Severity of Droughts in Arid Regions

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ABSTRACT

The increasing water shortage in Jordan threatens the environment and badly affects most of the scoi-economic activities. In central Jordan, where major agricultural and water storage projects are located, the October – May rainy season precipitation for two gauging sites; namely Amman Airport and Madaba, is used in the present study to investigate the occurrence of extreme droughts. The extreme regional dry year occurs when the precipitation in that year falls under the threshold of 1 Standard Deviation below the long-term mean at site. Historical precipitation data, 1938 – 2005, are used to simulate 50000 precipitation data using multivariate stochastic simulation model of order 1, MAR(1). Drought analysis using the historical precipitation shows that extreme droughts fall out as individual years, while using generated precipitation droughts is distributed as 1 year events mostly, and as 2 and 3 years duration although less. This study also presents a theoretical model to estimate the return period of extreme droughts. The estimated return period of the 1 year extreme drought in central Jordan is around 10 years, whereas it is 160 years or more for droughts of longer durations. The probability that an extreme drought occurs at least once in a planning period of 25 years, defined as the risk, is found to be more than 90% for drought of 1 year duration, while it is found to be 15% or less for events of 2 years or more.

KEYWORDS: Drought analysis, Precipitation in Jordan, Return period, Stochastic simulation.

INTRODUCTION

Jordan's climate is generally characterized by tremendous temporal and spatial variations. The geographical position of Jordan as an eastern Mediterranean region mainly governs the time variation, while the spatial variation is attributed to discrepancy in elevations that range from 416m below the mean sea level at the Dead Sea to 1800m above the mean sea level in the southern Highlands. In Jordan, the three main climatic zones are: the Jordan Rift Valley, the northern and southern highlands, and the eastern and southern deserts (MWI, 2004). The Jordan Rift Valley is characterized by its sub-tropical climate, mild winters and very hot summers, with an annual rainfall ranging from 350mm (northern part) to less than 50mm in the south towards the Red Sea. In the northern and southern highlands, mainly cool rainy winters and warm summers are dominant seasons having some regions receive around 600mm of rainfall in an average year. The eastern and

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southern deserts are distinguished by cool winter and hot summer with an average annual rainfall below 100mm. Figure 1 shows the distribution of the average annual rainfall in Jordan. Generally, the dry season in Jordan extends over the months May – September, while the moderate wet season starts in October and ends in April.

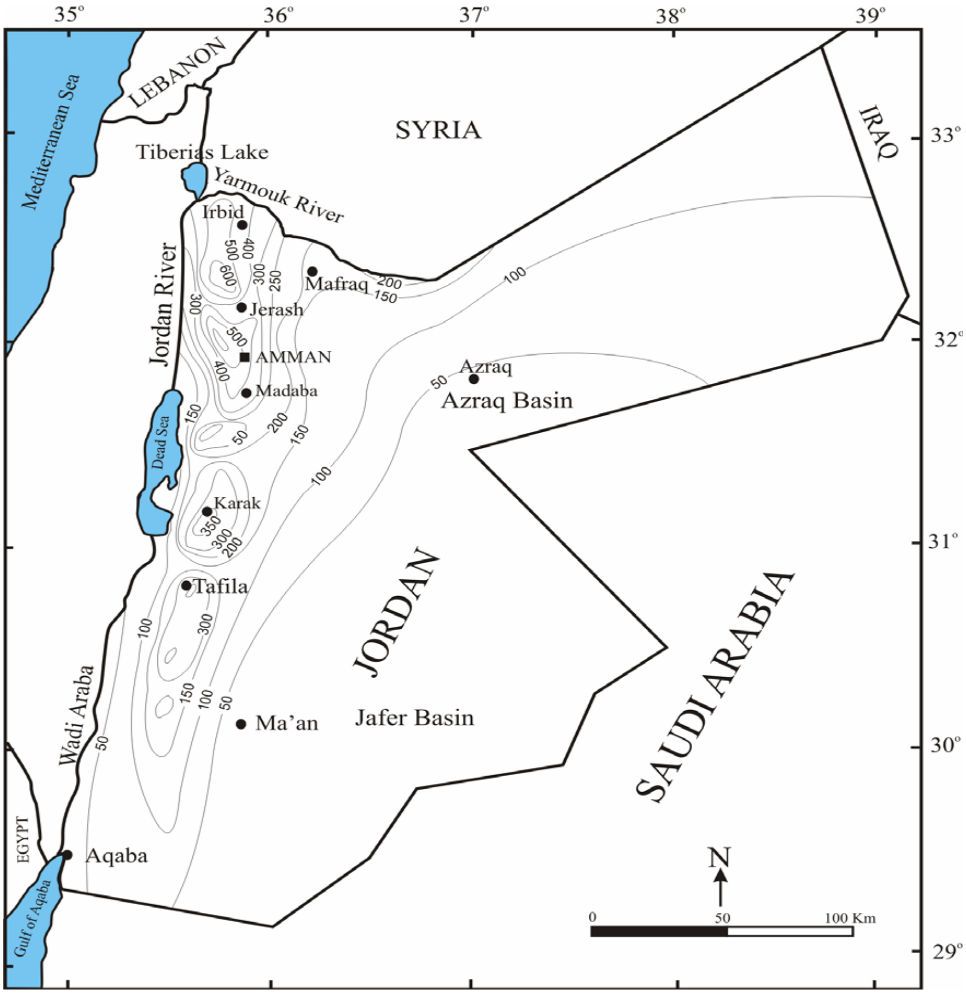

Fig. (1): Average rainfall distribution in Jordan based on records for the period 1938-2005. (Source: Water Authority of Jordan).

The term drought is used in literature to describe the complex natural phenomenon of moisture lack during a time period over a region (Sen, 1998). Each drought event is characterized by time length (duration), total deficit (magnitude) and return period. The drought duration is defined as an uninterrupted sequence (years) of observations below a predefined threshold, given that the dry sequence is preceded and followed by at least one observation above that threshold (Yevjevich, 1967). For the given drought duration, the drought magnitude is the sum of the single deficits over the duration of that drought (Sharma, 2000). A drought of a particular duration or magnitude that exceeds a predefined event (threshold) is associated with a return period that is defined as the expected value of the interarrival time between two successive occurrences of the event under consideration (Douglas et al., 2002). Although droughts are characterized by the correlated random quantities of magnitude and duration, in reality droughts are considered as regional incidents (Shin and Salas, 2000).

Table (1): The statistics of the rainy season total precipitation for the two sites in central Jordan, historical versus generated data.

Statistic	Historical precipitation		Generated precipitation	
	Amman Airport	Madaba	Amman Airport	Madaba
Mean (mm)	272.8	346.2	272.6	346.2
Standard deviation (mm)	95.9	125.8	96.04	125.9
Coefficient of variation	0.35	0.36	0.35	0.36
Skewness	0.66	0.60	0.78	0.78
Lag-1 serial correlation	-0.13	-0.14	-0.11	-0.13
Lag-0 cross correlation (between sites)	0.9		0.9	

Drought indices (e.g., the Palmer Drought Severity Index, the Palmer Hydrological Drought Index and the Drought Monitor) can be used to analyze regional droughts. Such indices are useful to monitor drought severity in a given year and describe its spatial evolution. However, common weaknesses of the current drought indices have been reported (Byun et al., 1999; Blenkinsop and Fowler, 2007). Furthermore, drought indices can not explain the occurrence frequency of extreme historical droughts (Rossi and Cancelliere, 2003; Salas et al., 2005). Alternatively, regional droughts can be analyzed efficiently employing statistical approaches. In literature, two main statistical approaches that incorporate the regional aspect of droughts have been used. The first approach adopts the proportion of the area covered by the drought deficit to characterize regional droughts (e.g., Tase, 1976; Santos, 1983; Shin and Salas, 2000; Hisdal and Tallaksen, 2003; Loukas and Vasiliades 2004; Hammouri and El-Naqa, 2007). The second approach relies on the joint analysis of the underlined hydrologic variable at several sites in the region under consideration as the key point to investigate regional droughts (e.g., Yevjevich, 1972; Sen, 1998; Bayazit and Onoz, 2005; Paulo et al., 2005, Bordi et al., 2007). In this study, the second approach is adopted to investigate regional extreme droughts in central Jordan.

Few studies have considered the region of Jordan for drought investigations. Hammouri and El-Naqa (2007) employed drought indices to study the drought patterns in Amman-Zarqa basin in Jordan. In general, droughts prevail in the months of October and December; while wet conditions are dominant in November and January. Moreover droughts of short duration that last 2 – 3 years were found to reoccur several times over the period 1975 – 2000. Likewise, using arbitrary truncation level, the foremost occurrence of short extreme droughts that last 1 – 3 years has been also observed by dendroclimatological study for the region of southern Jordan (Touchan et al., 1999). The average time interval between drought events that cover the region of southern Jordan is estimated as 4.2 years (Touchan et al., 1999). Generally, the last decade is characterized by frequent droughts of 2 – 3 years duration as observed to occur in the south side of the Jordan River basin (Al-Salihi, 2003).

Since the short precipitation records may not reflect consistent information about the random nature of extreme droughts (Woodhouse, 2001), one objective of this paper is to simulate longer precipitation data for Amman Airport and Madaba gauging sites in central Jordan using multivariate stochastic simulation model. Another objective is to analyze the historical and simulated precipitation at the two sites mutually to characterize extreme regional droughts. Moreover, the risk that particular drought occurs during a planning period of 25 years will be investigated.

DATA AND METHODOLOGY

Precipitation data for Amman Airport and Madaba gauging sites that represent the region of central Jordan is considered for the purpose of this study. The region considered forms part of the drainage area that contributes flow to major reservoirs at the King Talal and Wala dam sites. Furthermore, several agricultural activities and ground water recharging projects are taking place in that region. The monthly precipitation data for the two gauging stations have been obtained from the Meteorological Department of Jordan and covers the period 1938 – 2005 with no missing data. The total precipitation of the rainy season, hereafter referred to as the total precipitation, that starts in October and ends in May was obtained by accumulating the monthly precipitation values. Table 1 shows the descriptive statistics of the historical total precipitation for the two sites. The total precipitation data for both sites show insignificant serial correlation while precipitation is highly correlated between sites (Table 1). Moreover, the low values of the coefficient of variation indicates the moderate variability which the precipitation takes around its mean value for both sites, i.e.; no frequent extremes of very high and very low precipitations exist. The Anderson-Darling test of normality at 10% significance level rejects the null hypothesis that the total precipitation data for both sites are normally distributed (the statistic AD and p-values are: AD = 0.68 and p = 0.074 for precipitation for Amman Airport, while DA = 0.76 and p = 0.046 for precipitation for Madaba gauging site).

To investigate the extreme regional historical droughts, the threshold of one standard deviation (1SD) below the long-term mean is used, i.e.; 176.2mm and 219.4mm for precipitation at Amman Airport and Madaba sites, respectively. The extreme dry season is defined as the season of total precipitation that is below the threshold value. Moreover, the regional drought of duration L is said to occur when both sites observe individual drought of duration L at the same time. Figure 2 depicts the total precipitation truncated at the threshold of 1SD below the mean precipitation at both sites. The figure illustrates the dominant occurrence of extreme regional droughts of short duration, i.e.; 7 events of 1 year duration, while droughts of duration longer than 1 year never happened.

To estimate the return period T_L of extreme droughts, the expected value $E(w)$ of the interarrival time w between successive drought events of a given duration, i.e.; droughts of specified duration L = 1, 2, ..., is needed. Fernandez and Salas (1999) expressed T_L as:

$$T_L = E(w) \tag{1}$$

Shiau and Shen (2001) investigated the distribution of the interarrival time w for two state Markov processes for the purpose of estimating T_L, however when the distribution parameters are estimated from relatively short records, i.e.; the case of most historical precipitation records, then the estimated value of T_L may be unreliable. As an alternative procedure, the return period in (1) is expressed in terms of N_L, the number of drought events of particular duration, as follows:

$$T_L = \frac{w_1 + w_2 + ... + w_n}{n} \tag{2}$$

where n is the number of time intervals between the successive drought events of the same duration.

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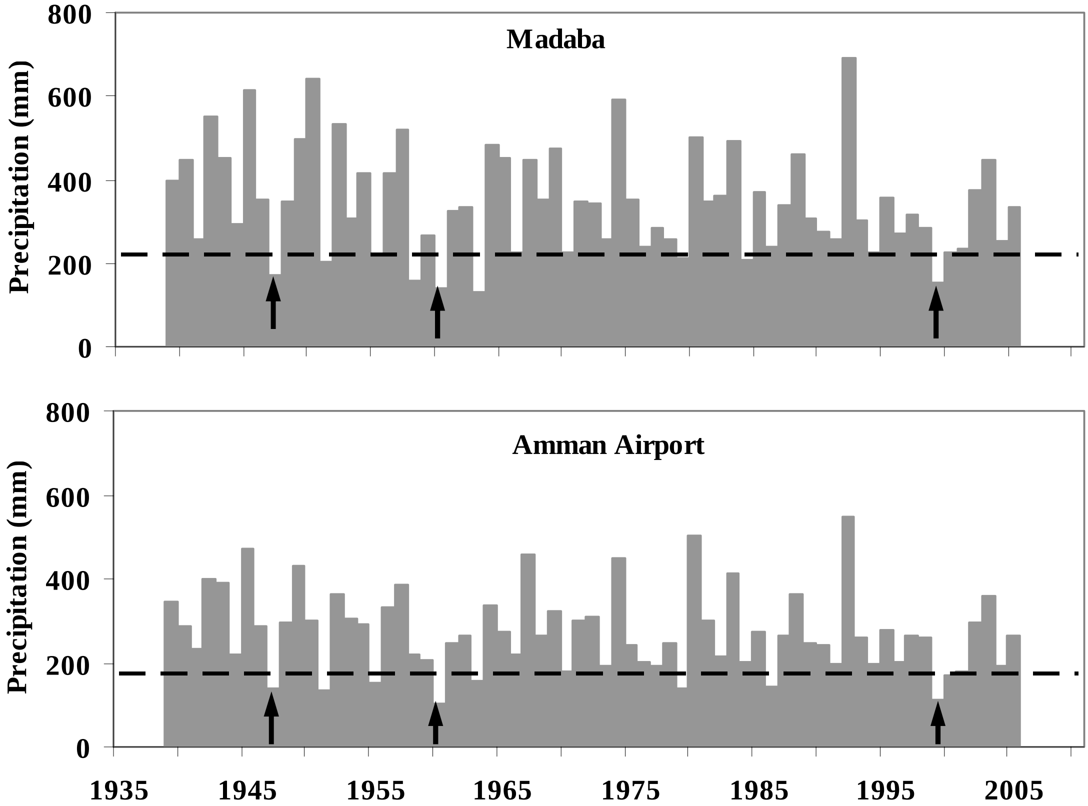

Fig. (2): The rainy season precipitation time series for the period 1939 – 2005. The dashed line represents the threshold of 1SD below the long-term mean, while arrows indicate years when some extreme regional droughts occurred.

When there is sufficient number of drought events (N_L is large), then the sum of w_1, w_2, …,w_n approaches the record length M. Furthermore, for given N_L droughts, there are n-1 intervals (n-1 waiting times between the N_L events), thus eqn. (2) is re-written as:

$$T_L = \frac{M}{N_L + 1} \qquad (3)$$

In the light that the successive drought events are emerging completely independent of each other, then for time independent processes Sen (1980) expressed the average number of drought events in a record of length M as $M\, q\,(1-q)$, where q is the non exceedance probability that a given year is a dry year. For this study, q is defined based on a regional basis as q = P ($X^{(1)} < x_o^{(1)}$, $X^{(2)} < x_o^{(2)}$), where $X^{(1)}$, $x_o^{(1)}$, $X^{(2)}$, $x_o^{(2)}$ are the precipitation and the threshold values at sites 1 and 2, respectively.

Given the distribution of drought duration, i.e.; $P[L=i]$, then N_L can be expressed as:

$$N_L = M\,q\,(1-q)\,P[L=i] \qquad (4)$$

where $P\ [L = i]$ is the probability distribution of drought of duration L = *i*.

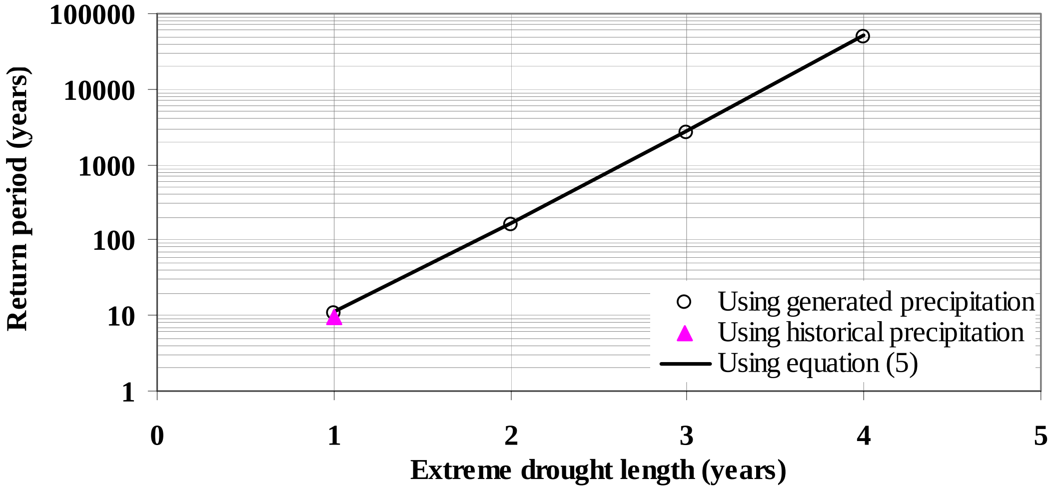

Fig. (3): The return period of extreme droughts in central Jordan, theoretical versus empirical from historical and generated data.

Substituting (4) in (3), rearranging and noting that the quantity ($\frac{1}{M}$) approaches 0 as *M* takes a large value, then the return period T_L is:

$$T_L = \frac{1}{q\,(1-q)\,P[L=i]} \qquad (5)$$

In (5), the probability $P\ [L = i]$, for i = 1, 2, 3 and 4, has been determined from simulation, because the analysis of the historical data provides only few events of the same type, i.e.; 7 events of 1 year duration, as previously mentioned.

While the short precipitation records may not reflect consistent information about the random nature of extreme droughts, the longer records generated utilizing stochastic simulation models provide more reliable drought statistics (Salas et al., 2005). The model used to simulate annual values of the rainy season total precipitation at the two sites mutually has the form of Multivariate Auto-Regressive of order-1, MAR(1), that is given as (Bras and Rodriguez-Iturbe, 1993):

$$\mathbf{Y}_t = \mathbf{A}\mathbf{Y}_{t-1} + \mathbf{B}\mathbf{e}_t \qquad (6)$$

where $\mathbf{Y}_t$ is a vector of generated values, **A** and **B** are model parameters estimated as in Bras and Rodriguez-Iturbe (1993) and $\mathbf{e}_t$ is a vector of white noises that are normally distributed with mean= 0 and standard deviation = 1.

Since the generated $\mathbf{Y}_t$ values are normally distributed, then the positively skew historical precipitation data (Table 1) has to be transformed to the normal domain for the purpose of estimating the model parameters **A** and **B**. The log transformation of the form $Y = ln\ (X + a)$ has been used for both sites, where X is the actual precipitation. For precipitation data at the sites of Amman Airport and Madaba, the values of a are 105.26 and 144.85, respectively.

The generated data **Y** is back transformed to precipitation values in its original domain *X* (positively skewed) for the analysis of droughts. To assess how well the generated precipitation represents the actual precipitation, Table 1 shows the statistics of the historical versus generated precipitation. Comparing the statistics obtained from the historical precipitation with those obtained from the generated precipitation, one observes how well the generated precipitation preserves the characteristics of the historical precipitation with the exemption of the skewness that is slightly higher than the skewness of the actual precipitation.

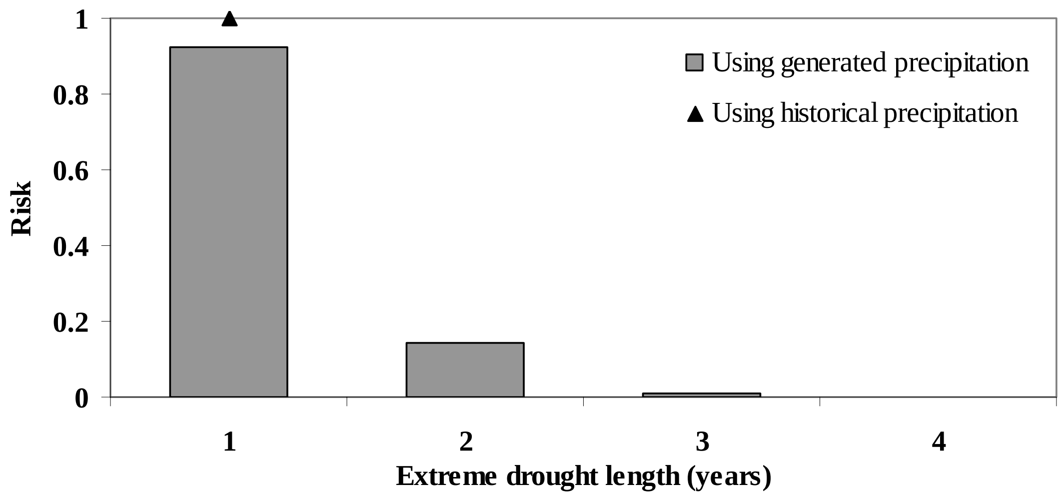

Fig. (4): The risk that an extreme drought occurs during 25 years planning horizon in central Jordan, empirical values from historical and generated data.

RESULTS AND DISCUSSION

The analysis of the truncated historical precipitation at both sites simultaneously shown in Figure2 indicates the frequent occurrence of short extreme regional droughts having a duration of 1 year, while droughts of a duration longer than 1 year never happened. This may generally illustrate the insufficiency of using the short precipitation records to analyze extreme events like droughts, especially of long duration. The return period of extreme droughts in central Jordan estimated empirically by averaging the waiting times, i.e.; equation 5, between the 1 year historical droughts is 9.6 years. For droughts of longer duration, the analysis of the historical precipitation data provides no information.

Truncating the 50000 years of the generated precipitation at the same threshold values used for the analysis of the historical data, and then analyzing for extreme droughts, the result indicates the dominant occurrence of the 1 year drought events, however droughts of longer durations (2, 3 and 4 years) are also found although less. The return period calculated empirically by averaging the waiting times between the regional droughts is plotted against the duration of the extreme drought as shown in Figure 3. For the 1 year extreme drought in the region of central Jordan, the return period estimated using the generated data is 10.8 years, while for droughts of longer duration its value is greater than 160 years. This particular information is very important to the decision maker for designing and planning purposes.

The return period results obtained using the model in equation (5), developed here, match very well with the results attained by analyzing both the historical and the generated precipitation. For example, the return period of the 1 year regional drought obtained using equation (5) is 10.1 years that is highly comparable to the values obtained empirically as mentioned above. In general, Figure 3 demonstrates that the return period increases as the duration of the drought increases, which is expected, because droughts become more extreme as the duration increases. It should be noted here that although the result from analyzing the longer generated data appears a sort of providing no much information beyond what the short historical records of precipitation do, however when the truncation level (the threshold of 1 SD below the mean) is reduced for example to 0.5 SD or 0 SD (e.g., Salas et al., 2005), then one would observe that only few drought events will emerge from truncating the short historical records. Those few events may provide unreliable drought statistics compared to what the plenty of events that are offered by truncating the long generated data can do. Furthermore, this study presents a theoretical model that can be consistently used to evaluate the return period.

Similar to Salas et al. (2005), the risk defined as the probability that a particular drought event occurs at least once within a planning period of 25 years is also investigated. In this case, the generated precipitation series (the 50000 data points) is divided into 2000 sub-samples each of 25 years. For a given drought event, each of the 2000 generated samples is analyzed and a count is made whenever one or more of the specified drought event has occurred. The ratio of the total count over 2000 gives an estimate of the risk that the specified drought event may occur in the 25 year horizon. For the historical data, 43 overlapping sub-samples each of the size of 25 years are obtained. The probability of observing at least one extreme regional drought event in central Jordan during a planning period of 25 years is shown in Figure 4 versus the duration of the drought. The risk of observing a 1 year drought in 25 years planning horizon is 100%, which is probably a little inflated, as the analysis of the historical precipitation over the region of central Jordan indicates, while it is 92.5% as the analysis of the generated precipitation points out. For droughts of longer duration, the risk appears very low (15% or less using generated data) as shown in Figure 4.

CONCLUSIONS

This study investigates the occurrence of extreme droughts in the region of central Jordan utilizing the rainy season precipitation over the period 1938 – 2005. The threshold used to indicate the occurrence of the extreme dry year is one standard deviation (1SD) below the long-term mean of the precipitation at site. The analysis of both historical and generated precipitation data for the two sites in central Jordan indicates the dominant occurrence of short regional droughts, frequently 1 year drought and rarely longer. This study also presents a theoretical model that can be used to evaluate the return period of extreme droughts. The results of return period obtained from the model suggested highly match with the results obtained from analyzing the historical and simulated data. The return period of the regional 1 year drought in central Jordan is around 10 years, and more than 160 years for droughts of duration longer than 1 year. The probability that a 1 year extreme drought occurs at least once in the 25 years planning period is more than 90%, and the probability that a drought longer than 1 year occurs is very low (15%) for the same planning period.

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