

## **Drought spatial analysis and development of severity–duration–frequency curves for an arid region**

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**Abstract** Drought is an integral part of climate variability. Drought is a common and familiar event in arid Mediterranean regions with spatio-temporally variable rainfall. Most of Iran is subject to a Mediterranean precipitation regime, where drought occurs frequently. Sistan–Belochestan (S&B) province, located in the south-eastern corner of the country, is characterized by very low annual rainfall and has a warm, dry climate. In this article, monthly S&B rainfall data were analysed from a drought standpoint. The severity, magnitude, and duration of drought periods on a monthly and longer time basis were determined based on a dimensionless Z-score and run theory. Severity–duration–frequency (SDF) curves for each station were then extracted. A number of interpolation techniques were examined in deriving regional drought maps for a range of drought duration and frequency. The results showed that the centre of the province is subject to more severe droughts. Also drought periods in the region were further studied using Markov chain analysis in conjunction with the run theory. The results showed that drought duration decreases from south to north, with the minimum in the historic Zabol area. The probability of drought terminating in the following month is only 28% in the south.

**Key words** Iran; meteorological drought; Markov chain; run theory; severity–duration–frequency; Z-score

## **INTRODUCTION**

Drought is an environmental phenomenon and an integral part of climate variability. Drought analysis is often restricted to descriptive evaluation (Dupigny-Giroux, 2001). The characteristics and consequences of drought may vary in different climatic regimes around the world. In sensitive dry regions, rainfall deficit has an intense effect on water resources and, in many cases, meteorological droughts are followed by hydrological and environmental droughts. Drought frequently occurs in arid and semi-arid regions, such as Iran, giving rise to economic and environmental damage and losses. Derivation of drought severity–duration–frequency (SDF) curves, or alternatively magnitude–duration–frequency (MDF) curves, and iso-severity maps is of paramount importance in environmental and agricultural planning (Dalezias *et al.*,

2000). Frequency analysis of droughts in the form of SDF is complex and difficult, since any of these parameters may have its own distribution and stochastic and probabilistic characteristics (Moye *et al.*, 1988; Sharma, 2000). Time series techniques, such as Markov chain analysis, are widely used in drought prediction (Thompson, 1999).

The aim of this paper is to analyse droughts in Sistan and Belochestan province (S&B) in Iran using Run Theory (RT) and Markov chain. SDF curves and iso-severity maps of the study area are derived, and the drought duration and severity for the coming months are predicted. Long-term predictions for the region are performed based on state transition matrix.

## STUDY AREA

S&B province is located in the southeast corner of Iran, north of the Oman Sea, geographically limited between  $24^{\circ}55'$  to  $31^{\circ}28'N$  latitude and  $58^{\circ}40'$  to  $63^{\circ}13'E$  longitude (Fig. 1(a)). The climate of the area is dominated by a subtropical high for most of the year. This phenomenon causes a hot and dry climate in the summer. Almost 95% of rainfall in S&B is produced by Mediterranean synoptic systems, which move eastward along with westerly winds in the cold season. Synoptic systems and year-to-year variation in the number of passing cyclones cause high variability in annual rainfall. Due to a long trajectory and loss of moisture, these systems do not produce substantial rainfall when reaching the region. The maximum temperature may reach  $44^{\circ}C$  in the summer. The prevailing summer winds, called 120-day winds, also affect the study area with great intensity and increase the potential evapotranspiration. Therefore, the region is extremely dependent on surface water resources, such as the Hirmand River entering the country from Afghanistan. There is hardly any groundwater resource in the region. The study area has gone, and is still going through, a severe persistent drought which is forcing many local people to migrate. To make matters worse, the trans-country Hirmand River, providing a large portion of water resources for the north of the region, is almost entirely dry. Table 1 summarizes some climatological variables at Zahedan synoptic station.

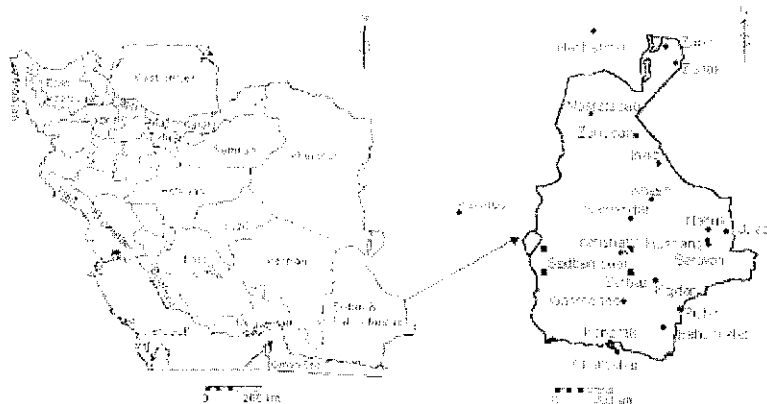


Fig. 1 (a) Geographical location of S&B in Iran, and (b) spatial distribution of stations.

**Table 1** Climatological variables at Zahedan synoptic station.

Variable	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.	Annual
Rainfall (mm)	22.7	19.1	17.7	12.0	5.0	0.4	1.6	0.6	0.1	2.3	3.7	11.0	96.2
Mean temp. (°C)	7.1	9.9	14.7	19.7	24.2	27.4	28.4	26.4	22.4	17.9	12.7	8.7	18.3
Abs. max temp. (°C)	27.0	28.0	32.2	38.0	41.0	43.0	42.0	43.0	40.0	38.0	31.0	28.0	43.0
Abs. min temp. (°C)	-22.0	-14.0	-7.0	-1.0	1.4	11.0	11.0	8.0	2.0	-4.0	-11.0	-16.0	-22.0

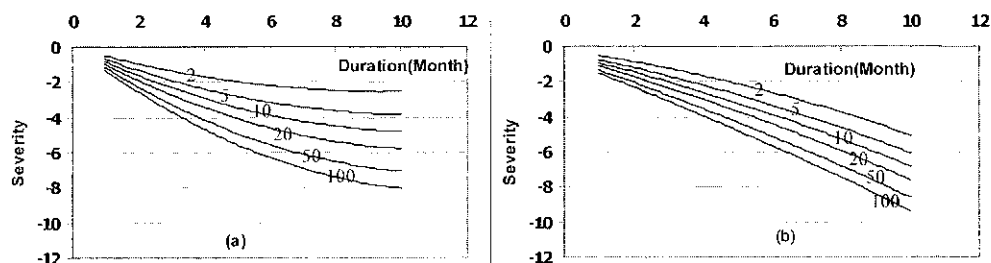
## METHODS

Meteorological drought was defined using monthly rainfall data collected from 22 raingauge stations (Fig. 1(b)) with 27 years of records. The data was checked for errors and non-homogeneity and missing data was estimated from neighbouring stations by regression methods. Monthly data were then transformed to Z-score values:

$$Z = (x - \mu) / \delta \quad (1)$$

where  $Z$  is the standard index;  $x$  is monthly rainfall value,  $\mu$  is the mean; and  $\delta$  is the standard deviation (SD). A review of the literature showed that many investigators have used equation (1) for the entire rainfall time series in humid regions. In such regions, the frequency distribution of rainfall data may be normal. On the contrary, in arid regions such as S&B, the rainfall data almost follows a gamma distribution. Annually, more than six months in most stations may have recorded no rainfall. Because of a great variability of rainfall and the existence of zero values in the time series, it was decided to split the time series into 12 monthly groups. The Z-scores of each group were calculated based on the mean and SD of individual months. The overall Z-score time series was then serially re-arranged.

One of the common methods for analysis of drought is the run theory (RT), which was first proposed by Yevjevich (1967). A run analysis of drought is based on the theory of runs for discrete variables, although the theory is also applicable to continuous variables. RT quantitatively describes how a hydrological process crosses above and below some critical threshold value called truncation level (Dracup *et al.*, 1980a, 1980b). The truncation level,  $x_0$ , is the value of  $x$  for which negative departures are defined as drought. The truncation level may be set anywhere; setting it at the mean recognizes that even small negative departure from the mean is considered



**Fig. 2** SDF curves of (a) Zabol and (b) Zahedan stations.

drought. According to the climatic characteristics of the study area, truncation level was set at  $x_0 = \pm 0.25$ . Therefore, small amount of noise is considered normal. A down crossing occurs when at time  $t - \Delta t$ ,  $(x - x_0) > 0$ , and at time  $t$ ,  $(x - x_0) < 0$ . For any drought event, the negative run length  $L_i$ , representing drought duration, is defined as the time span of consecutive sequence of negative deviations preceded and succeeded by a positive deviation. The sum of negative deviations in any run length is called the run sum ( $S_i$ ) and measures drought severity. The ratio  $S_i/L_i$  is also defined as the drought magnitude (Dracup *et al.*, 1980a).

## DERIVATION OF SDF CURVES

In deriving SDF curves, drought duration and severity for each event were defined using RT. Drought events with different duration (one month, two months, and so on) were then tabulated. The severities of any given duration were ranked in a decreasing order and the severity corresponding to six different return periods were calculated based on the Weibul method. While it is desirable to have a large data set, in practice data of longer duration is lacking. To overcome this problem, we generated additional data series and extended the record to 40 years via statistical and stochastic methods. Accordingly, SDF curves for 2-, 5-, 10-, 20-, 50- and 100-year return periods were developed. Figures 2(a) and 2(b) show the SDF curves for two important Zahedan and Zabol stations.

## DROUGHT PREDICTION USING MARKOV CHAIN

Markov chains are classified by the number of lags that are used to define the present state. The time dependency in the stochastic process can be incorporated by using either serial correlation coefficients or state transition probabilities. A lag1 Markov chain indicates that the probability of having a drought (state) this month depends on whether drought conditions existed the previous month. The degree of dependence between states can be expressed as a state transition probability of moving from the current state  $i$  to the future state  $j$  in the next time step. At each step  $i$  the environment is in one of three possible states: drought ( $D$ ), normal ( $N$ ), or wet ( $W$ ). The state transition probabilities ( $P_{ij}$ ) for each state  $i$  indicate the chance of remaining in the present state or moving to another state  $j$ . We denote the state transition probabilities for drought states by  $P_{D,D}$ ,  $P_{D,N}$  and  $P_{D,W}$ . If the transition probability matrix is multiplied by itself again and again, the individual state transition probabilities  $P_{ij}$  approach equilibrium. These equilibrium probabilities, shown by  $P^*_i$ , where  $i$  denotes the state, comprise a new ( $1 \times 3$ ) matrix called the  $n$ -step equilibrium matrix  $P^n$ . From the theory of runs, the expected number and length of down crossings,  $E(D)$  and  $E(L)$ , are equal to  $P_{D,L}$  and  $P^*_D/P_{D,D}$ , respectively. The probability of going from normal ( $N$ ) and wet ( $W$ ) states to drought ( $D$ ) state may be estimated as:

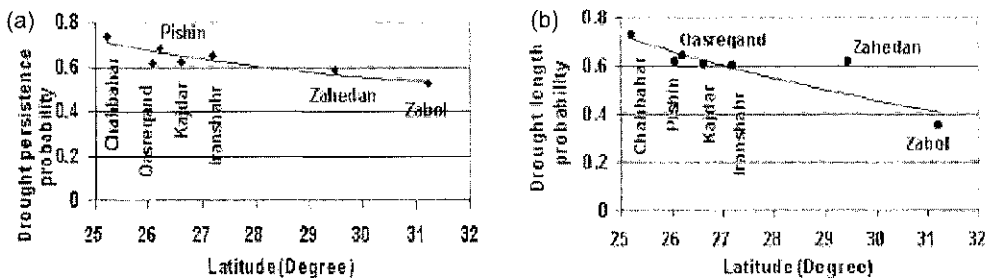
$$P_D = P^*_N P_{N,D} + P^*_W P_{W,D} \quad (2)$$

Table (2) shows the transition probability matrices of Zahedan and Zabol stations. The diagonal of transition probability matrix describes the persistence of the climate state.

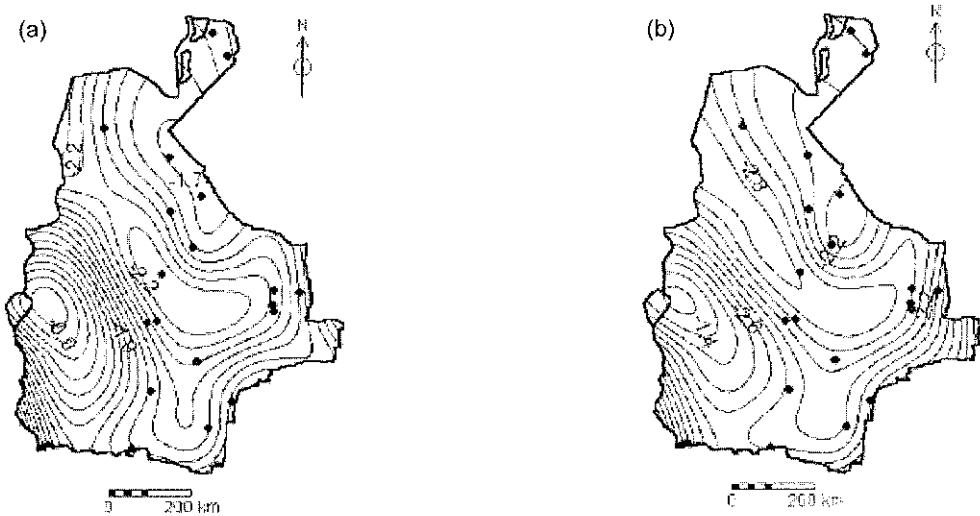
**Table 2** Transition probability matrices of Zahedan & Zabol stations.

Station	State	<i>D</i>	<i>N</i>	<i>W</i>
Zabol	<i>D</i>	0.526	0.232	0.241
	<i>N</i>	0.170	0.707	0.122
	<i>W</i>	0.457	0.305	0.237
Zahedan	<i>D</i>	0.581	0.234	0.183
	<i>N</i>	0.539	0.206	0.253
	<i>W</i>	0.781	0.062	0.156

The  $P_{D,D}$  at Zahedan station is about 0.58, which means that if the region is in a drought status it will persist by a chance of 58%. Similarly, in the case of a wet state (*W*), the chance of remaining in that state is very low (16%). Therefore, while drought spells are more likely to last longer the wet spells are less persistent. Each value of equilibrium matrix is representative of periods that the region will be in that state in the coming months. A computed equilibrium transition matrix reveals that the Zahedan station has an overall 61% chance of being in a drought state, 20% in a normal state, and 19% in a wet state for the coming months. Figure 3(a) shows the variation of drought persistency as a function of latitude in the region based on transition probability matrix. Chahbahar area, in the south of the province, has the most persistent drought conditions with a low chance of breaking the drought, while Zabol area, in the north of the region, has the highest chance of escaping the drought. Figure 3(b), showing the probability of drought occurrence in the region, indicates an overall decrease in a south to north direction. Table 3 summarizes the estimated numbers and lengths of drought events for the next 10 years. Based on this table, Zahedan is the most drought prone station in the region, while Zabol may have a less chance of drought in the coming months. The predicted number of drought events for Zahedan and Zabol are 30.75 and 19.70, respectively. The longest and shortest predicted drought durations will occur in Chahbahar and Zabol, with an average of 3.77 and 2.11 months, respectively.

**Fig. 3** (a) Drought persistence and (b) drought length probability of the region.**Table 3** Predicted numbers and lengths of drought events.

Station	Zahedan	Zabol	Iranshahr	Kajdar	Qasreqand	Pishin	Chahbahar
Number	30.75	19.70	25.27	27.04	24.19	27.96	22.84
Duration (month)	2.39	2.11	2.83	2.66	3.16	2.62	3.77



**Fig. 4** Predicted drought severity of the region for three-month duration: (a) 5-year return period, and (b) 20-year return period.

## DEVELOPMENT OF ISO-SEVERITY MAPS

Geostatistical methods were used to develop drought iso-severity maps for the study area. Weighted moving average (WMA), ordinary kriging (OK) and thin plate smoothing spline (TPSS) methods were examined for interpolation. It was found that TPSS yielded the best results. Figures 4(a) and 4(b), show two samples of iso-severity maps. Based on these figures, drought severity decreases from the centre of the province to the borders. Consequently, the province centre faces the most severe drought and requires more attention with regard to water resources planning and allocation.

## CONCLUSIONS

Because of high temporal variability in rainfall and the existence of many zero values in the rainfall time series of the study area, common analysis of the drought based on RT leads to exaggeration of wet spells and downplays the importance of dry periods. In this study, the Z-scores were derived for every individual month and were further used for drought/wet state separation. The time series of Z values revealed that the region is seriously and continuously threatened by droughts. The drought phenomenon is a prevailing climatic characteristic of the region and may last for several consecutive months and even years. As Fig. 4(a) and 4(b) show, the most severe droughts occur in the centre of the province. Drought persistence decreases from south to north and reaches its lowest value in Zabol. Drought severity also decreases eastward and northward where the majority of the province population live.

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