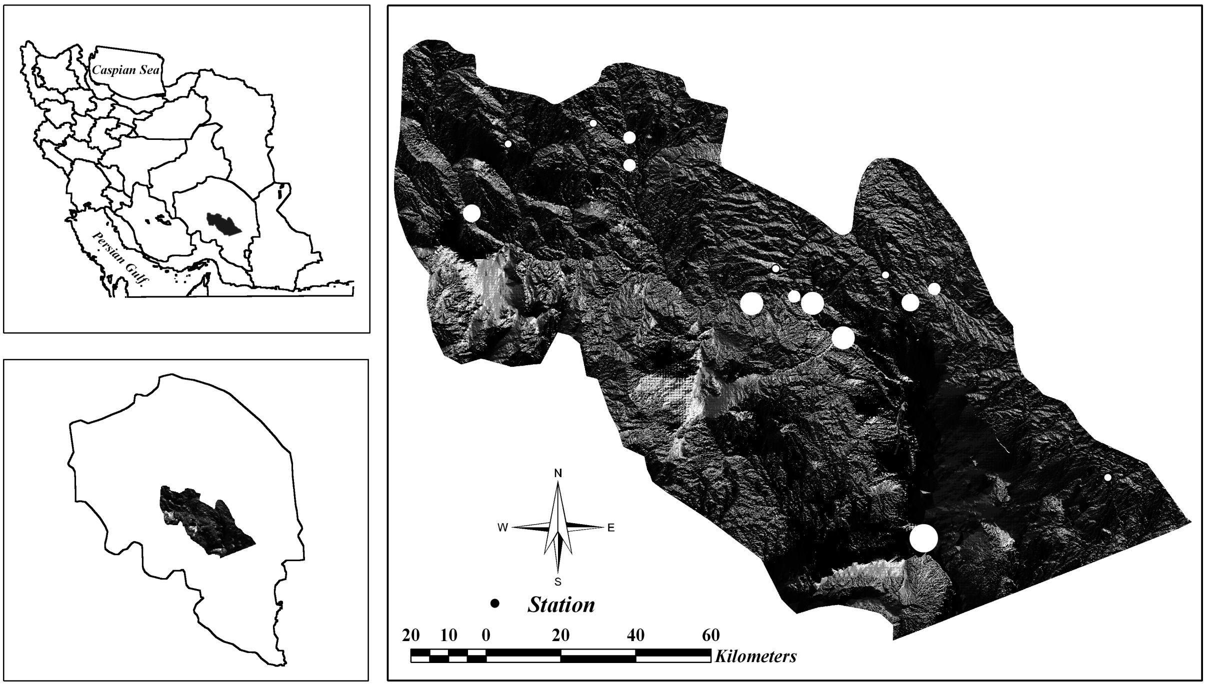

Figure 2. Location map of Halilrud basin with flow direction map and selected stations (diameter of the circles is proportional to catchment area)

STUDY AREA AND DATASET

In this study, Halilrud basin was selected as the study area. Located in the south of Kerman province in arid and semi-arid regions of Iran, Halilrud basin with the area of 1·6 Mha, 250 mm annual rainfall and average elevation of 1774 m is considered as one of the most vulnerable watershed of southeast territory of Iran to flash flooding hazard. There are two permanent rivers in this basin which originate from upward mountains and tilt to the flat area. Characterized by wide cross section and high flood magnitude in wet season, these rivers cause heavy damages to the population centres. As shown in Figure 2, high mountain ranges and abruptly slope changing in the foot of mountains have made special hydrogeomorphical characteristics for Halilrud basin as a vulnerable region to the flooding hazard. These conditions accompanied with usual heavy storms of arid and semi-arid regions increase the risk of flood damages to residential and commercial centres in the Halilrud basin. Therefore, it is important to estimate flood magnitude at ungauged sites based on identifying the seasonal distribution of flash floods in hydrologically homogenous catchments, which can help decision makers and managers in an optimum management and for planning mitigation strategies to cope with the flood hazard.

In this study, daily streamflow of 15 stations across the two main catchments of Halilrud basin (Halil and Shur catchments) are used. The location of these stations has been illustrated in Figure 2. The circle size presents a scale for the area of each catchment. The length of available data record is different, so that the shortest length of data belongs to Kenaruieh station (15 years) and the longest record belongs to Soltani station (36 years). The mean of record length for all stations is 22 years. It is worth noting that short data record is a common problem in arid and semi-arid regions of the world and this study aims to propose a methodology to find the best flood regionalization method in arid regions with the problem of insufficient available data for better quantile estimation.

The catchment properties were determined using digital elevation model of the basin. The following hydrogeomorphic and climatic characteristics in each subcatchment were extracted using HEC-GEO HMS extension in Arc GIS 9·3 software. Land use characteristics are also extracted by ETM+ images of Landsat satellite taken in 2002 (Modarres and Sarhadi, 2010). The main variables used in this study for fitting regional regression model are as follows:

- Area, drainage area (km^2)
- MAR, mean annual rainfall (mm)
- BS, basin slope (%)
- Dd, drainage density (km/km^2)
- ME, mean elevation, maximum elevation and minimum elevation (m)
- RS, river slope (%)
- BL, bare land (km^2)
- BA, building area (km^2)
- VC, vegetation cover (km^2)

The characteristics of these 15 selected stations are given in Table I.

METHODOLOGY

Flood seasonality measurements

RFs of flood occurrence. Identification and clustering of flood occurrences dates into calendar months can

Table I. Characteristics of 15 selected basins at Halilrud basin

Station name	Mean annual rainfall (mm)	Area (km^2)	Basin slope (%)	Drainage density (km/km^2)	Minimum elevation (m)	Maximum elevation (m)	Mean elevation (m)	River slope (%)	Bare land (km^2)	Urban area (km^2)	Vegetation cover (km^2)
Aroos	293·08	292·73	32·0	0·74	1283·8	3586·9	2337·7	3·8	235·80	0·19	56·74
Cheshme	320·28	76·42	29·9	0·98	2627·4	3386·7	2971·62	3·18	45·39	19·25	11·78
Dehrood	284·41	1136·87	38·62	0·87	1158·2	3503·9	2155·19	2·2	742·15	57·4	337·32
Hanjan	312·42	265·17	34·27	0·85	2330·0	3350·0	2784·9	2·44	177·10	78·35	9·72
Hossienabad	288·44	8775·94	12·45	0·85	977·24	3586·9	2244·11	0·79	7142·51	1075·48	557·95
Kahnak	273·99	14 181·12	12·45	0·91	530·0	3586·9	1925·28	0·63	10 350·87	2360·92	1469·33
Kaldan	295·84	134·02	51·9	0·79	1620·0	3288·6	2420·3	4·71	79·66	1·25	53·11
Kenarueih	290·55	7781·28	12·45	0·9	1420·0	3499·3	2294·8	0·7	6234·73	1074·92	471·63
Meidan	309·68	554·94	34·27	0·87	2212·6	3386·7	2718·8	2·2	298·85	221·29	34·80
Narab	289·81	8306·88	12·45	0·89	1160·0	3586·9	2278·24	0·64	6693·23	1075·11	538·54
Polbaft	308·13	165·07	12·37	0·85	2475·2	2897·3	2680·9	1·63	129·50	22·98	12·59
Ramoon	285·46	33·71	44·15	0·57	1637·3	2463·1	2186·68	5·79	30·98	0	2·73
Soltani	300·49	853·52	12·45	0·9	2180·0	3090·6	2518·67	0·97	662·63	152·46	38·43
Tighsiah	286·2	4·39	42·4	0·64	1829·6	2907·6	2134·3	4·1	3·64	0	0·75
Zarrin	282·3	353·95	29·75	0·91	1461·8	3112·6	2095·4	2·81	216·18	54·39	83·38

represent detailed information about flood seasonality. This approach is usually used for each single month. In this method, dates of flood occurrences are grouped into months and the RFs of flood occurrences are calculated for every month. An adjustment must be accompanied when converting time into angles. Mardia (1972) proposed a frequency-based method in which the frequencies can be adjusted so that they correspond to 360 days with all months having the same length and 1° will correspond to 1 day. To achieve this, the observed frequencies for months with 31 days are multiplied by 30/31 and the frequency for February by 30/28 or by 30/29 respectively for a normal or a leap year. The year is then reduced to 360 days but the sum (S) of the original frequencies RF_i does not equal the sum (S') of the adjusted frequencies $\mathrm{RF}_i{}'$. To preserve the sum S, the final adjusted frequencies are obtained by multiplying $\mathrm{RF}_i{}'$ by S/S'.

$$\sum_{i=1}^{12}\mathrm{RF}_i = \sum_{i=1}^{12}\mathrm{RF}_i^{'}\frac{S}{S^{'}} \tag{1}$$

Therefore, the use of this method can represent flood seasonality pattern and similarity between two sites based on RF. The similarity of two catchments ($\mathrm{Sim}_{i,j}$) is then expressed as the following (Cunderlik and Burn, 2002):

$$\mathrm{Sim}_{i,j} = \sqrt{\frac{\sum_{k=1}^{12}(\mathrm{RF}_i^k - \mathrm{RF}_j^k)}{12}} \tag{2}$$

where RF_i^k and RF_j^k are the adjusted RFs of flood occurrence at catchments i (j) for month k. This method will be hereafter abbreviated as the 'RF' method.

Directional statistics. In this approach, flood seasonality can be described by converting dates of flood occurrences into a directional statistics (Fisher, 1993), so that each of the individual dates of flood occurrences is defined as a directional variable by converting Julian day (JD_i) to an angular value (θ_i) using the following equation:

$$\theta_i = \mathrm{JD}_i\frac{2\pi}{\mathrm{ND}} \qquad 0 \leq \theta_i \leq 2\pi \tag{3}$$

where ND is the number of days in a year (ND = 365 or 366 for a leap year and 1 January corresponds to day 1). θ_i is the angular value representing the date of flood event i (in radians). Therefore, a date of flood occurrence represents a vector with a unit magnitude and a direction given by θ_i. The mean direction, $\overline{\theta}$ (or the mean day of flood occurrences) MDF, is calculated by unit vectors:

$$\overline{\theta} = \tan^{-1}\left(\frac{\overline{y}}{\overline{x}}\right) \quad \overline{x} \neq 0 \quad \mathrm{MDF} = \overline{\theta}\frac{\mathrm{ND}}{2\pi} \tag{4}$$

where

$$\overline{x} = \frac{1}{n}\sum_{i=1}^{n}\cos(\theta_i) \qquad \overline{y} = \frac{1}{n}\sum_{i=1}^{n}\sin(\theta_i) \tag{5}$$

and n is the number of samples for a given site, the mean direction ($\overline{\theta}$) represents a directional location measure of a sample consisting dates of flood occurrence.

A dimensionless dispersion measure of the individual dates of flood occurrence around mean value can also be defined as a variable (Bayliss and Jones, 1993):

$$\overline{r} = \sqrt{\overline{x}^2 + \overline{y}^2} \qquad 0 \leq \overline{r} \leq 1 \tag{6}$$

The value of $\overline{r}$ close to 1 indicates that events in the sample are tightly grouped around the mean direction, whereas a value close to 0 indicates that variability in the date of flood occurrence is very high.

The direction mean and the variance measure defined in a polar coordinates by $\overline{\theta}$ and $\overline{r}$ can be represented in Cartesian coordinates by the average coordinates $\overline{x}$ and $\overline{y}$. In this way, the coordinates can describe similarity in flood seasonality at a given site and can be used to measure similarity between sites by the Euclidean distance (Burn, 1997):

$$\mathrm{D}_i\mathrm{S}_{i,j} = \sqrt{(\overline{x}_i - \overline{x}_j)^2 + (\overline{y}_i - \overline{y}_j)^2} \qquad (7)$$

where $\overline{x}_i$ and $\overline{y}_i$ are the coordinates defined in the Equation (5).

The application of this method can be found in Magilligan and Graber (1996), Cunderlik and Burn (2002) and Ouarda *et al.* (2006). They concluded that this is an appropriate method for linking flood seasonality and the influencing factors such as area and rainfall. In this study, this method will be hereafter called as 'XY' method.

POT method. Three different ways can be considered to extract information from a flow records for regional flood frequency analysis: (1) the annual maximum series (AM), (2) the partial duration series or POT and (3) the time series (TS) data. In the AM flow series, the maximum annual observation is only considered. However, the use of AM series may involve some loss of information. For example, the second or the third peak flood within a year may be ignored while they are greater than the maximum flow in other years. This problem is obviated in the POT models where all peaks above a certain base value are considered (Rao and Hamed, 2000).

In this study for regional flood frequency analysis based on POT method, we use an approach which was proposed by Ouarda *et al.* (1993):

$$\xi_\nu = \begin{Bmatrix} 0; & Q_\nu \leq Q_\mathrm{B} \\ Q_\nu - Q_\mathrm{B}; & Q_\nu \geq Q_\mathrm{B} \end{Bmatrix} \qquad (8)$$

where Q_B is the base level, Q_ν the river flow at time τ_ν and ξ_ν the exceedance at time τ_ν.

To definite a truncation level for delineation of similar flood seasonality based on POT method, we select the carrying capacity of river channel as the threshold level. For the calculation of carrying capacity of a cross section, the HEC-GEO RAS program is applied on digital terrain model with 2 m resolution at each study site. Accuracy of extracted cross sections was then tested by channel surveying.

In the 'POT-DS model', the year is divided into 'n' seasons, where exceedances belong to the Kth season, $K = 1, \ldots, n$, are taken to be identically distributed, regardless of their year of occurrence (Gupta *et al.*, 1976; Ouarda *et al.*, 1993, 2006). Hence with 'n' seasons, we obtain 'n' different distribution functions to fit to the exceedances on record. The discrete seasonal model makes two assumptions concerning flood characteristics. The first assumption is that different storm types produce different flood characteristics from one season to another, and the second is that within each season, variation in flood magnitude are negligible (Ouarda *et al.*, 1993, 2006).

The POT-DS model consists of plotting the cumulative mean number of floods exceeding threshold, Λ (t), in a time interval (1, T) equal to 1 year, against the time t, for each station, and for a truncation base level. Changing slope and piecewise linearity of the Λ (t) plots indicate significant seasons for each station. Therefore, this graphical method can illustrate seasonal variation of flood events and allows grouping sites into graphical regions that are homogenous in seasonal flood distribution. This method can also help to identifying a specific season that includes significant flood events. The application of this method can be found in Gupta *et al.* (1976), Ouarda *et al.* (1993) and Ouarda *et al.* (2006). This method will be hereafter referenced as POT-DS method.

Other reference methods

The results of the application of the RF, XY and POT-DS methods are also compared to those obtained from a traditional regionalization method which uses only catchment's hydrogeomorphic characteristics similarity for identification of homogeneous regions (no seasonality measures). This method provides a common basis to compare the performances of various seasonal-based methods (which follow the same general approach for identifying homogenous regions) in flood quantile estimation at ungauged sites. This traditional regionalization method which does not use seasonality measures will be hereafter referenced as 'PG' method.

The results obtained by the three seasonality-based methods are also compared to the results from a scenario where the set of all sites without any restoring to the delineation of homogenous regions is treated as one region, and all available information is used in the flood regionalization. The value of applying this method is that to allow identifying the advantages of the subdivision of study basin into homogenous regions according to various seasonality methods. In the remainder of this study, this method is denoted as 'ALL' method.

Comparison methodology

In the POT-DS model, the identification of seasonally homogenous regions requires the evaluation of the graphs of exceedances plotted for each site in the region. After extraction of mean number of exceedances at each station, sites are grouped according to these characteristics (the mean number of flood events). The study region is then subdivided into smaller subregions according to the duration and location of the flood events on a timescale.

To delineate homogenous regions according to flood seasonality-based methods of RF and XY, cluster analysis is also applied. The hierarchical approach is used for grouping stations into similar regions based on 12 RFs of flood occurrences in RF method, $(\overline{X}, \overline{Y})$ of the mean vector $\overline{r}$ in XY method. This method is also applied for traditional regionalization method based on catchments hydrogeomorphic characteristics similarity. As the variables have different units, it is necessary to normalize the data set prior to cluster analysis.

Hierarchical clustering is a method for simultaneously investigating grouping in data over a variety of scales, by creating a cluster tree. The hierarchical clustering technique that is used as a tool for the delineation of homogeneous regions in this study will be described in the following Section on Cluster Analysis.

Cluster analysis. The aim of hydrologic variables clustering is to group observations or variables into clusters based on high similarity of hydrologic features, such as geographical, physical and statistical properties of observations. In this method, each cluster contains the least variance of variables (the smallest dissimilarity). In this study, the hierarchical cluster technique (described by Kaufman and Rousseuw, 1990) is applied in order to classify catchments into similar regions. Several methods have been proposed for hierarchical cluster analysis, including single, average and complete linkage, and Ward's minimum variance method. The last two methods are widely used in different fields of hydroclimatic classification (Nathan and McMahon, 1990 Jackson and Weinand, 1995; Ramos, 2001; Modarres and Sarhadi, 2011). All above studies indicated that the Ward's method gives better results for classification than other methods. Therefore, Ward's method is used for partitioning the data into regions according to the similarity in flood seasonality achieved by methods of RF, XY and POT-DS, and traditional regionalization of PG method.

In Ward's method, the distance between two clusters is calculated as the sum of squares between two clusters, added up over all variables. At each iteration, the sum of squares is minimized. If CK and CL are two clusters that merged to form the cluster CM, the distance between the new cluster and another cluster CJ is

$$d_{\mathrm{J.M}} = \frac{((n_{\mathrm{J}} + n_{\mathrm{K}}))d_{\mathrm{JK}} + (n_{\mathrm{J}} + n_{\mathrm{L}})d_{\mathrm{JL}} - n_{\mathrm{J}} d_{\mathrm{KL}})}{n_{\mathrm{J}} + n_{\mathrm{M}}} \qquad (9)$$

where n_{J}, n_{K}, n_{L} and n_{M} are the number of the stations in clusters J, K, L and M, respectively, and d_{JK}, d_{JL} and d_{KL} represent the distances between the observations in the clusters J and K, J and L and K and L, respectively.

After clustering of sites, due to regional flood frequency analysis requires to homogenous regions, to ensure about homogeneity of clustered sites, heterogeneity measures of L-moments approach are applied.

L-moments approach. The method of L-moments (Hosking and Wallis, 1997) is now a common and robust method for regional frequency analysis of different hydrologic and climatic variables. For example, Kumar *et al.* (2003), Modarres (2008a,b) and Yurekli *et al.* (2009) have used L-moments method for flood, low flow, wind speed and extreme rainfall, respectively.

L-moments are linear combinations of order statistics, which is used for summarizing theoretical distribution of an observed sample of a random variable (X). Hosking and Wallis (1997) defined L-moments as linear functions of probability weighted moments (PWMs), which are robust to outliers and virtually unbiased for small sample. Greenwood *et al.* (1979) defined PWMs as:

$$\beta_r = E\left\{X[F(X)]^r\right\} \qquad (10)$$

where $F(X)$ is the cumulative distribution function of X, and β_r is the rth-order PWM. The first four L-moments related to the PWMs are calculated as

$$\lambda_1 = \alpha_0 = \beta_0 \qquad (11)$$

$$\lambda_2 = \alpha_0 - 2\alpha_1 = 2\beta_1 - \beta_0 \qquad (12)$$

$$\lambda_3 = \alpha_0 - 6\alpha_1 + 6\alpha_2 = 6\beta_2 - 6\beta_1 + \beta_0 \qquad (13)$$

$$\lambda_4 = \alpha_0 - 12\alpha_1 + 30\alpha_2 - 20\alpha_3 = 20\beta_3 - 30\beta_2 + 12\beta_1 - \beta_0 \qquad (14)$$

In general:

$$\lambda_{r+1} = (-1)^r \sum_{k=0}^{r} p^*_{r,k}\alpha_k = \sum_{k=0}^{r} p^*_{r,k}\beta_k \qquad (15)$$

Different L-moment ratios can then be defined (Hosking and Wallis, 1997). λ_1, is measure of central tendency, $\tau = \lambda_1/\lambda_2$ is a measure of scale and dispersion (or the L-coefficient of variation, L-CV), the ratio λ_3/λ_4 is referred to as τ_3 or the measure of skewness (L-coefficient of skewness, L-CS), whereas the ratio λ_4/λ_2 referred to as τ_4 is the measure of kurtosis (L-coefficient of kurtosis, L-CK).

Hosking and Wallis (1997) also derived three useful statistics for (i) estimation of the degree of homogeneity of a group of sites (Heterogeneity measurement, H_i), (ii) determination of an unusual site in a group (Discordancy measurement, D_i) and (iii) identification of regional distribution function (Z^{DIST}). In this study, we apply the first two statistics to test the homogeneity of the groups identified by cluster analysis of different flood seasonality indices and to find the discordant station(s) within each group.

For the sake of brevity, the detailed information and formulas of L-moments and the statistics are not given in this article and the reader is referred to Hosking and Wallis (1997) for more details.

Flood estimation at gauged sites

For at-site flood quantile estimation, different frequency distributions are fitted to flood data, and the parameters of the distribution are estimated by maximum likelihood method. The best at-site frequency distribution for flood data can be assessed by least-square error. The root mean square error (RMSE) is used as a measure of goodness-of-fit test for each single distribution fitted to flood data series derived from various methods.

Model performance for flood estimation at ungauged sites

When no discharge record exists at site of interest, a regional regression model can be used to estimate streamflow statistics at the ungauged sites. Therefore, using a region of gauged river sites, this method (multivariate regression analysis) requires relationship between flood quantiles at different probabilistic levels (specific return periods) and hydrogeomorphic characteristics to be developed. Performance evaluation of different models for quantile estimation at ungauged sites is done based on Jack-knife resampled multiple linear regression (MLR). The primary advantage of Jack-knife resampling is that the goodness-of-fit statistics are based on the predictions from data that are independent of the calibration data. Thus, they more likely indicate the accuracy of future prediction than the statistics based on calibration of all data set and the main advantage is that the methodology is easy to apply.

An MLR model between at-site flood quantiles and basin characteristics is first developed in each homogeneous region identified by each seasonality method. To evaluate the flood estimation accuracy at ungauged basins, the Jack-knife procedure is used. In other words, in each region, a site is considered as an ungauged target site and is removed from the data base. All remaining sites are then used to build a multiple regression model for the estimation of flood quantiles corresponding to different return periods at the removed target site. Final estimation of quantiles is then obtained in each target basin using the selected seasonality-based approach for determination of homogenous regions coupled with a multiple regression estimation procedure.

The following relative performance measures, the BIAS_T and the RMSE_T, are calculated for each regionalization methods:

$$\mathrm{BIAS}_T(\%) = \frac{1}{N}\sum_{i=1}^{N}\left(\frac{\hat{Q}_T^i - Q_T^i}{Q_T^i}\right) \times 100 \qquad (16)$$

$$\mathrm{RMSE}_T(\%) = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(\frac{\hat{Q}_T^i - Q_T^i}{Q_T^i}\right)^2} \times 100 \qquad (17)$$

where $\hat{Q}_T^i$ is the estimated T-year quantile at a site i which has been removed from the regional regression model and considered as an ungauged site, Q_T^i is the estimated quantile at site i from frequency distribution function and N is the number of sites in the region.

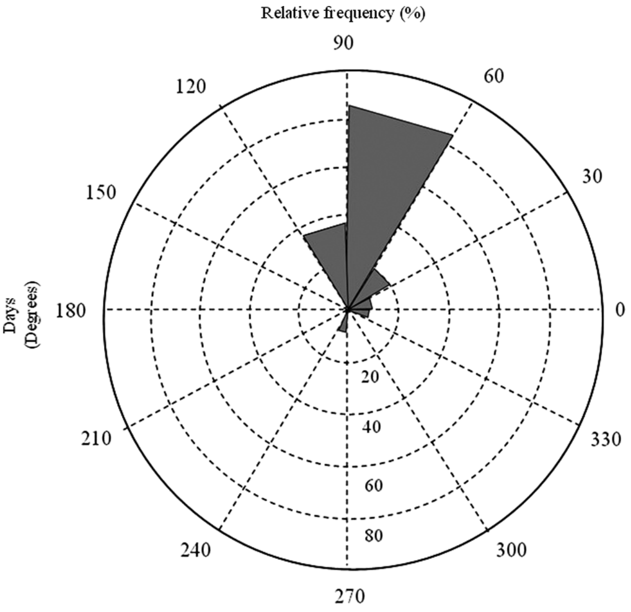

Figure 3. Flood seasonality of Soltani station according to the RF method

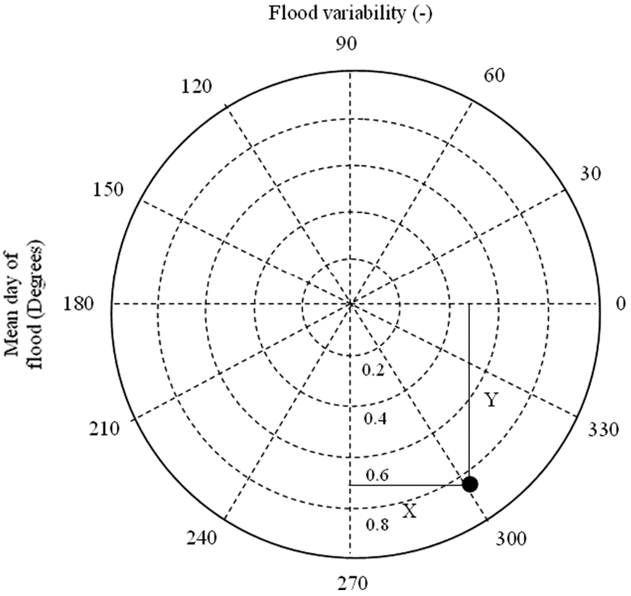

Figure 4. Flood seasonality of Soltani station according to the XY method

RESULTS

Part A

Identification of flood groups. After approving independency and homogeneity of all streamflow data with Wald–Wolfowitz and Wilcoxon methods, flood seasonality of daily streamflow was accomplished using regionalization methods described in the Section on Methodology.

A rose diagram depicting the RFs of flood occurrences using RF method in Soltani station is presented in Figure 3. Figure 4 shows the flood seasonality at this station using directional method (XY). The location of site in polar location–variance coordinates is shown using the mean day of flood occurrence (day 302) and the flood variability measure $\bar{r} = 0{\cdot}83$. For POT-DS method, after calculating of the truncation level according to stream carrying capacity at the location of each station, the cumulative average numbers of exceedances were extracted during year. Stations with similar seasonal partitioning of the year are then grouped into seasonality homogenous regions. As shown in Figure 5, except Hossein–Abad station, all sites could be considered as a hydrologically homogenous region.

Hierarchical clustering is then applied to group sites into homogenous regions for seasonality-based methods RF, XY and POT. To ensure about homogeneity of derived groups, heterogeneity measures are then used. These measures provide good indicators of how well the data fits into the structure suggested by the classification. Table II represents the homogeneity statistics of similar groups extracted from hierarchical clustering for seasonality-based approaches. According to H1 criterion, all groups are acceptably homogenous. This measure was

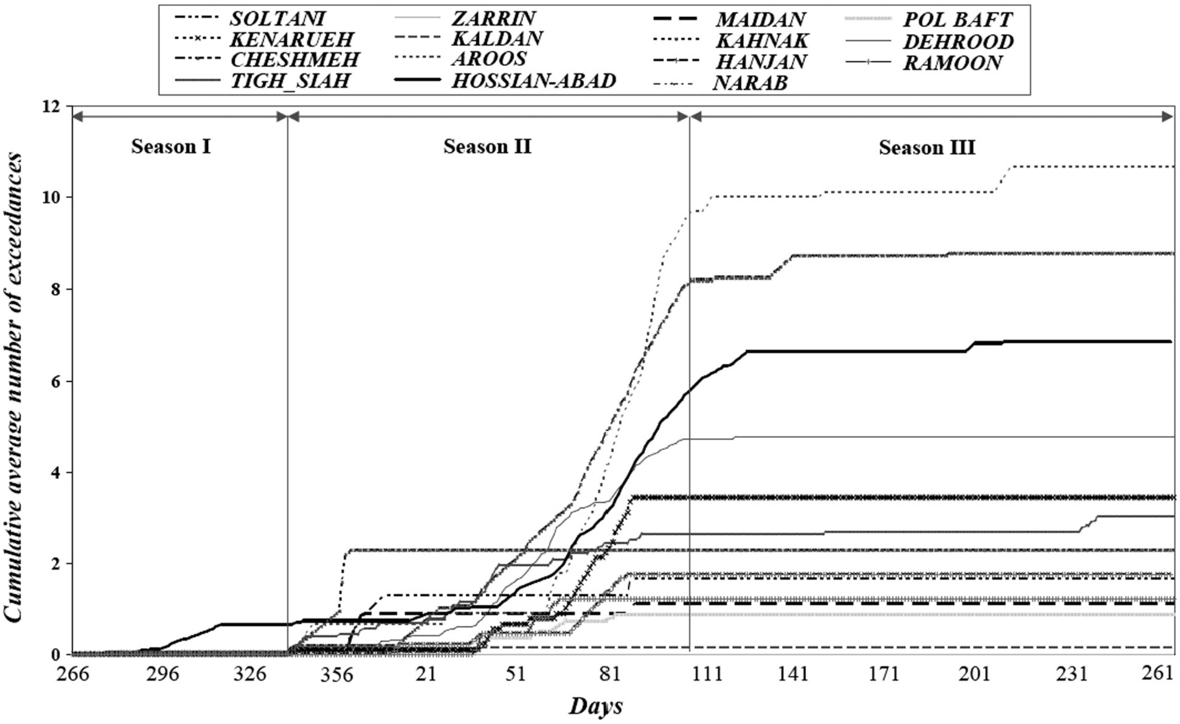

Figure 5. Flood seasonality at each station according to the POT-DS method

Table II. Homogeneity measures (H_i) of derived groups according to various regionalization methods

Methods	Regions	Number of stations	H_1	H_2	H_3
RF	G1	13	**0·27**	−0·24	−0·81
	G2	2	**1·05**	1·66	1·95
XY	G1	11	**0·94**	0·82	0·67
	G2	2	**−1·07**	−1·52	−1·52
	G3	2	**−0·73**	−1·27	−1·11
POT-DS	G1	14	**0·25**	0·16	−0·72
	G2	1	—	—	—
PG	G1	12	**0·69**	0·35	−0·17
	G2	3	**1·54**	0·96	0·59
ALL	G1	15	**1·90**	0·75	−0·04

also calculated for two alternatives of traditional regionalization methods based on basin hydrogeomorphic similarity (PG) and the scenario where all available information is used for regional analysis (ALL).

Figure 6 shows the spatial pattern of the regions of similar flood seasonality which are delineated based on the RF, XY, POT methods and two alternative methods (PG and ALL). Figure 6 reveals that except XY method which divides study area into three regions, the rest of seasonality-based approaches show two homogenous regions. This figure also exhibits that except PG method, the regions delineated with seasonality-based method RF, XY and POT cover approximately the same geographic areas.

Model evaluation for flood estimation at ungauged basins. After identification of homogenous regions by various techniques, we applied Jack-knife MLR procedure for regional flood estimations. After removing one gauged site from the region, considered as an ungauged site, at-site flood quantiles are used as dependent variables and the physiographic and climatic characteristics are used as independent variables in a stepwise multiple regression procedure. For flood quantiles at return periods of 2, 5, 10 and 20 years, the maximum elevation (max elv.) and vegetation cover (VC) remain in models. The MLR models are defined as

$$Q_T = a_0 + a_1\ (\mathrm{VC}) + a_2\ (\text{max elv.}) \tag{18}$$

For higher return periods, 50, 100, 200, 500 and 1000 years, the area (A) and the barelands enter to the regression models. The following equations represent regression models for these return periods:

$$\begin{aligned} \mathrm{Log}(Q_T) &= a_0 + a_1\ (\mathrm{A}) \\ \mathrm{Log}(Q_T) &= a_0 + a_1\ (\text{barelands}) \end{aligned} \tag{19}$$

where Q_T is the flood at the return period T, and a_0 and a_1 are regression coefficients. In the above models, the coefficient of determination (R^2) is higher than 0·90. This indicates that the relation between flood quantiles in different return periods and watershed properties is clearly significant and the current regression models are valid for prediction of flood quantiles at ungauged basins.

The regression models show that land use characteristics and sever topography are dominant factors controlling frequent floods, because catchment's topography characteristics forming hydraulic head difference allows surface water to flow to the main channel, and vegetation cover controls the infiltration of surface water and

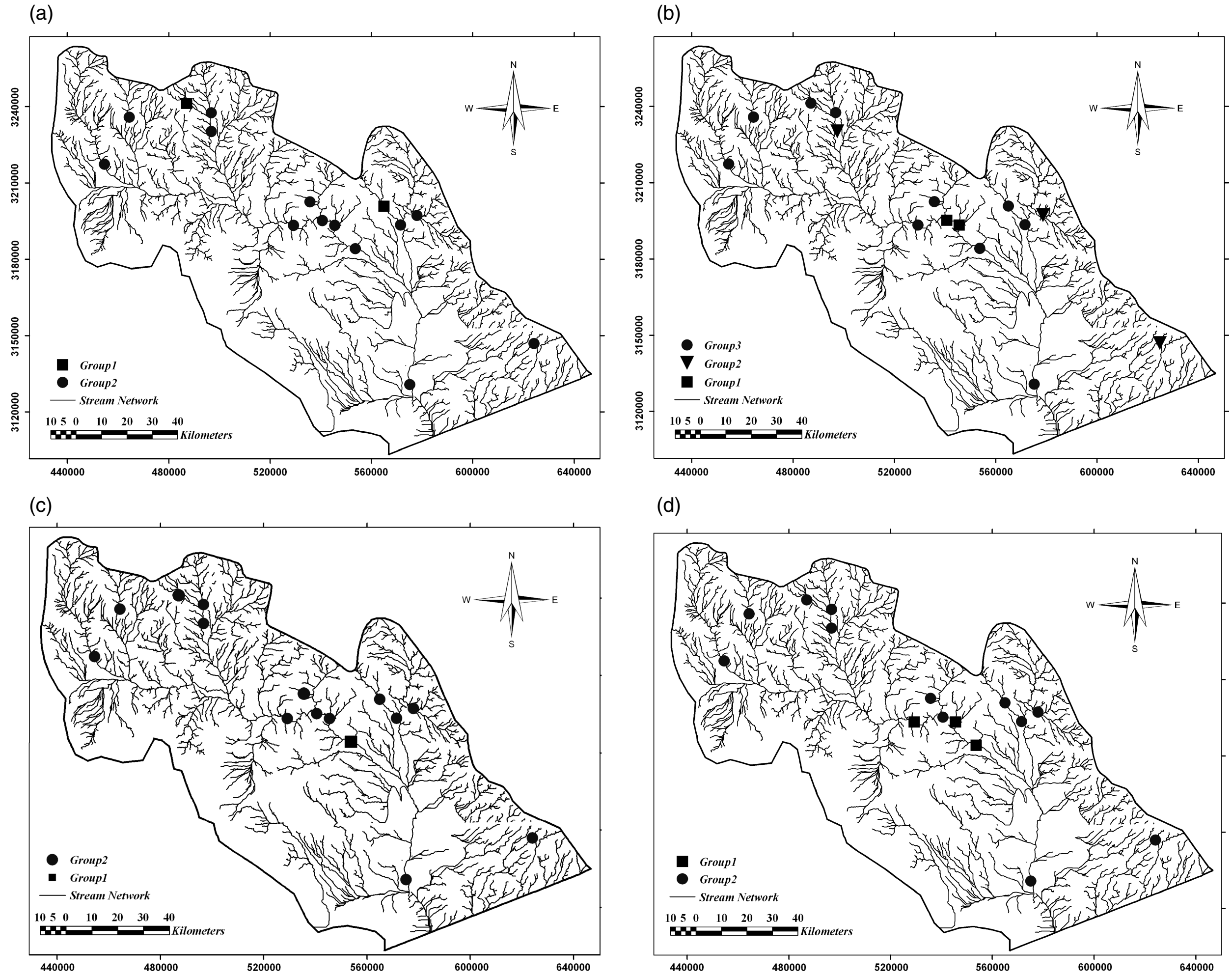

Figure 6. Homogenous regions delineated by flood seasonality-based approaches and two alternative methods: (a) RF method, (b) XY method, (c) POT-DS method and (d) PG method

Table III. Performance measures for flood quantile estimation in different return periods based on different regionalization methods

Return period (year)	BIAS$_T$ (%)					RMSE$_T$ (%)				
	RF	XY	POT-DS	PG	ALL	RF	XY	POT-DS	PG	ALL
2	**7·58**	8·04	7·89	8·71	9·01	**48·26**	67·13	50·78	61·31	69·88
5	7·11	8·21	**6·04**	8·06	8·97	49·78	59·41	**48·02**	57·91	61·23
10	9·77	8·97	**8·79**	9·22	9·12	57·31	68·83	**52·83**	63·57	67·07
20	8·75	9·07	**8·41**	8·78	9·56	66·7	79·12	68·81	**61·97**	84·60
50	11·7	12·62	**10·9**	11·07	12·60	87·01	81·33	**71·15**	77·19	85·47
100	13·41	14·81	**12·05**	13·79	15·87	84·69	84·36	**75·92**	86·97	89·06
200	15·61	14·97	**13·78**	14·21	15·80	**77·97**	81·98	78·64	84·36	86·58
500	16·11	15·51	**14·09**	16·34	16·90	82·51	92·17	**80·18**	89·78	92·23
1000	17·04	16·87	**14·89**	16·85	17·63	89·71	95·15	**82·47**	92·47	96·30

increases the soil moisture retention capacity. As physiographic characteristics are not manageable, soil conservation and land use proper management are important practices to control flood event occurrences. On the other hand, in higher return periods (infrequent floods), area of bare lands as the main characteristics of arid and semi-arid regions have a key role in flood generation process. Although there is no valid information of land use change in arid and semi-arid regions of Iran, land use change, usually rangelands and forest areas to agricultural land use can be assumed to be the main reason of decreasing soil infiltration and water retention capacity which lead to surface runoff and increasing of the number of flash flood events in arid and semi-arid regions of Iran.

For performance evaluation of different methods, Jackknife resampling procedure was then employed. Table III shows the relative BIAS$_T$ and RMSE$_T$ for flood estimation corresponding to the five regionalization techniques in different return periods. These results indicate that in most of the return periods, the POT-DS approach allocates the lowest RMSE_T values. Therefore, we can conclude that this method shows a significant improvement in quantile estimation at ungauged basins.

Now the question is that if we can improve flood quantile estimation at ungauged sites without losing the information of sites? In other words, is this possible to delineate more homogenous region than the best selected seasonality-based approach in part A? To answer these questions, we applied a discrete critical season POT model (POT-CS) in part B.

Part B

POT-CS approach. POT-CS approach is the same as the POT-DS in identification of flood seasons method, with this difference that POT-CS method considers only mean number of exceedances in a specific season for delineation of homogenous regions in return of all exceedances during year. Characterizing by the slopes of the exceedances plots, this season is included the most of significant flood events. For this reason, we named it as 'critical season'.

To execute POT-CS, the POT-DS method which is described in the part A is applied. As shown in Figure 5, the graphs present mean number of exceedances plotted for each sites according to truncation levels in POT-DS method. The behaviour of Λ (t) based on the slopes of these exceedances plots indicates the numbers and the starting and ending dates of seasons. POT-DS identifies three distinct seasons of flood occurences in the study area. Season I from day 266 to day 345, season II from 345 to 102 and season III from 102 to 265. Since the slopes of exceedances plots is changed in season II (with piecewise increasing linearity), this season is distinguished as critical season. The flood information of all sites during this season is then separated from dataset. The homogeneity of these flood TS is then checked with the heterogeneity measures of L-moments approach.

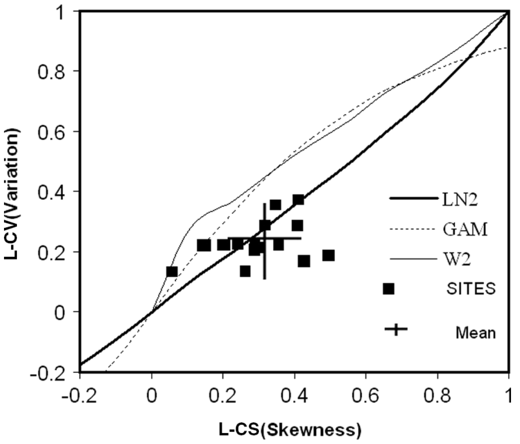

Figure 8. L-CV–L-CS MRD for all stations

Homogeneity and discordancy tests for flood POT-CS data. The L-moment ratio diagrams (MRDs) of flood magnitudes extracted from POT-CS method are illustrated in Figures 7 and 8, and the values of L-moments are also given in Table IV. These diagrams are useful to identify those sites that may have different statistical characteristics. Although comparative scattering of data points, which is due to flood magnitude differences in various sites, a degree of homogeneity can be identified from the L-MRDs. We used two heterogeneity statistics introduced by Hosking and Wallis (1997) to ensure about regional homogeneity of extracted flood TS of critical season. Results of applying discordancy measure (D), revealed that there is no discordant site. The homogeneity statistics were then calculated ($H_1 = 0{\cdot}38$, $H_2 = -0{\cdot}51$ and $H_3 = -1{\cdot}12$). According to H_1 measure, which is reported to be discriminatory more powerful than either H_2 or H_3 (Hosking and Wallis, 1997), the study area is acceptably homogenous. In the other words, based on POT-CS method without removing any site, hydrologically homogenous region with similar flood seasonality can be delineated.

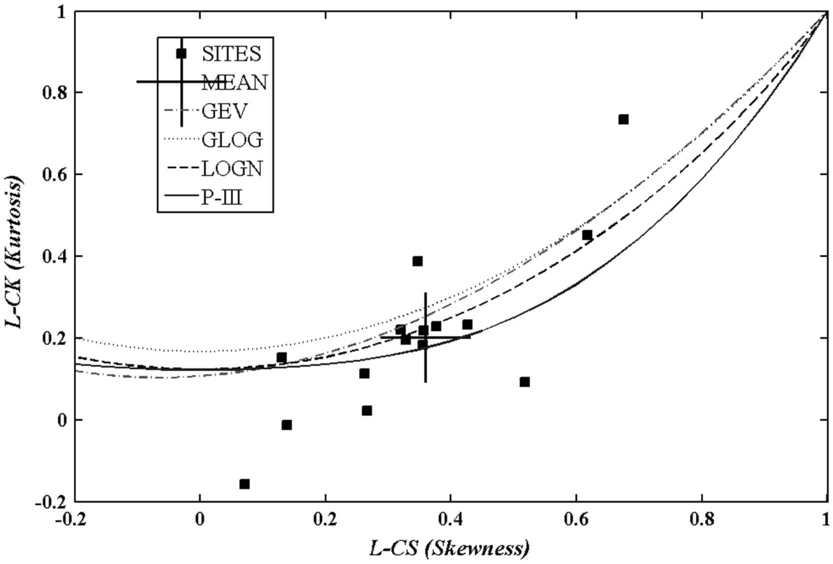

Figure 7. L-CS–L-CK MRD for all stations

Table IV. Descriptive and L-moments statistics of floods in critical season

Station numbers	Name	Sample size	Area (km^2)	L-CV	L-CS	L-CK	D
1	Aroos	10	292·73	0·140	0·469	0·574	1·29
2	Cheshme	9	76·42	0·322	0·438	0·172	1·41
3	Dehrood	34	1136·87	0·188	0·262	0·073	1·25
4	Hanjan	22	265·17	0·157	0·329	0·258	0·46
5	Hossienabad	141	8775·94	0·243	0·424	0·234	0·53
6	Kahnak	28	14 181·12	0·199	0·258	0·152	0·21
7	Kaldan	10	134·02	0·205	0·148	0·205	1·37
8	Kenarueih	12	7781·28	0·169	0·488	0·424	1·18
9	Meidan	23	554·94	0·200	0·151	0·058	0·79
10	Narab	10	8306·88	0·140	0·089	0·125	1·41
11	Polbaft	96	165·07	0·206	0·325	0·202	0·13
12	Ramoon	10	33·71	0·151	0·271	0·379	1·04
13	Soltani	161	853·52	0·214	0·374	0·232	0·24
14	Tighsiah	33	4·39	0·349	0·352	0·191	1·27
15	Zarrin	14	353·95	0·255	0·303	0·233	0·42

Table V. MLR models for estimation of flood quantiles at different return periods based on POT-CS approach

Return period (year)	Best regression model
2	$Q_2 = -252\cdot75 + 0\cdot005\ (\mathrm{VC}) + 0\cdot1\ (\text{Max Elv.})$
5	$Q_5 = -334\cdot2 + 0\cdot007\ (\mathrm{VC}) + 0\cdot132\ (\text{Max Elv.})$
10	$Q_{10} = -398\cdot14 + 0\cdot008\ (\mathrm{VC}) + 0\cdot158\ (\text{Max Elv.})$
20	$Q_{20} = 127\cdot2 + 0\cdot12\ (\mathrm{VC})$
50	$Q_{50} = 154\cdot9 + 3\cdot49 \times 10^{-8}\ (\text{Area})$
100	$Q_{100} = 177\cdot19 + 4 \times 10^{-8}\ (\text{Area})$
200	$Q_{200} = 201\cdot7 + 0\cdot001\ (\text{Bareland})$
500	$Q_{500} = 237\cdot2 + 0\cdot001\ (\text{Bareland})$
1000	$Q_{1000} = 264\cdot6 + 0\cdot001\ (\text{Bareland})$

Model evaluation for flood estimation at ungauged sites. The second step of a regionalization procedure involves the application of a regional estimation method to transfer information from gauged sites to the target site within delineated homogenous region. To estimate the POT-CS-based flood quantiles at ungauged regions, a resampled MLR is applied using a set of hydrogeomorphic characteristics as dependent variables and at-site flood quantiles, estimated from flood events TS of critical season as independent variables. Table V represents the best linear stepwise regression models for different return periods. All equations are significant at 1% significant level. The estimated models indicate that based on POT-CS method, some physiographic and land use parameters are responsible for flood generation at low return periods, whereas for high return periods, the area of bare lands which is the main characteristic of the arid regions is mainly responsible for flash flood generation.

Performance evaluation of two POT models. In this section, the performance of POT-DS and POT-CS methods are compared for flood quantile estimation at ungauged regions. Performance measures obtained by the Jack-knife resembling procedure for two POT models are presented in Table VI. These results illustrate the relative BIAS_T and RMSE_T for flood quantile estimates. Performance results reveal that in almost all of return periods the lowest RMSE_T values are obtained by the POT-CS method. Although POT-DS leads also to good performances in a few return periods, but the lowest RMSE_T are related to POT-CS approach. Similar results can be deduced from the relative bias values.

The results reveal that POT-CS leads to slightly better performances and a slight improvement in the quantile estimation at ungauged sites in comparison to POT-DS. These results indicate that though POT-DS method leads to better performances than other seasonality-based approaches (RF and XY), and other two alternative methods, applying flood information in specific season provides more homogenous region in comparison to using all of exceedances information during year and leads to slight improvement in quantile estimation at ungauged sites.

SUMMARY AND CONCLUSION

In arid and semi-arid regions, which suffer from insufficiency of site-specific records of data, regional flood frequency is used to transfer hydrological information

Table VI. Performance measures for flood quantile estimation at ungauged sites based on POT-DS and POT-CS methods at different return periods

Return periods	BIAS_T (%)		RMSE_T (%)	
	POT-CS	POT-DS	POT-CS	POT-DS
2	**6·50**	7·89	**41·56**	50·78
5	**5·49**	6·04	**43·80**	48·02
10	**5·97**	8·79	55·14	**52·83**
20	8·74	**8·41**	72·06	**68·81**
50	**7·91**	10·9	**66·63**	71·15
100	**8·59**	12·05	**68·12**	75·92
200	**10·13**	13·78	**70·75**	78·64
500	**11·37**	14·09	**76·08**	80·18
1000	**12·97**	14·89	**82·93**	82·47

from gauged site to the site of interest. The fundamental step in regional estimation approach is delineation of hydrologically homogenous regions. In this study, in order to find the best method for delineation a homogenous region based on flood seasonality, in part A, three flood seasonality-based regionalization methods were applied: the method based on the relative frequencies of flood occurrences (RF), the method based on directional statistics (XY) and a graphical approach based on POT-DS model. The results of these three methods were also compared to results of two alternative methods: a traditional regionalization method based on catchment's hydrogeomorphic characteristics similarity (PG) and a scenario which uses all available information without subdividing the area into homogenous region (ALL).

The results of Jack-knife resampling procedure were used to compare the general performances of study methods. The relative bias and the RMSE of flood quantiles in different return periods show that POT-DS method based on the use of POT data leads to a better performance than other seasonality-based approaches (RF and XY). POT-DS method also leads to slight improvement in quantile estimation in comparison to PG method which is based on catchment's hydrogeomorphic similarity (no seasonality measures). The approach that uses all available information without restoring area to homogenous regions leads to poor performances. In part B, to delineate better homogenous region and to improve flood quantile estimation at ungauged sites, we applied POT-CS model that uses only information of exceedances in a specific season. The performance evaluation of results of POT-CS method in critical season shows slight improvement in flood quantile estimation at ungauged sites in comparison to POT-DS method that uses all exceedances information during year. These results indicate that POT-CS that uses flow peaks above a certain base truncation in a specific season captures more information about flood seasonality than other approaches, and without removing any site, this method leads to delineation of better homogenous region for regional flood frequency analysis.

The results of this study confirm the study of Ouarda *et al.* (2006) that compared three seasonality-based methods in Quebec, Canada, but there is no published rational comparison of the same approaches in arid and semi-arid regions area available prior to this study. Therefore, the generality of the finding of this study needs to be tested in other arid and semi-arid regions of the world. The methodology of this study can also be directed towards the application of seasonality-based techniques especially POT-CS approach for the regionalization of other hydrologic variables such as precipitation or sediment loads.

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