Frequency Distribution of Extreme Hydrologic Drought of Southeastern Semiarid Region, Iran

Reza Modarres[1] and Ali Sarhadi[2]

Abstract: Hydrologic drought is a type of drought which directly affects the water supply of a region. Long streamflow dry spells or streamflow under a specific threshold are usually considered as hydrologic drought. The annual extreme hydrologic dry spell length (AEHDSL) data of the Halilrud basin in the southeastern semiarid region of Iran were considered to estimate the return period of hydrologic drought and the associated risk in this region. The method of *L*-moments was applied to check discordant stations and test the homogeneity of the region which consists of 15 gauging watersheds. One discordant station was found and the region was homogeneous according to the homogeneity measure after removing the discordant station. The three-parameter lognormal distribution was found to be representative of the regional distribution for the entire region based on the goodness-of-fit test. For prediction in ungauged basins, the AEHDSL regional regression was developed for the region. The regression model indicates that the vegetation cover and relief of watersheds play important roles in the hydrologic drought length of the Halilrud basin. These two variables control the infiltration and hydraulic slopes of a watershed, respectively.

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Introduction

A hydrologic drought or streamflow drought is a period during which the discharge is below normal or a period of insufficient discharge to meet water demand and is a prolonged period with unusually low streamflow. Hydrologic drought is usually studied in two ways. One way is to study droughts on the basis of low flow characteristics such as a time series of the annual minimum *n*-day discharge or a percentile from the flow duration curve (Hisdal et al. 2004). The other way of studying droughts is to look at the discharge series as a time depending process and to identify the complete period of a drought event from its first day to the last one.

The estimation of hydrologic drought characteristics at ungauged watersheds is a main problem in hydrology and water resources planning and management. There are many methods of prediction drought characteristics at ungauged basins. These methods can be classified into two types (Durrans and Tomic 1996). The first group finds the relationship between certain hydrologic characteristics and physiographic and climatic characteristics. The multiple linear regression (MLR) is a common method of this type (e.g., Mazvimavi et al. 2004). The second type of regional analysis is referred to as regional frequency analysis (RFA). In recent years, many investigators have focused on the hydrologic drought using different drought indices such as *n*-day low flows (e.g., Tasker 1987; Vogel and Kroll 1990; ARIDE 1999; Rifai et al. 2000; Kroll and Vogel 2002; Chen et al. 2006) or the flow duration curve (e.g., Zelenhasić and Salvai 1987; Vogel and Fennessey 1994).

Among the different RFA methods, the method of *L*-moments has been used increasingly by hydrologists. Durrans and Tomic (1996) applied the methods of the RFA to estimate low flows in 128 gauged stations in the United States and concluded that the log-Pearson Type 3 distribution (LPIII) is a suitable candidate for low flow modeling. Kumar et al. (2003) used *L*-moments and concluded that the generalized extreme value (GEV) distribution is a robust distribution for the flood frequency analysis of the Middle Gang Plains subzone in India. Lim and Lye (2003) found that GEV and generalized logistic (GLOG) distributions were appropriate for the distribution of extreme flood events in the Sarawak region of Malaysia.

Kroll and Vogel (2002) used the *L*-moments to identify the probability of low flows in the United States and recommended Pearson Type 3 (PIII) and three-parameter log-normal (LN3) distributions to be used in the United States. More recently, Chen et al. (2006) carried out a regional low flow frequency analysis for the south of China and recommended the LN3 distribution for the region.

It is necessary, for the analysis of any kind of droughts, to select an appropriate indicator for defining droughts. Almost all drought indices are based on the basic method of truncation used to derive drought events from continuous or discrete records of streamflow, precipitation, temperature, ground water drawdown, and lake elevation (Chang and Kleopa 1991). A drought is defined as an uninterrupted sequence of streamflow below an arbitrary level (Yevjevich 1967). The streamflow denoted by x_i, where i

[1]Institut National de la Recherche, 490 Rue de la Couronne, PQ, Canada G1K 9A9 (corresponding author). E-mail: reza.modarres@ete.inrs.ca

[2]Research Assistant, Faculty of Natural Resources, Isfahan Univ. of Technology, Isfahan 8415683111, Iran. E-mail: alisarhadi2005@yahoo.com

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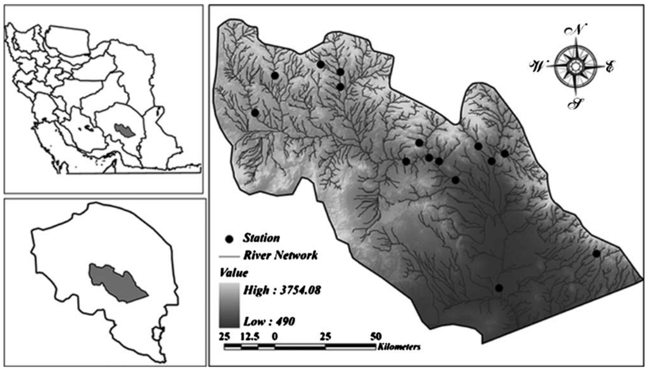


Fig. 1. Location map of the Halilrud basin with digital elevation model and selected stations

indicates the time and the arbitrary level, called the truncation level and denoted by x_0, is assumed to be constant. Examples of applied truncation level are the mean (Bonacci 1993), the median (Griffiths 1990), mean and 75% of the mean (Clausen and Pearson 1995), and lower percentage exceedances, for example, 90 or 95% flows found from flow duration curves (Zelenhasić and Salvai 1987; Chang and Stenson 1990).

In the present study, we proposed a hydrologic drought index, *hydrologic dry spell length* (HDSL), which is defined as the number of consecutive days without streamflow (i.e., zero streamflow) or days with a streamflow lower than a critical threshold.

The aim of this study is to investigate the frequency distribution of the annual extreme hydrologic dry spell length (AEHDSL) or the longest period of consecutive days below the critical threshold in each year in southeastern Iran. In this study, we apply a 7-day, 10-year return period low flow as the truncation level to define AEHDSL. The main advantage of the index is that AEHDSL describes the annual longest period of insufficient streamflow which is an important issue for a variety of tasks such as reservoir risk management for drinking and agricultural water supply and water quality risk associated with a long period of drought events. In other words, the AEHDSL defines the period of drought and the associated risk of the length of a critical time period of low streamflow while other hydrologic drought indices such as n-day low flows or the flow percentiles (e.g., 95th quantile) describe the critical flow rate and its associated risk in different water resources management strategies.

It is also important to know the return period or the probability of a multiyear drought in which the HDSL exceeds 365 days or 1 year. Thus, the probability of AEHDSL occurrence or the return period of drought is a key factor for drought risk management of agricultural and water resources systems in the study basin which is located in arid and semiarid regions of Iran.

Study Area and Data

Located in the southeastern semiarid region of Iran, with the area of $11,847\ \text{km}^2$ and the main stream of 271.5 km, the Halilrud basin is one of the major basins of Kerman Province (Fig. 1). Under the control of an arid climate, the hydrology and water availability of the Halilrud basin demonstrate flash flood seasons as well as intermittent flow and severe hydrologic drought periods. Hydrologic drought characteristics such as drought period or severity fluctuate from year to year. A summer drought is dominant in the region. However, the population and economy in the basin are increasingly growing and generating increasing demand on the water resources. Information on the extreme hydrologic drought frequency or the return period for the Halilrud basin is of vital importance in regional water resources planning and the sustainable use of water resources in the region. The Halilrud basin provides the water supply for agricultural fields of the region. Thus, the study of hydrologic drought is a vital task for water resources managers. In this study, 15 gauged sites in the region were selected and the daily streamflows of these sites were used to calculate the longest annual hydrologic drought period. The descriptive statistics of the AEHDSL time series of the Halilrud basin are given in Table 1.

In this table, the maximum observed AEHDSL of four stations (Hanjan, Hesseinabad, Polbaft, and Soltani) exceeds 1/3 of the year and for two other stations (Meidan and Ramoon) the maximum observed AEHDSL is near 1/3 of the year. In the other four stations (Cheshme, Kaldan, Tighsiah, and Zarrin) the maximum

Table 1. Descriptive and *L*-Moment Statistics of AEHDSL Time Series of Halilrud Basin

Station name	Sample size (year)	Record period	Minimum (day)	Maximum (day)	Mean (day)	Standard deviation (day)	Coefficient of skewness	Coefficient of kurtosis	LCV	LCS	LCK	*D*
Aroos	11	1992–2003	1	14	8	4	−0.02	0.16	0.23	0.15	0.26	2.17
Cheshme	17	1986–2003	3	90	32	22	1.20	2.06	0.36	0.23	0.22	0.71
Dehrood	31	1972–2003	1	28	8	7	1.66	2.19	0.44	0.38	0.23	0.05
Hanjan	14	1989–2003	7	178	73	51	0.64	−0.26	0.40	0.19	0.13	0.71
Hossienabad	32	1971–2003	1	20	5	5	2.00	4.05	0.44	0.40	0.25	0.14
Kahnak	18	1985–2003	2	146	47	48	0.81	−0.79	0.55	0.31	−0.02	1.20
Kaldan	17	1986–2003	2	93	31	25	1.04	0.64	0.44	0.26	0.13	0.22
Kenarueih	10	1993–2003	3	24	8	7	1.86	3.69	0.41	0.43	0.24	1.30
Meidan	18	1985–2003	6	115	34	28	1.75	3.42	0.40	0.35	0.28	0.28
Narab	11	1992–2003	5	40	12	10	2.49	6.90	0.40	0.62	0.47	2.19
Polbaft	23	1980–2003	4	146	37	40	1.64	1.70	0.51	0.45	0.20	0.52
Ramoon	11	1992–2003	3	116	42	44	0.86	−1.01	0.52	0.30	−0.12	1.57
Soltani	32	1971–2003	2	156	54	45	0.93	−0.03	0.48	0.27	0.09	0.39
Tighsiah	17	1986–2003	1	87	17	20	2.87	9.78	0.50	0.45	0.35	2.90
Zarrin	19	1984–2003	4	81	22	21	1.73	3.13	0.48	0.36	0.18	0.12

observed AEHDSL reaches to 1/4 of the year. In other words, the risk of a dry period in 75% of the stations could reach to 25–33% of the year. The maximum observed AEHDSL differs from 3.83% (at Aroos station) to 48.76% (at Hanjan station) of the year. The mean AEHDSL also varies from 1.4% (at Hosseinabad station) to 20% (at Hanjan station) of the year. This illustrates the merit of the investigation of the AEHDSL at the Halilrud basin as an important region of agricultural production in southeast Iran.

Methodology

Regional Frequency Analysis of AEHDSL

The method of *L*-moments is now a popular method in regional hydrologic frequency analysis. Details about the method can be found in Hosking and Wallis (1997). The mathematical formulation of *L*-moments using probability weighted moments (PWMs) is briefly presented below. Hosking and Wallis (1997) presented the following relationships:

$$\lambda_1 = \beta_0 \tag{1}$$

$$\lambda_2 = 2\beta_1 - \beta_0 \tag{2}$$

$$\lambda_3 = 6\beta_2 - 6\beta_1 + \beta_0 \tag{3}$$

$$\lambda_4 = 20\beta_3 - 30\beta_2 + 12\beta_1 - \beta_0 \tag{4}$$

where λ_r=*L*-moments and β_r=PWMs defined as

$$\beta_r = \int_0^1 x(F)F^r dF \tag{5}$$

where F=nonexceedance probability and $x(F)$=inverse function or the quantile function of x.

The *L*-moments are directly interpretable as measures of the scale and shape of probability distribution models. Clearly λ_1, the mean, is a measure of location. λ_2=a measure of scale or dispersion of the random variable.

To make the *L*-moments independent of the units of measure of x, it is often convenient to standardize the higher moments as

$$\tau_r = \lambda_r/\lambda_2 \quad \text{for} \quad r = 3,4 \tag{6}$$

Analogous to the conventional moment ratio, such as the coefficient of variation, the *L*-coefficient of variation (LCV) is defined as

$$\text{LCV} = \lambda_2/\lambda_1 \tag{7}$$

The corresponding *L*-coefficient of skewness (LCS or $\tau_3=\lambda_3/\lambda_2$) reflects the degree of symmetry of a sample. It has limits $-1 < \text{LCS} < 1$; the symmetric distribution models have LCS=0. Similarly, LCK, or $\tau_4=\lambda_4/\lambda_2$, is a measure of peakedness and is referred to as the *L*-coefficient of kurtosis.

Formation of Homogeneous Regions

In the formation of a homogeneous group, all sites that have a high similarity with the site of interest are grouped together. A number of similarity measures based on the Euclidean distance computed in a multidimensional attribute space have been proposed in the literature (Reed et al. 1999; Cunderlik and Burn 2002). In the present work, the homogenous groups for the AEHDSL in the Halilrud basin formed based on the method of *L*-moments (Hosking and Wallis 1997).

The formation of the homogenous region includes three steps. In each step, a statistical measure (discordancy measure, heterogeneity measure, and goodness-of-fit measure) is used (Hosking and Wallis 1997).

Discordancy Measure

The discordancy measure, D_i, is used to find out unusual sites from the pooling group (i.e., the sites whose at-site sample *L*-moments are markedly different from the other sites). D_i is defined as follows:

$$D_i = \frac{1}{3}(u_i - \bar{u})^T S^{-1}(u_i - \bar{u}) \tag{8}$$

where u_i=vector of *L*-moments, LCV, LCS, and LCK, for a site i

$$S = (N_s - 1)^{-1}\sum_{i=1}^{N_s}(u_i - \bar{u})(u_i - \bar{u})^T \tag{9}$$

$$\bar{u} = N_s^{-1}\sum_{i=1}^{N_s} u_i \tag{10}$$

and N_S=number of sites in the group. The large value of D_i indicates the discordancy of site i with other sites. Hosking and Wallis (1997) suggested some critical values for the discordancy test which are dependent on the number of sites. In general, a site in a region with $n \geq 15$ sites is declared discordant if $D_i > 3$.

Heterogeneity Measure

The heterogeneity measure estimates the degree of heterogeneity in a group of sites and is used to assess whether the group might reasonably be treated as homogeneous. This measure compares the variability of *L*-moment ratios for the sites in a group with the expected variability, obtained from simulation, for a collection of sites with the same record lengths as those in the group. The statistics used for the homogeneity test are three heterogeneity measures (H), namely, H_1, H_2, and H_3 with respect to the LCV scatter, LCV-LCS, and LCS-LCK, respectively. A region is homogenous if any of the H_i is less than 1, possibly heterogeneous if H_i is between 1 and 2, and definitely heterogeneous if H_i is greater than 2 (Hosking and Wallis 1997).

Hosking and Wallis (1997) observed that the statistics H_2 and H_3 lack the power to discriminate between homogeneous and heterogeneous regions and that the H_1 based on LCV had a much better discriminating power. Therefore, the H_1 statistic is recommended as a principal indicator of heterogeneity.

Goodness-of-Fit Measure

The goodness-of-fit measure is used to identify the regional distribution function for the group. The quality of fit is judged by the difference between the regional average $\bar{t}_4$ and the value of τ_4^{Dist} for the fitted distribution model. The statistic Z^{Dist} for a chosen distribution function is as follows (Hosking and Wallis 1997):

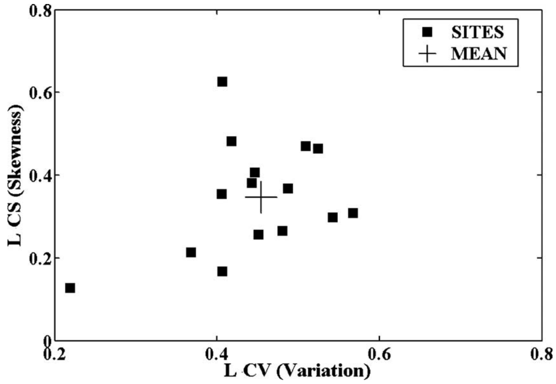


Fig. 2. LCV-LCS moment ratio diagram for AEHDSL of the Halilrud basin

$$Z^{\mathrm{Dist}} = \frac{\bar{t}_4 - \tau_4^{\mathrm{Dist}}}{\sigma_4} \tag{11}$$

where $\bar{t}_4$=average L-kurtosis value computed from the data of a given region; τ_4^{Dist}=average L-kurtosis value computed from the simulation for a fitted distribution model; and σ_4=standard deviation of L-kurtosis values (from simulation).

A given distribution model is declared a good fit if $|Z^{\mathrm{Dist}}| \leq 1.64$. If more than one distribution model meets the above criterion, the preferred distribution model is the one that has the minimum $|Z^{\mathrm{Dist}}|$ value.

Prediction in Ungauged Basins

It is likely that most catchments of the world are ungauged or poorly gauged. To estimate hydrologic characteristics at ungauged watersheds, multiple regression analysis (MLR) is often used. The MLR is a common method to incorporate hydrologic information from many sites in the neighborhood of a particular watershed (e.g., Pandey and Nguyen 1999; Chiang et al. 2002). For the AEHDSL prediction in an ungauged watershed of the Halilrud basin we can write

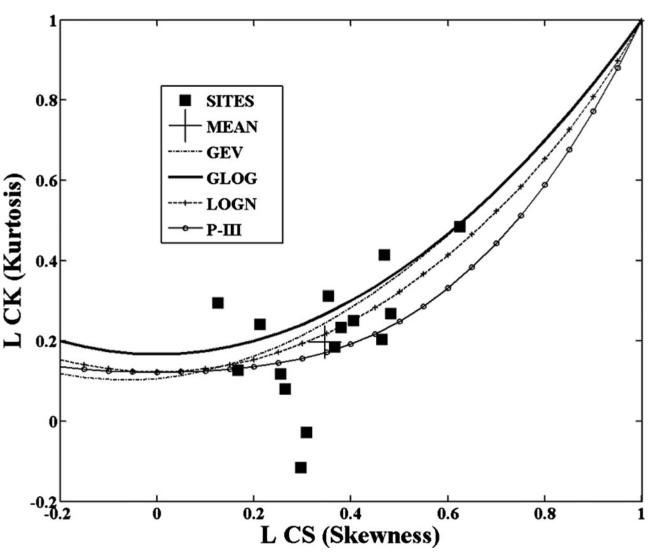


Fig. 3. LCS-LCK moment ratio diagram for AEHDSL of the Halilrud basin

Table 2. Parameters of the LN3 Distribution

Station name	μ	σ	a
Aroos	3.05	0.14	−13.0
Cheshme	3.8	0.42	−16.39
Dehrood	1.78	0.82	−0.09
Hanjan	4.67	0.43	−44.37
Hossienabad	1.0	1.12	0.46
Kahnak	2.96	1.55	1.42
Kaldan	3.31	0.74	−4.24
Kenarueih	1.86	0.64	−9.60
Meidan	3.4	0.70	−1.98
Narab	2.24	0.60	−3.03
Polbaft	3.04	1.08	2.35
Ramoon	3.30	1.09	2.36
Soltani	3.55	1.0	−1.96
Zarrin	2.47	0.95	−0.35

$$q_i^{\mathrm{AEHDSL}} = k + \alpha_1 X_1 + \alpha_2 X_2 + \cdots + \alpha_p X_p \tag{12}$$

where q_i^{AEHDSL}=ith quantile of AEHDSL (day); k=regression intercept; independent variables $X_1, X_2, \ldots, X_p$=watershed and climatic characteristics; and $\alpha_1, \alpha_2, \ldots, \alpha_p$=regression coefficients.

To check the accuracy of the model, the residuals are tested to be normally distributed and independent. To avoid multicollinearity of regressors, the variance inflation factor (VIF) is estimated. If the VIF associated with any regressor exceeds 4–5, we would suspect that multicollinearity is present (Montgomery et al. 2004).

Cross-Validation of Regression Model

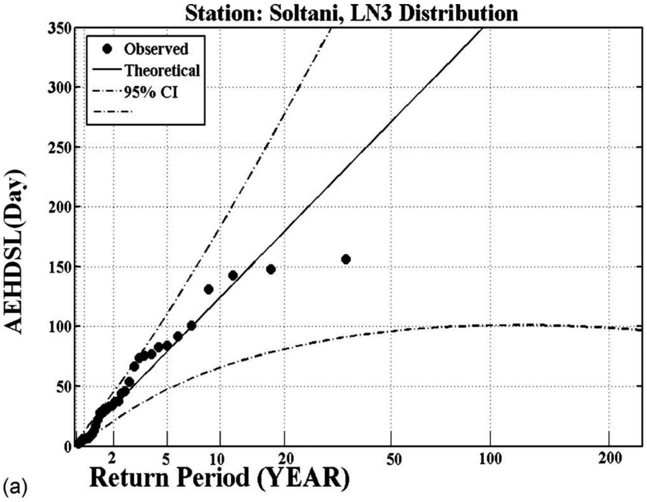
The value of the regression model for the purpose of estimating the AEHDSL at ungauged sites cannot be fully assessed with goodness-of-fit statistics. Therefore, the prediction errors are calculated by the leave-one-out cross-validation method. The leave-one-out cross-validation consists of the following steps (Laaha and Bloschl 2006):

1. Remove watershed i from the data set;
2. Update the watershed classification for the remaining $n-1$ watersheds;
3. Estimate the coefficients of the regression model for the region using all watersheds in the region apart from watershed i;
4. Apply the regression model obtained in (3) to predict the AEHDSL at site i;
5. Repeat Steps (1) to (4) for all n watersheds; and
6. Calculate the predictive error for watershed i by the relative mean bias (BIASr) and the relative root mean square error (RMSEr) computed by the following equations:

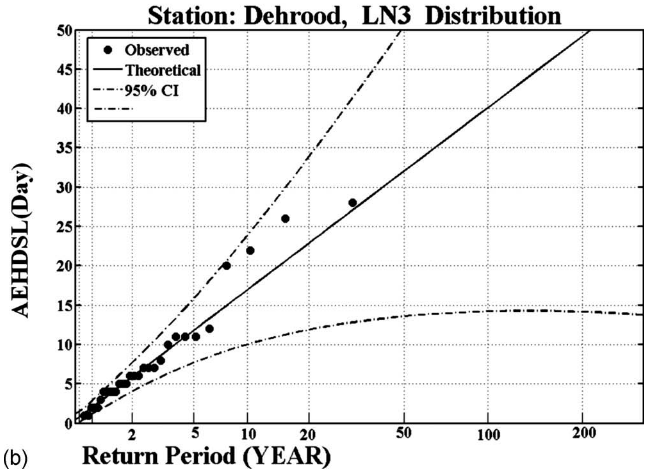
$$\mathrm{BIASr} = \frac{1}{N}\sum_{i=1}^{N}\left(\frac{\hat{Z}_i - Z_i}{Z_i}\right) \tag{13}$$

$$\mathrm{RMSEr} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(\frac{\hat{Z}_i - Z_i}{Z_i}\right)^2} \tag{14}$$

where $\hat{Z}_i$ and Z_i=respectively, the model prediction without using the observed AEHDSL from watershed i and the observed AEHDSL for watershed i.



(a)



(b)

Fig. 4. LN3 cumulative density function of AEHDSL for two stations: (a) Soltani; (b) Dehrood

Results and Discussions

Forming Homogeneous Region

The *L*-moment ratio diagrams of the AEHDSL time series are illustrated in Figs. 2 and 3 and the values are given Table 1. In this study, the sample size of 11 stations is less than 20 years. According to Hosking and Wallis (1997), the bias of the sample *L*-moments is negligible in the sample size 20 or more. However, short data record is a common problem in arid and semiarid regions of the world as well as arid regions of Iran. Therefore, we accept these *L*-moments for regionalization AEHDSL conventional moments are substantial more bias than *L*-moments.

These diagrams are useful to identify sites that may have different statistical characteristics. For example two stations, the Kahnak and Ramoon stations, have negative LCK values. These two stations are the largest and smallest watershed areas and the highest and smallest relief (or the difference between maximum and minimum elevations) among the region (see Table 3). We can see in the next section that these two variables are the most important factors on the AEHDSL statistical properties.

From Fig. 3, it seems that the mean values of LCS and LCK are located on the LN3 distribution function. However, it is very important to check the homogeneity and the existence of discordant stations before deciding on the regional distribution function as Peel et al. (2001) showed that for the heterogeneous region, the sample average is not useful for selecting the parent distribution function.

The discordancy measures together with the sample *L*-moment ratios for the 15 sites in the Halilrud basin are given in Table 1. According to the critical values, it can be seen that there is no discordant site in the region. However, the D_i value for the Tighsiah station (D_i=2.90) is very close to the critical value for the discordancy statistics of a region with 15 stations, (i.e., D_i=3). As the number of sites is right on this threshold, the Tighsiah station is removed from the region. Therefore, in the section the homogeneity of the region with 14 stations is investigated.

For selected sites of the Halilrud basin, the heterogeneity mea-

Table 3. Characteristics of 15 Selected Basins at Halilrud Watershed

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 (%)	Uncover area[a] (km^2)	Urban area (km^2)	VC (km^2)
Aroos	293.08	292.73	32	0.74	1,283.8	3,586.9	2,337.7	3.8	235.80	0.19	56.74
Cheshme	320.28	76.42	29.9	0.98	2,627.4	3,386.7	2,971.62	3.18	45.39	19.25	11.78
Dehrood	284.41	1,136.87	38.62	0.87	1,158.2	3,503.9	2,155.19	2.2	742.15	57.4	337.32
Hanjan	312.42	265.17	34.27	0.85	2,330	3,350	2,784.9	2.44	177.10	78.35	9.72
Hossienabad	288.44	8,775.94	12.45	0.85	977.24	3,586.9	2,244.11	0.79	7,142.51	1,075.48	557.95
Kahnak	273.99	14,181.12	12.45	0.91	530	3,586.9	1,925.28	0.63	10,350.87	2,360.92	1,469.33
Kaldan	295.84	134.02	51.9	0.79	1,620	3,288.6	2,420.3	4.71	79.66	1.25	53.11
Kenarueih	290.55	7,781.28	12.45	0.9	1,420	3,499.3	2,294.8	0.7	6,234.73	1,074.92	471.63
Meidan	309.68	554.94	34.27	0.87	2,212.6	3,386.7	2,718.8	2.2	298.85	221.29	34.80
Narab	289.81	8,306.88	12.45	0.89	1,160	3,586.9	2,278.24	0.64	6,693.23	1,075.11	538.54
Polbaft	308.13	165.07	12.37	0.85	2,475.2	2,897.3	2,680.9	1.63	129.50	22.98	12.59
Ramoon	285.46	33.71	44.15	0.57	1,637.3	2,463.1	2,186.68	5.79	30.98	0	2.73
Soltani	300.49	853.52	12.45	0.9	2,180	3,090.6	2,518.67	0.97	662.63	152.46	38.43
Tighsiah	286.2	4.39	42.4	0.64	1,829.6	2,907.6	2,134.3	4.1	3.64	0	0.75
Zarrin	282.3	353.95	29.75	0.91	1,461.8	3,112.6	2,095.4	2.81	216.18	54.39	83.38

[a]Uncover area: bare soil+rock hills and mountains.

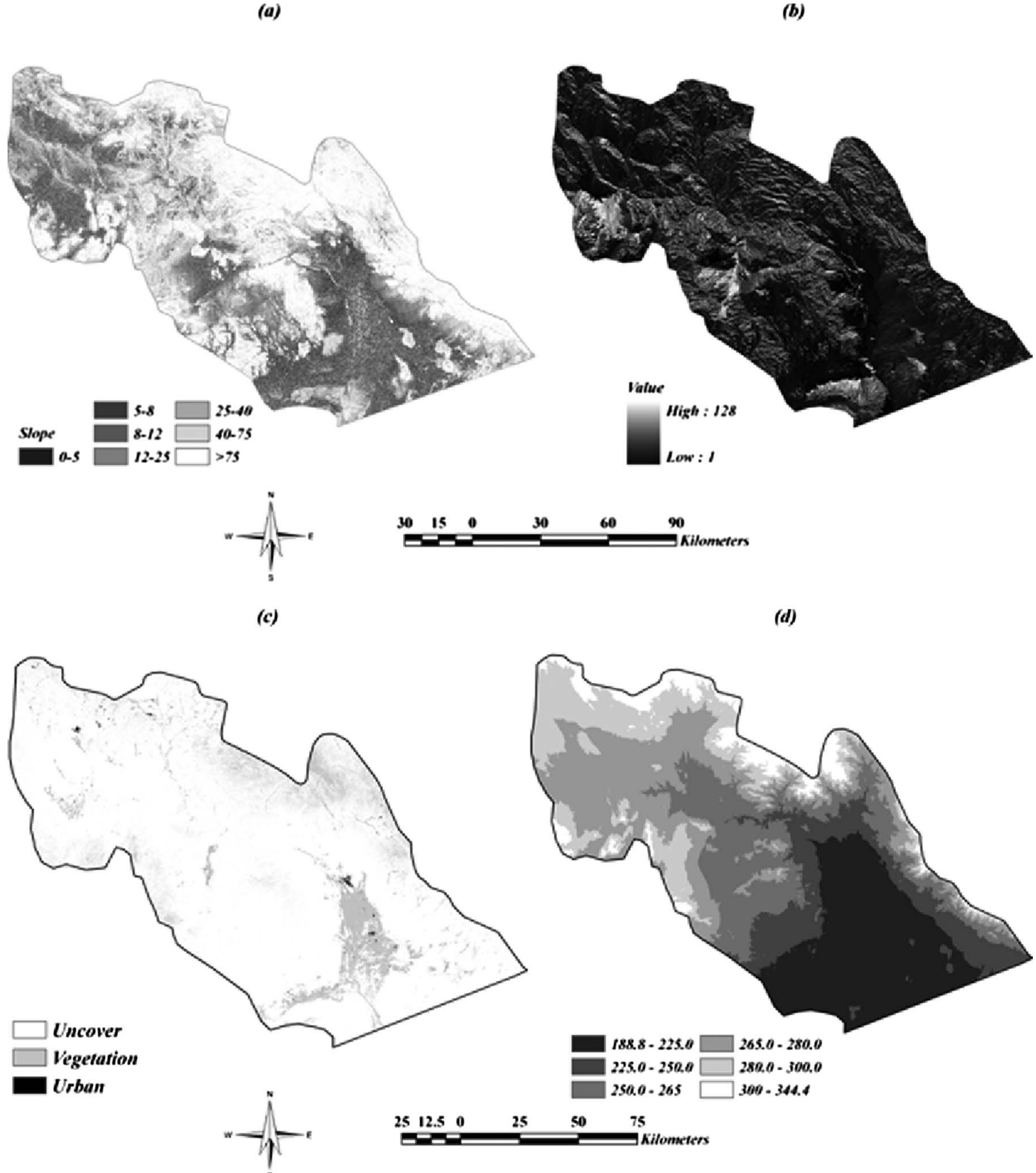


Fig. 5. Map of different watershed characteristics: (a) slope; (b) flow direction; (c) land use; and (d) mean annual rainfall (mm)

sures are $H_1=0.03$, $H_2=-0.99$, and $H_3=-1.16$. Therefore, the region demonstrates an acceptable homogeneity and we find the regional distribution function in the next step.

The $|Z^{\mathrm{Dist}}|$ values for the GLOG, GEV, LN3, PIII, and Pareto distribution functions are 1.79, 1.08, 0.25, -1.15, and -1.04, respectively. It is clear that except for the GLOG distribution, other distributions can be selected as the regional distribution function. However, the LN3 distribution function is more acceptable than the other functions due to the smaller value of $|Z^{\mathrm{Dist}}|$.

The probability density function of LN3 is

$$f(x)=\frac{1}{(x-a)\sigma_y\sqrt{2\pi}}\exp\left\{-\frac{1}{2\sigma_y^2}[\ln(x-a)-\mu_y]^2\right\} \qquad (15)$$

where μ_y and σ^2=location and scale parameters which correspond to the mean and variance of the logarithm of the shifted variable $(x-a)$. The LN3 parameters for each site are given in Table 2. The regional AEHDSL based on regional distribution (LN3) are 28, 49, 62, 75, 92, 103, 116, 132, 144, and 186 days for 2-, 5-, 10-, 20-, 50-, 100-, 200-, 500-, 1,000-, and 10,000-year return periods, respectively. The cumulative density functions of the AEHDSL for two typical stations are given in Fig. 4.

MLR

As the AEHDSL shows the duration of hydrologic drought, one can assume that the hydrogeomorphic parameters that affect hydrologic drought may influence the AEHDSL. Thus, the hydrogeomorphic characteristics of the basins were estimated using GIS techniques. The drainage characteristics and the boundary of watersheds were derived using Arc Hydro and the HEC-HMS

Table 4. MLR Models for AEHDSL (Days) at Different Return Periods

Return period (year)	Best regression model	R^2	VIF
2	AEHDSL=52.07−0.019R+0.002VC	0.96	VC:2.497 Relief:1.508
5	AEHDSL=98.12−0.036R+0.004VC	0.98	VC:1.335 Relief:1.229
10	AEHDSL=133.03−0.049R+0.006VC	0.97	VC:2.661 Relief:2.649
20	AEHDSL=184.3−0.082R+0.001VC	0.98	VC:1.331 Relief:1.000
50	AEHDSL=730.4+0.007VC−0.193MEL	0.97	VC:1.890 Maximum elevation:1.609
100	AEHDSL=955.3+0.009VC−0.255MEL	0.96	VC:1.860 Maximum elevation:2.614

software. The physical characteristics of watersheds were estimated by the ARCGIS 9.2 software. The correlation matrix (not shown here) shows the significant relationship between watershed characteristics and the AEHDSL. Therefore, we apply 11 physiographic, climatic, and land use variables of the watersheds as the independent variables (Table 3) and AEHDSL of 2-, 5-, 10-, 20-, 50-, and 100-year return periods as dependent variables. In Fig. 5, the maps of some hydrophysical characteristics have been illustrated.

Different land use classes such as forest, agriculture, rangeland, and horticulture classes were summarized into vegetation cover (VC). The bare soil and rock areas were also summarized into an uncover class. The best linear stepwise regression models are presented in Table 4 for different return periods. In this table, the (VC) is the area of the VC of the watershed (%), the relief (R) is the difference between maximum and minimum elevations of the watershed (m), and the (MEL) is the maximum elevation of the watershed. All regression parameters are significant at the 1% level. For example, the performances of the two regression models for 2- and 50-year return periods are given in Fig. 6 in terms of R^2. The validation of the models was investigated by normal and independent tests of the residuals. The VIF was also given in this table to check if multicollinearity exists between regressor variables. Because the VIFs are quite small in Table 4, there is no apparent problem with multicollinearity in the data set.

The results of the cross-validation experiment have been given in Table 5. The coefficient of determination (R^2) of each regression model and the homogeneity measures (H_1, H_2, and H_3) after removing each station have also been given in this table. According to the homogeneity measures, the region is homogeneous after removing one station from the region. On the other hand, the regression models are significant at the 95% significant level. The BIASr and RMSEr values of different regression models are relatively small. Thus, the relation between the AEHDSL and the watershed properties is clearly significant and the current regression model is valid for the prediction of AEHDSL at ungauged basins. According to the regression model, it is clear that the relief and the land use of the watershed play important roles on hydrologic drought in the Halilrud basin. In other words, the hydrologic or streamflow drought is dependent on the hydraulic head difference of the watershed which allows subsurface water to the main channel (Furey and Gupta 2000) and the VC which controls the infiltration of the surface water to subsurface water storage. The area of VC represents the effective part of the watershed area which controls the base flow of the watershed (Furey and Gupta 2000).

Most of the physical properties of the watershed such as area and slope are out of the access of a human being to control but the VC can be directly affected by anthropogenic activities. The effect of land use change on the hydrologic behavior of the watershed has received considerable attention in recent years (e.g., Legesse et al. 2003; Croke et al. 2004; Li et al. 2007). However, the impact of land use change on the hydrologic behavior of watersheds has not been studied in Iran yet and should be carefully investigated in the future.

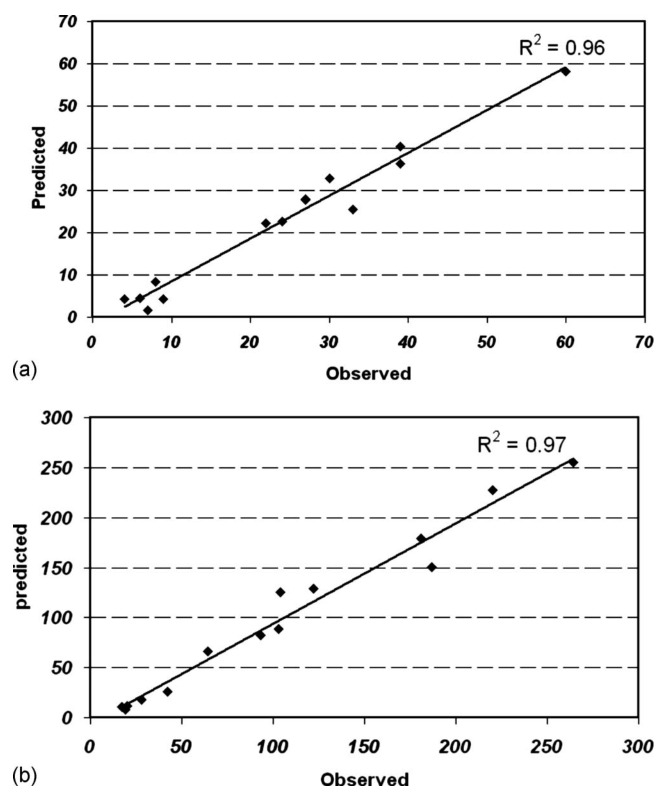


Fig. 6. Comparison of observed and estimated AEHDSL by regression method for return periods of (a) 2 years; (b) 50 years

Table 5. Results of the Leave-One-Out Cross-Validation Experiment for the MLR Model

Left out station	R^2 (%) Q2	Q5	Q10	Q20	Q50	Q100	Regional homogeneity measures H_1	H_2	H_3	BIASr (%)	RMSEr (%)
Aroos	71	87	76	85	72	72	−0.76	−1.07	−1.11	12.6	19.90
Cheshme	89	84	83	72	75	76	0.21	−0.98	−1.12	4.5	6.60
Dehrood	80	78	76	70	73	74	0.58	−0.50	−0.85	15.5	21.6
Hanjan	86	67	70	82	85	85	0.43	−0.91	−1.11	6.60	9.10
Hossienabad	68	77	85	85	78	74	0.58	−0.71	−1.10	5.07	7.70
Kahnak	83	87	85	82	77	79	−0.20	−0.99	−1.33	10.2	14.30
Kaldan	74	80	79	71	75	76	0.49	−0.70	−1.03	7.45	11.60
Kenarueih	77	82	80	70	73	74	0.43	−0.78	−1.01	8.23	12.02
Meidan	73	79	78	72	75	76	0.53	−0.51	−0.93	8.50	12.14
Narab	70	78	77	70	72	74	0.41	−0.92	−1.20	7.50	11.81
Polbaft	70	79	80	72	77	70	0.23	0.94	−1.12	6.30	10.02
Ramoon	74	78	70	70	70	70	0.21	−0.83	−1.28	5.60	8.23
Soltani	70	78	70	70	73	74	0.30	−0.97	−1.45	22.00	32.1
Zarrin	74	80	71	75	79	71	0.43	−0.50	−0.76	9.50	13.05

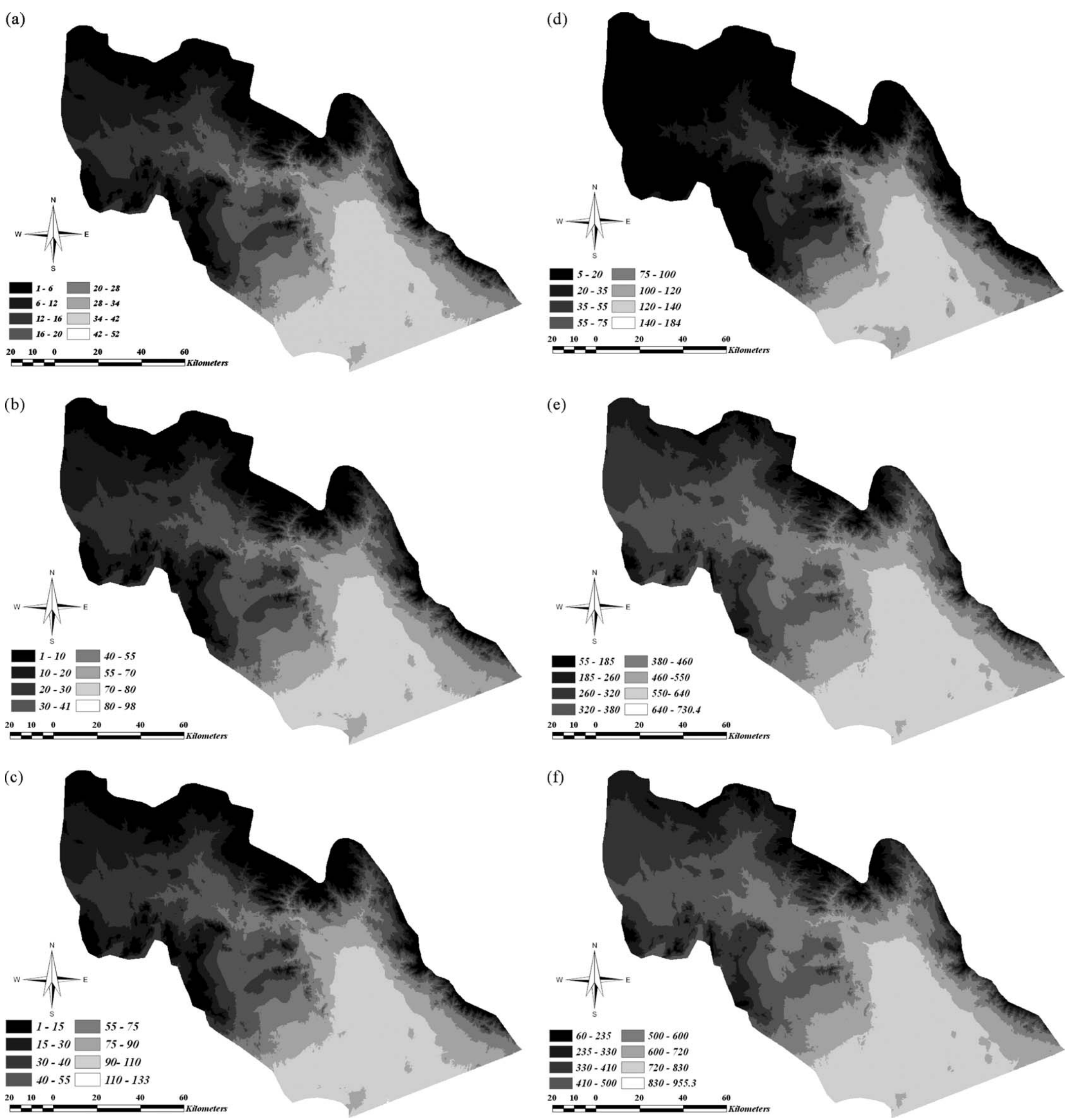


Fig. 7. Map of the spatial distribution of AEHDSL (days) over the watershed for (a) 2-, (b) 5-, (c) 10-, (d) 20-, (e) 50-, and (f) 100-year return periods

The maps of the spatial variation of AEHDSL (days) for different return periods are presented in Fig. 7 using the inverse distance interpolation method. These maps show the effect of the elevation and VC of the watershed on the AEHDSL. The drought duration is higher in a lowland than in a mountainous region. The lowland regions, the population and agriculture centers, expose to multiyear drought events and their consecutive risk of severe drought every 50–100 years in average. However, the mean, the 2-, 5-, and 10-year return period drought durations also last for 1/3 to 1/2 of the year. This implies a continuous drought risk in the Halilrud watershed during the year.

It is also clear that the 50- and 100-year return period drought lengths exceed 1 year (i.e., multiyear drought). These severe drought events which last for a long period of time have destructive impacts on water resources, agricultural economy, and weak ecosystems of the basin which is located in arid and semiarid regions of Iran. A comprehensive planning and management system, especially land use and land cover management as one of the main factors influencing drought duration in the Halilrud basin, is therefore necessary for water resource and agricultural development in the Halilrud basin to cope with the risk associated with long period drought events.

Summary and Conclusion

A different view of the hydrologic drought is proposed in this study by a drought index called "AEHDSL," that is the annual longest period of successive days in which streamflow is less than critical values. The statistical and probabilistic characteristics of the AEHDSL of the Halilrud basin in the southeastern semiarid region of Iran were investigated in this study.

The RFA of AEHDSL of the Halilrud basin was carried out in this study. The use of *L*-moments showed that the region is homogeneous according to statistical characteristics of AEHDSL and the LN3 distribution function performs a better fit than other distributions in the basin for the regional frequency distribution of AEHDSL.

The AEHDSL statistical characteristics can be used as decision support tools for the management of water and agricultural resources as well as food reserves by providing decision makers with ways to evaluate the likelihood of drought risk impacts in arid and semiarid regions. For the Halilrud basin, which is located in a semiarid region of Iran, the AEHDSL takes long near 25% of the year or 90 days in average. This demonstrates the high risk of hydrologic drought in the Halilrud basin and the need for careful water resources management and planning.

The estimation of AEHDSL for ungauged basins was also carried out using the MLR model. The linear regression was fitted to find the relationship between physical and climatic properties of watershed and different AEHDSL quantiles. The MLR demonstrated that land use and hydraulic head difference are dominant factors controlling the hydrologic drought of the basin. Therefore, the management of different vegetation types such as agricultural, range, and forest areas in the Halilrud basin plays a key role in drought management in this basin. In other words, the water scarcity and crisis in this basin are strongly related to soil and vegetation conservation of the basin. Although there is no valid information of land use change in arid and semiarid regions of Iran, land use change, usually rangelands and forest areas to agricultural rainfed land use, can be assumed to be the main reason of land degradation which may result in a water crisis in arid and semiarid regions of Iran.

Finally, the results of this paper provide useful information for regional drought analysis in arid and semiarid regions and give a better perspective to the risk associated with long consecutive days, sometimes a multiyear drought, of water supply below critical thresholds for regional water resource planners and managers. The present study also indicated the factors, the elevation gradient and VC, which affect the low streamflow process in the watershed scale in arid and semiarid regions, at least for the Halilrud basin in southeastern Iran.

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