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Spatio-temporal Drought Analysis in Arid and Semi-arid Regions: A Case Study from Palestine

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Abstract Arid and semi-arid regions are generally characterized by water scarcity and low per capita water allocation. This situation is further exacerbated when such areas are agriculturally dominated with high-density residential areas. Faria catchment (320 km^2), located in the northeastern part of the West Bank, Palestine, is one of these arid to semi-arid catchments where recently, the prolonged drought periods in the catchment and the increasing water demand have made the existing obtainable water resources vulnerable. Catchment drought analysis provides useful information for a sustainable water resources management. In this study, spatial and temporal dimensions of meteorological drought vulnerability in Faria catchment have been investigated using the Standardized Precipitation Index (SPI) as a measure for drought severity. The SPI method was used to detail geographical variations in the drought vulnerability based on frequency and severity of drought events at 1-year time step. This study is applied to rainfall records (1960–2003) for 6 rainfall stations located within the Faria catchment. Magnitude–duration curves are plotted to depict the relationships between drought duration and magnitude. Critical (threshold) drought values were derived spatially to determine the least amount of rainfall required to avoid from drought initiation. Once drought duration and magnitude have been found objectively, it is possible to use this when manage resources for bridging the supply-demand gap to drought affected areas either from alternative water resources or from water stored during wet periods.

Keywords Drought · Semi-arid region · SPI · Water resources · Faria catchment · Palestine

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الخلاصة

تتميز المناطق الجافة وشبه الجافة بعامة بشح المياه وانخفاض نصيب الفرد من المياه المتاحة. ويزداد هذا الوضع سوءا في المناطق الزراعية ذات الكثافة السكانية العالية. يقع حوض الفارعة (مساحته 320 كم^2) في الجزء الشمالي الشرقي من الضفة الغربية بفلسطين، ويُعد واحدا من المناطق الجافة وشبه الجافة التي تتعرض لزيادة في فترات الجفاف جعلت موارد المياه المتاحة فيها غير كافية لتغطية الزيادة الملحوظة في الطلب على المياه. إن دراسة وتحليل الجفاف من شأنه ان يقدم معلومات تساعد في الإدارة المستدامة لموارد المياه في منطقة الفارعة.

تركز هذه الورقة على دراسة الأبعاد المكانية والزمانية للجفاف الناتج عن قلة الأمطار باستخدام مؤشر الأمطار المعياري (SPI) كمقياس لشدة الجفاف في المنطقة. وقد استخدم مؤشر الأمطار المعياري (SPI) لدراسة تغيرات الجفاف المكانية على أساس التكرار الزماني لشدة حالات الجفاف السنوية. وقد تم تطبيق هذه الدراسة على سجلات هطول الأمطار (1960-2003) لمحطات الأمطار الست التي تقع داخل حوض الفارعة. لقد تم رسم منحنيات العلاقة بين فترة الجفاف وقيمته لكل محطة. وتم أيضا معرفة القيم الحرجة للجفاف مكانيا وصولا لتحديد كمية أمطار أقل من المطلوب لتجنب حدوث الجفاف في منطقة الدراسة. إن معرفة العلاقة بين فترة الجفاف وقيمته بشكل موضوعي من الممكن أن تسهم في إدارة موارد المياه في المنطقة من أجل سد الفجوة بين ما هو متوفر وما هو مطلوب في المناطق المتضررة من الجفاف إما من موارد مائية بديلة، وإما من خلال تخزين المياه الزائدة خلال الفترات الممطرة.

1 Introduction

The Mediterranean climate is characterized by the irregularity of its rainfall, which may intensify water stress in certain periods, together with the existence of a period of water deficit [1]. This deficit is high in arid and semi-arid regions, where precipitation is highly variable in time, space, amount and duration [2]. Arid and semi-arid regions are characterized by the low natural replenishment of water resources. This situation leads to the limited availability of water, the uncertainty of available quantities and the need to manage these resources. There are many aspects of water resources management including the optimal water allocation, quality assessment and preservation, and prediction of future water demands to strategize water utilization, planning, and decision making. As a preliminary step, these management aspects and others necessitate the characterization of the water sources in the area of interest. One of the established methods to carry out this assessment is through the analysis of the spatial and temporal variability of rainfall. In semi-arid regions that have extensive agricultural areas, water availability and shortage problems are further exacerbated. In the Mediterranean region, many semi-arid catchments are under extreme stresses due to the climate changes and drought conditions that influence water availability in a negative manner when considering the increasing need to boost the agricultural production rate.

Droughts are generally perceived to be a prolonged period with significantly lower precipitation relative to normal levels. Different types of drought definition are found in the literature. Among them, meteorological, hydrological, agricultural and socio-economic drought definitions are the most common. Meteorological drought is related to precipitation deficits which cause decreases in water supplies for domestic and other purposes affecting the flora and fauna of a region. Hydrological drought results from low stream flows that directly affect established water uses under a given water resources management system. Agricultural drought is linked to crop failure as a consequence of decreases in soil moisture and has no reference to stream flow [3,4]. Socio-economic drought is used to refer to the situation that occurs when water shortages begin to affect people and their lives, and it associates the supply and demand of some economic goods and services with elements of meteorological, hydrological, and agricultural drought [5]. However drought has to be perceived as natural part of climate under all climatic regimes. It occurs in high as well as low rainfall areas [6].

In order to understand whether a deficit of precipitation has different impacts on the groundwater, reservoir storage, soil moisture, snowpack, and streamflow, the standardized precipitation index (SPI) was developed [7]. The SPI was designed to quantify the precipitation deficit for multiple time scales, which reflect the impact of drought on the availability of different water resources. Soil moisture conditions respond to precipitation anomalies on a relatively short time scale, while groundwater, streamflow, and reservoir storage reflect the longer-term precipitation anomalies. For these reasons, the SPI was originally calculated for 3-, 6-, 12-, 24-, and 48-month moving average time scales [7]. The SPI is probability-based and was designed to be a spatially invariant indicator of drought which recognizes the importance of time scales in the analysis of water availability and water use. It is essentially a standardizing transformation of the probability of the observed precipitation [8]. It can be calculated for a precipitation total observed over any duration desired by a user. It is well known in practice that short-term durations (weeks or months) are important to agricultural activities, whereas long-term durations (seasons, years, etc.) are significant in water supply management. A classification system that is normalized so that wetter and drier climates can be represented in the same way by means of the SPI was developed and used [7]. In addition, wet periods can also be monitored using the SPI [9]. They also defined the criteria for a "drought event" for any of the time scales. A deficit occurs any time that the SPI is negative. The accumulated magnitude of deficits during a dry period is referred to as drought magnitude, and is the sum of the absolute values of SPI for all the months within a drought event. The output of SPI is in units of standard deviation from the median based on the time series record [10]. The SPI has been used to monitor the intensity and spatial extension of droughts at different time scales in South Africa [11], in Turkey [12–14], in the Iberian Peninsula [15], in Europe [16], and also in Palestine [17].

Faria catchment is an important agricultural area which is considered as a food basket that provides the West Bank, Palestine with the main agricultural products. Drought has increasingly impacted the obtainable existing water resources in the Faria catchment. Al-Faria spring, one of the main freshwater springs in the catchment with average annual discharge estimated at about 5×10^6 m^3, is drying up. It is suggested that the spring is drying up due to prolonged drought periods. However, it is later noted that droughts are generally only moderate and the actual reason for spring drying up is over-utilization of the groundwater resources in the catchment.

Reliability assessment of water availability in the Faria catchment is of great importance to optimally manage the local water resources. This situation has compelled the motivation for assessing the drought duration and magnitude for the catchment. The objective of this study was to investigate the temporal and spatial characteristics of meteorological droughts in the Faria catchment, a semi-arid region in Palestine. For this purpose, long-term rainfall data of more than 40 years for the 6 rainfall stations located in the catchment were used. The SPI method was employed in the analysis. This analysis is essential to provide input data for a management system and to enable the development of optimal water allocation policies and management strategies to bridge the gap between water needs and obtainable water supply under possible drought conditions. In this study, SPI values were derived both temporally and spatially for quantitative comparisons of drought occurrence over the 43 year period and 6 different rain gage locations.

The main purpose of this study is to identify various drought properties on the basis of run analysis and SPI with applications to 6 rainfall stations located in the Faria catchment. Empirical relationships are provided through scatter diagrams between the drought magnitude and duration.

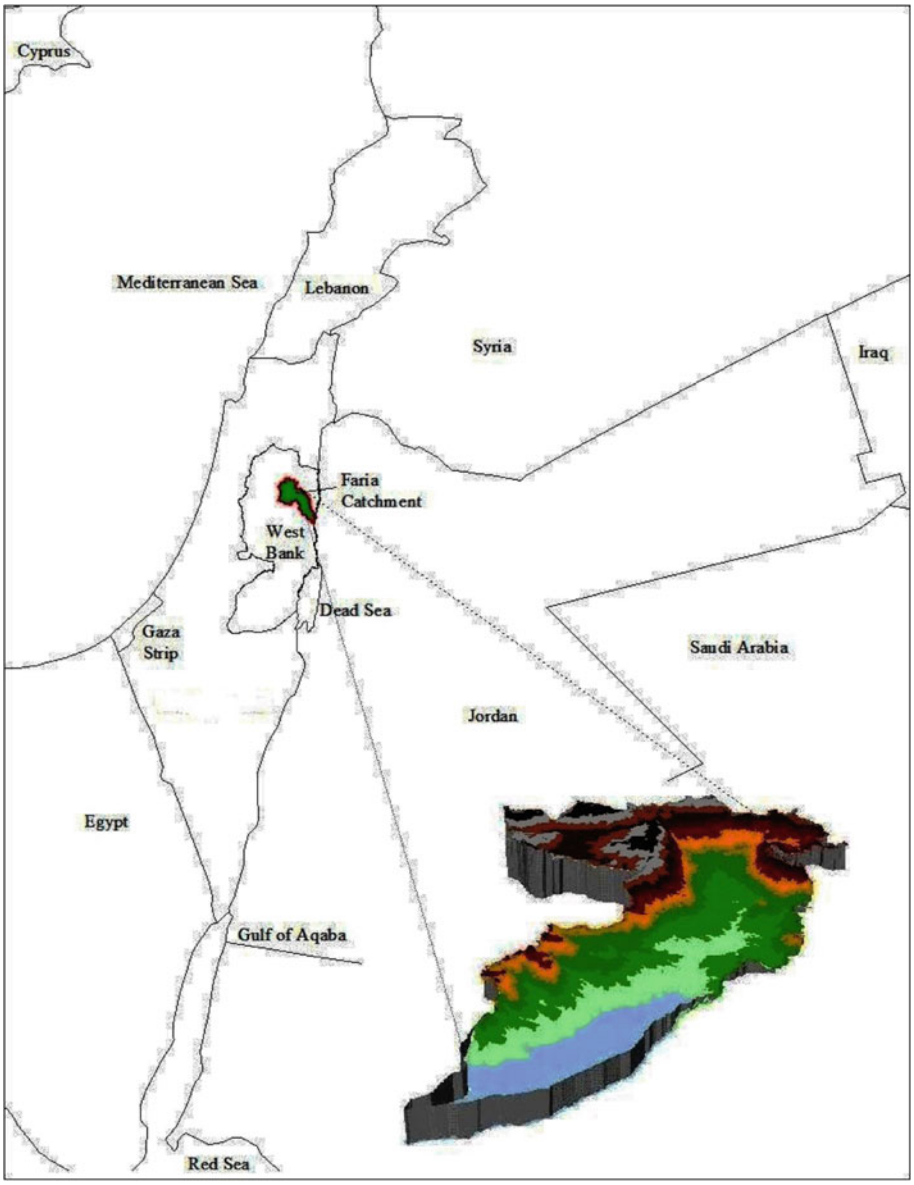

Fig. 1 Regional location of the Faria catchment

2 Description of the Study Area

The Faria catchment is one of the major tributaries draining into the Jordan River. Geographically, it is located in the northeastern part of the West Bank, Palestine with a total area of about 320 km^2 accounting for 6 % of the total area of the West Bank (Fig. 1). Ground surface elevations range from 350 m below to 900 m above sea level. The catchment is inhabited. The native rural population of the catchment is estimated at about 21,000 people. The climate in Faria catchment is arid to semi-arid, characterized by mild rainy winters and moderately dry, hot summers. Climatic parameters are highly variable and influenced by topography and circulation of air-masses. The catchment is characterized by high temperature variations over space and time. The mean annual temperature changes from 18 °C in the western to 24 °C in the eastern side of the catchment. The evaporation rate is particularly high in the summer due to strong insulation. Evaporation greatly exceeds the rainfall in the period from April to October. The winter rainy season is from October to April. Rainfall events predominantly occur in autumn and winter to account for 90 % of the total annual precipitation. The magnitude of rainfall in the Faria catchment varies with space and time.

Water resources in the catchment are either surface or groundwater. In the winter season the majority of generated surface runoff leaves the catchment, as there is no infrastructure to store excess water. Most springs are located in the upper and middle parts of the basin. In total, 11 springs provide baseflow for the upper main river preventing it from dry-

Table 1 The rainfall stations utilized in this study

Rainfall station	Elevation (m) (a.m.s.l)	Geographic coordinates	
		X (km)	*Y* (km)
Nablus	570	178	178
Taluza	500	186	178
Tubas	375	192	185
Beit Dajan	520	178	185
Tammun	340	188	187
Al-Faria	−237	172	196

ing up during hot summers. Spring discharges exhibit high variability. Annual totals of spring discharge vary between 3.8 and 38.3 × 10^6 m^3 with an average of 14.4 × 10^6 m^3. Accounting for more than 70 % of the total runoff, baseflow in the Faria catchment is highest of all easterly draining catchment in the West Bank.

3 Methods and Data Analysis

3.1 Rainfall Data Gathering

The Faria catchment is gauged by six rainfall stations that record rainfalls. These stations are: Nablus, Taluza, Tammun, Tubas, Beit Dajan and Al-Faria. The Nablus station is a regular weather station in which most climatic data are measured. Al-Faria station is located in Al-Jiftlik village in the lower part of the catchment and is still under Israeli control. The other four rainfall stations are located in the schools of Taluza, Tubas, Tammun and Beit Dajan. These stations are simple rain gauges which measure daily rainfall. The main characteristics of the stations are listed in Table 1.

The rainfall data used in this study for the six stations were obtained from the Palestinian water authority (PWA) and cover the period between 1960 and 2003 except for Al-Faria station where rainfall data are available up to 1989. Therefore, the missing data for Al-Faria station from 1990 through the end of 2003 were filled from the surrounding stations by employing the normal ratio method. The available rainfall data (more than 40-year period of data) are sufficient to establish a long-term climatology [18].

The database was maintained in a spreadsheet format that is accessible by MS Excel and digitally encoded into a GIS database for ease of analysis and manipulation. After the database was compiled, spatio-temporal drought analysis was carried out.

3.2 Rainfall Data Analysis

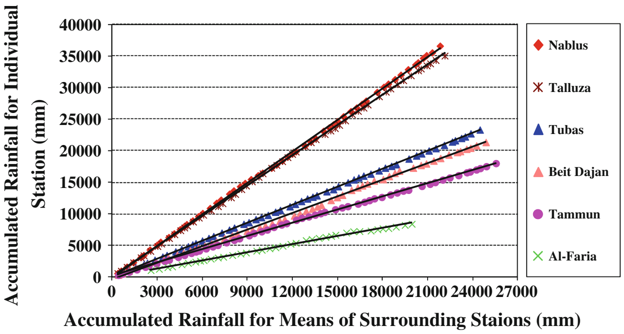

Fig. 2 Double mass curve for the stations of Faria catchment

Table 2 Descriptive statistics of annual rainfall data for different stations

Parameter	Nablus	Talluza	Tubas	Beit Dajan	Tammun	Al-Faria
Mean (mm)	658	627	419	391	322	190
Median (mm)	606	608	407	385	307	184
Std.deviation (mm)	210	191	138	137	102	78
Skewness	1.31	1.13	1.00	0.73	0.61	0.53
Kurtosis	2.48	2.63	1.97	1.46	0.71	1.21
Minimum (mm)	341	292	202	141	124	30
Maximum (mm)	1,388	1,303	900	777	616	424
Range (mm)	1,047	1,011	698	636	492	394

When analyzing rainfall data, it is essential to check the consistency of the records of the rainfall stations. Double mass curve technique was used to check the consistency of the stations of the Faria catchment. The cumulative rainfall data of a specific station are plotted against the accumulative average rainfall of the remaining stations (Fig. 2). The figure demonstrates that all the stations are internally consistent, and the data can be further analyzed.

Since the objective of the analysis is to study the temporal and spatial variability of rainfall in Faria catchment, basic statistical analyses were conducted on the annual rainfall data including the annual mean, median, standard deviation, skewness, kurtosis, minimum and maximum measurements. Table 2 summarizes the basic descriptive statistical measures of annual rainfall data.

From the table, it can be inferred that the mean annual rainfall varies from a minimum of about 190 mm in Al-Faria to 658 mm in Nablus. For all stations, the mean is greater than the median. This indicates that the annual rainfall values are skewed to the right. The high standard deviation values can be easily correlated with the high rainfall range. The rainfall range signifies the difference between the maximum and minimum annual rainfall. The standard deviation and the range indicate the variability of annual rainfall and hence denote how reliable the rainfall is in terms of its persistence as a constant and stable replenishing source.

In order to test whether the annual rainfall data follow a normal distribution, the skewness and kurtosis were

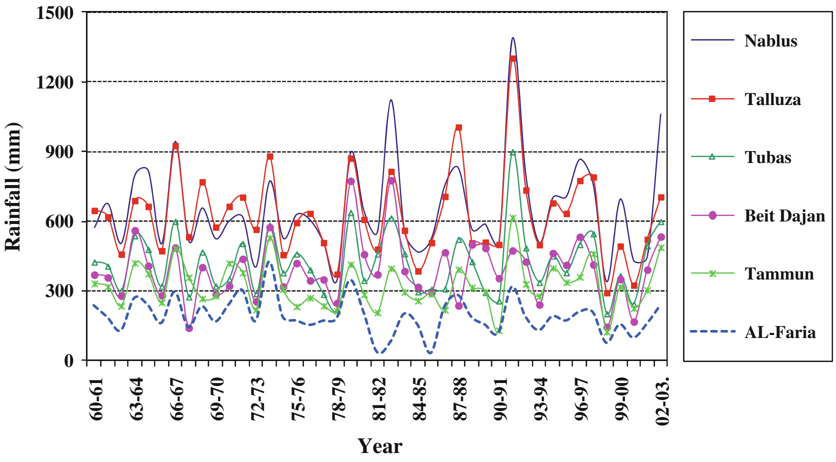

Fig. 3 The temporal pattern of annual rainfall variability

computed. The standard normal distribution has a kurtosis of zero. Positive kurtosis indicates a peaked distribution and negative kurtosis indicates a flat distribution.

The temporal annual rainfall variation for various rainfall stations in the Faria catchment is given in Fig. 3. Apparently, high oscillation in the annual rainfall values can be observed which in turn reflects the variability and uncertainty in the replenishment of local water resources in the catchment. From Fig. 3 and for Nablus station, it can be inferred that in 25 out of 43 years the annual rainfall was below the average. More than twice of the average annual rainfall occurred in the year 1992 where 1,388 mm was recorded. This is the maximum rainfall that occurred in the catchment during the last 50 years.

The SPLINE method was applied, under the GIS environment, to spatially interpolate the average annual rainfall from the six stations (Table 2) and create a region-wide average annual rainfall map for the 43 years of the study period (Fig. 4). Overall, average annual rainfall varied from minimum about 190 mm, in the proximity of the Jordan River, to a maximum of over 650 mm in the headwater in Nablus city. In general, rainfall averages decrease from west to east.

3.3 SPI Calculation

Rainfall was used in the drought index calculations where rainfall variability indices were used to identify droughts and to establish some values for drought identification. These simple indices with rainfall as the only input perform comparatively well compared to more complicated indices in depicting periods and density of droughts [19].

Meteorological drought is frequently described in terms of drought indices, which are convenient and relatively simple to use. One of them is the Standardized Precipitation Index (SPI) which is utilized in this study. The SPI is simply the transformation of the rainfall time series into a standardized normal distribution (*z*-distribution) [7].

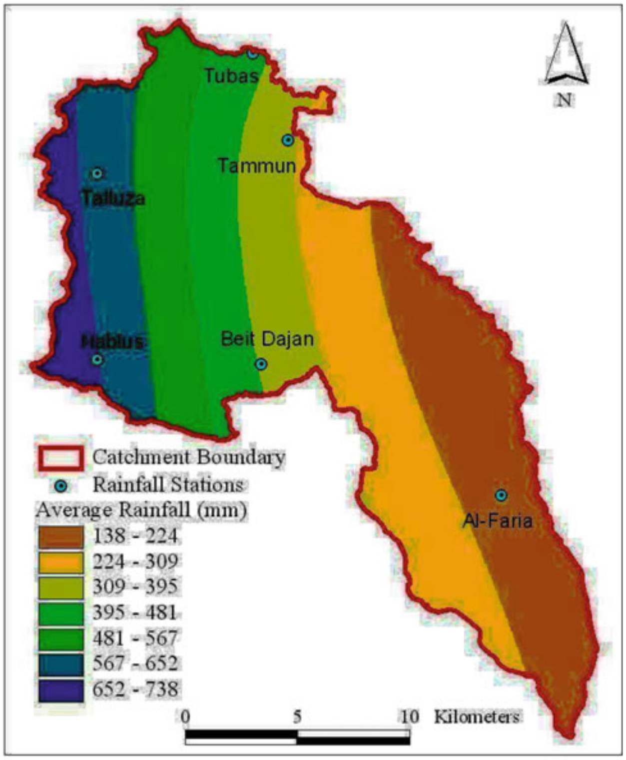

Fig. 4 The spatial pattern of average annual rainfall in 43 years period

The SPI is a dimensionless index where negative values indicate drought and the positive values indicate wet conditions.

Drought severity was classified into four intervals of SPI values, such as mild, moderate, severe and extreme drought. The SPI categories are shown in Table 3 [7,9].

The SPI calculation for any location is based on the long-term rainfall record for a desired period. This long-term record is fitted to a probability distribution, which is then transformed into a normal distribution so that the mean SPI for the location and desired period is zero [20]. The probability distribution of the rainfall data recorded by the six stations

Table 3 SPI drought categories

Category	SPI value
Mild drought	0.0 to −0.99
Moderate drought	−1.00 to −1.49
Severe drought	−1.5 to −1.99
Extreme drought	≤−2.00

in the Faria catchment was studied by [21]. They concluded that the Gumbel distribution fits the data and can be used for future analysis (see Fig. 5).

The fitted Gumbel cumulative probability distribution, *H(x)*, is then transformed into the standard normal distribution to yield the SPI. The process of graphical equiprobability transformation is illustrated in Fig. 6. For large numbers of data points (like the case of Faria stations), the graphical transformation approach, while straightforward, is tedious and time consuming for computing the SPI. Accordingly, the approximate conversion process provided by [22] and used by [16,20] is employed as a workable alternatives:

$$z = \mathrm{SPI} = -\left(t - \frac{c_0 + c_1 t + c_2 t^2}{1 + d_1 t + d_2 t^2 + d_3 t^3}\right)$$

$$\text{for} \quad 0.0 < H(x) \leq 0.5 \tag{1}$$

$$z = \mathrm{SPI} = +\left(t - \frac{c_0 + c_1 t + c_2 t^2}{1 + d_1 t + d_2 t^2 + d_3 t^3}\right)$$

$$\text{for} \quad 0.5 < H(x) < 1.0 \tag{2}$$

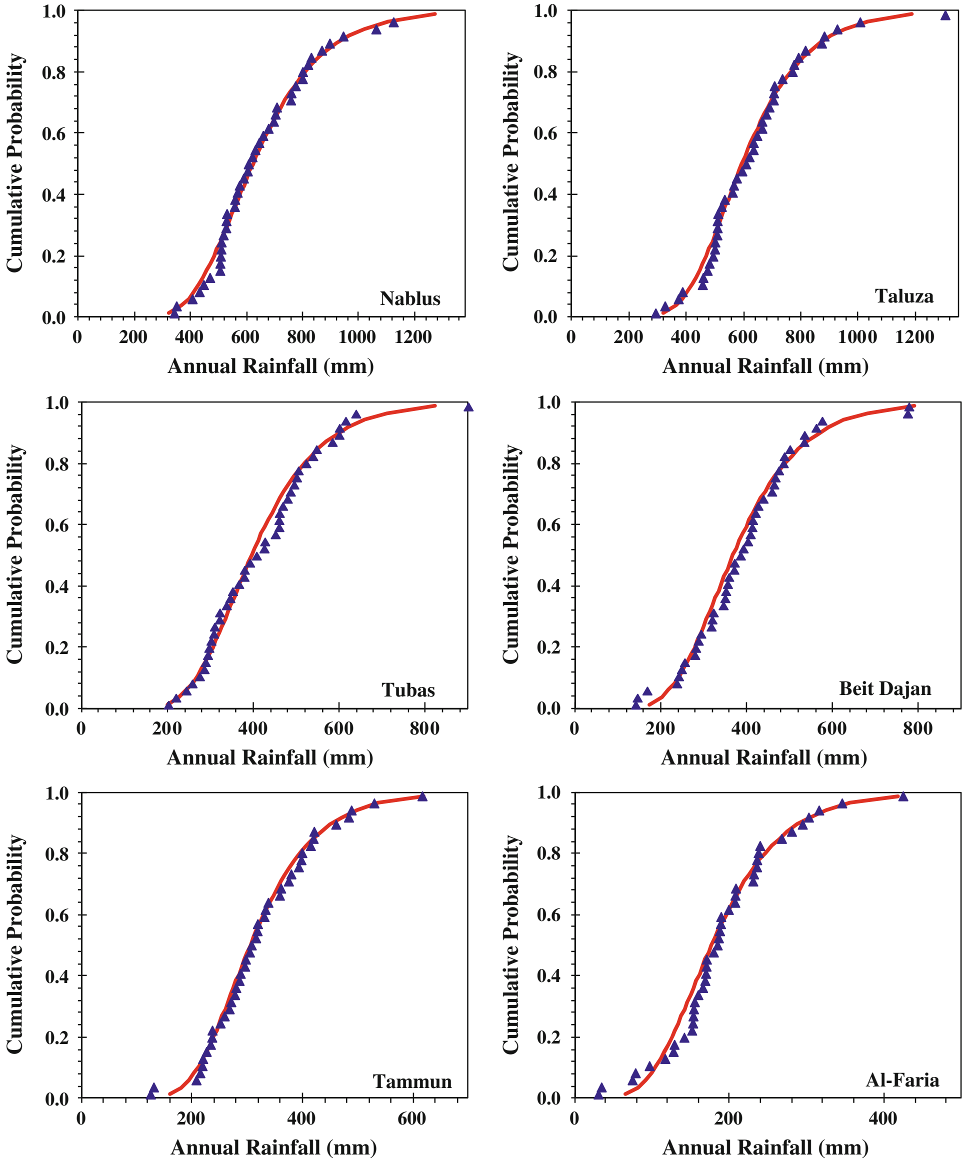

Fig. 5 Cumulative frequency distribution for annual rainfall in the Faria catchment. The *smooth curve* is the estimated Gumbel distribution

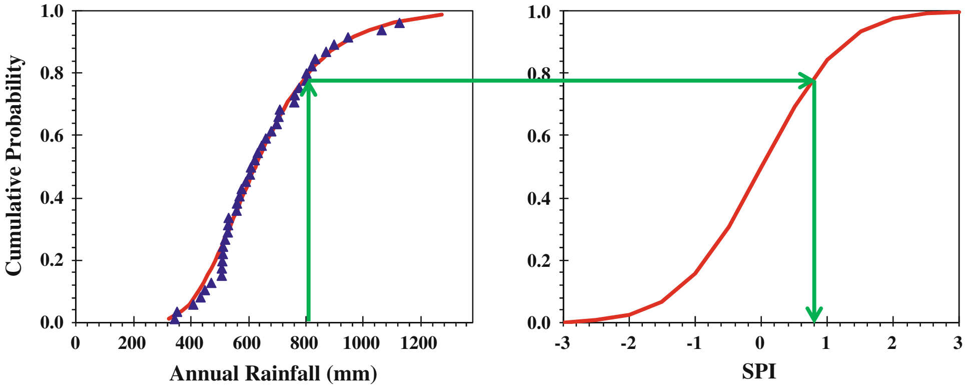

Fig. 6 Example of equiprobability transformation from a fitted Gumbel distribution to the standard normal distribution

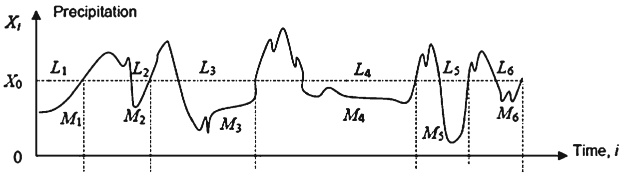

Fig. 7 Schematic representation of wet and dry spells. (M_i drought magnitude, L_i drought duration)

where

$$t = \sqrt{\ln\left[\frac{1}{(H(x))^2}\right]} \quad \text{for} \quad 0.0 < H(x) \leq 0.5 \tag{3}$$

$$t = \sqrt{\ln\left[\frac{1}{(1 - H(x))^2}\right]} \quad \text{for} \quad 0.5 < H(x) < 1.0 \tag{4}$$

and
$c_0 = 2.515517$, $c_1 = 0.802853$, $c_2 = 0.010328$,
$d_1 = 1.432788$, $d_2 = 0.189269$, and $d_3 = 0.001308$.

In the mathematical modeling of droughts, most often precipitation records are taken as the basis, where a time series of records, $X_1, X_2, X_3, \ldots, X_n$, is truncated at a threshold precipitation value, X_0, as shown in Fig. 7 [12]. Hence, simply and conceptually, the drought is defined on the basis of comparing a given precipitation time series with a threshold value and, according to their relative positions, different drought features appear.

Several threshold values were presented in literature to differentiate between drought and non-drought periods. Some of them employed the percentile values and others used the SPI values. A year with annual rainfall above the P_{75} was considered a wet year and a year was considered as a drought year when the annual rainfall is less than P_{10} (e.g. P_{10} is approximately equal to SPI value of -1) [23]. In this study, the zero SPI value is taken as threshold value for a wet spell or a dry spell [12]. A wet spell occurs when any time series value at the ith instant is greater than the threshold level, $(X_i > X_0)$. Accordingly, the difference $(X_i - X_0) > 0$ is named as the precipitation surplus. Otherwise, a dry spell takes place as $(X_i < X_0)$. Accordingly, the difference $(X_i - X_0) < 0$ is the precipitation deficit. A sequence of wet spells preceded and succeeded by a dry spell is referred to as the duration of wet period during which there is no water supply problem.

For further analysis of drought, drought intensity, magnitude, and duration can be determined from the historical time series rainfall data.

Drought magnitude (M_j) is defined as:

$$M_j = \sum_{i=1}^{m} |X_i - X_0| \tag{5}$$

where m is the number of deficits during a drought period and X_0 is a threshold precipitation value considering the zero SPI values.

The drought intensity (I_j) of the jth dry period is defined as the ratio of drought magnitude to drought duration (L_j) as:

$$I_j = \frac{M_j}{L_j} \tag{6}$$

3.4 Application

In this study, and for the six rainfall stations, the SPI was calculated based on the fitted Gumbel cumulative probability distribution using the aforementioned procedure. The results are depicted in Fig. 8. From the figure it is clear that the annual rainfall of all stations varies with time, whereas the unsymmetrical upward and downward movement of the graph corresponds, respectively, with periods of the above and below average rainfall. Moreover, the wet and dry spells are related to this variation. On average, it was found that drought occurs in 21 out 43 years in the Faria catchment.

Drought occurrences in the Faria catchment have been investigated based on the frequency of the events for each drought category at 1-year time step. The SPI index has been applied to long-term rainfall data at the 6 stations for 1960–2003 period. The occurrences in varying drought categories in the Faria catchment were analyzed as depicted in Table 4. In the table, percentage of drought occurrence is expressed at

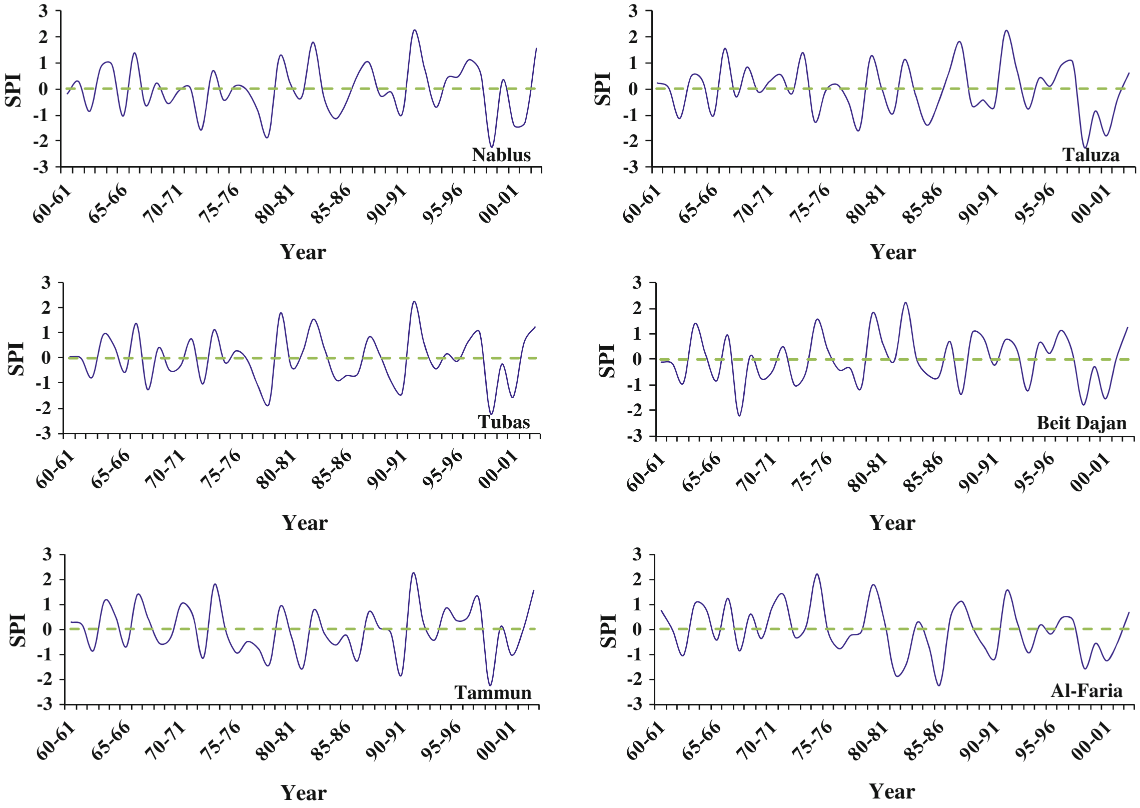

Fig. 8 Time series of SPI for annual rainfall in the Faria catchment

Table 4 Average percentage of drought occurrences in the Faria catchment at corresponding drought categories and 1-year time step

Category	Average percentage
Mild drought	67
Moderate drought	19
Severe drought	10
Extreme drought	5
All drought	100

1-year time step for varying drought severity categories. The numbers are obtained by taking the ratio of drought occurrences to the total drought occurrences in the same drought category. The table indicates that mild drought is prevailing in the catchment, while severe to extreme droughts are occurring less frequent in the catchment.

In Table 5, various statistical parameters concerning drought duration, magnitude and intensity are tabulated. These drought features refer to past observations, but their statistical parameters are useful for what-if analysis, conditionally valid also for the future. For instance, one can find drought magnitude, which corresponds to a given drought duration, as shown in Fig. 9.

It is clear from the figure that increases in the drought duration result in increased drought magnitude. Given the expected maximum drought duration (*L*) for each station, it is possible to read drought magnitude (*M*) from Fig. 9. The magnitude of water deficit (WD), in mm, can be calculated for any given station as:

$$\mathrm{WD} = \left(X_i - \overline{X}\right) = M\sigma \tag{7}$$

where $\overline{X}$, M and σ represent the arithmetic average value, drought magnitude and the standard deviation, respectively for each rainfall station.

Considering the long term areal annual rainfall average ($\overline{X}_\mathrm{a}$= 372 mm) of the Faria catchment, the actual magnitude of water deficit ($\mathrm{WD_a}$), in mm, can be calculated as:

$$WD_\mathrm{a} = \left(X_i - \overline{X}_\mathrm{a}\right) \tag{8}$$

From Eq. 7,

$$X_i = \left(\mathrm{WD} + \overline{X}\right) \tag{9}$$

Substituting in Eq. 8, result

$$\mathrm{WD_a} = \left(\mathrm{WD} + \overline{X} - \overline{X}_\mathrm{a}\right) \tag{10}$$

Table 5 Statistical parameters of magnitude (*M*), duration (*L*), and intensity (*I*) for different stations

Parameters	Nablus			Talluza			Tubas		
	M	*L*	*I*	*M*	*L*	*I*	*M*	*L*	*I*
Max	2.64	3.00	2.23	2.23	3.00	2.23	2.99	3.00	2.23
Min	0.17	1.00	0.17	0.12	1.00	0.12	0.12	1.00	0.12
Median	0.94	1.00	0.67	1.13	1.00	0.77	0.91	1.00	0.75
Average	1.21	1.50	0.85	1.23	1.54	0.82	1.19	1.43	0.84
Std.deviation	0.85	0.76	0.58	0.78	0.78	0.55	0.92	0.76	0.59
Skewness	0.59	1.23	1.09	−0.09	1.11	1.22	0.64	1.53	0.99
Parameters	Beit Dajan			Tammun			Al-Faria		
	M	*L*	*I*	*M*	*L*	*I*	*M*	*L*	*I*
Max	3.65	3.00	2.23	3.57	4.00	2.23	3.84	4.00	1.60
Min	0.06	1.00	0.06	0.42	1.00	0.42	0.17	1.00	0.17
Median	1.28	1.50	0.72	1.13	2.00	0.85	0.98	1.00	0.88
Average	1.41	1.75	0.86	1.54	1.91	0.88	1.41	1.75	0.77
Std.deviation	0.93	0.87	0.59	0.93	1.14	0.50	1.24	1.14	0.46
Skewness	1.02	0.57	1.02	0.99	1.21	2.15	0.99	1.47	0.36

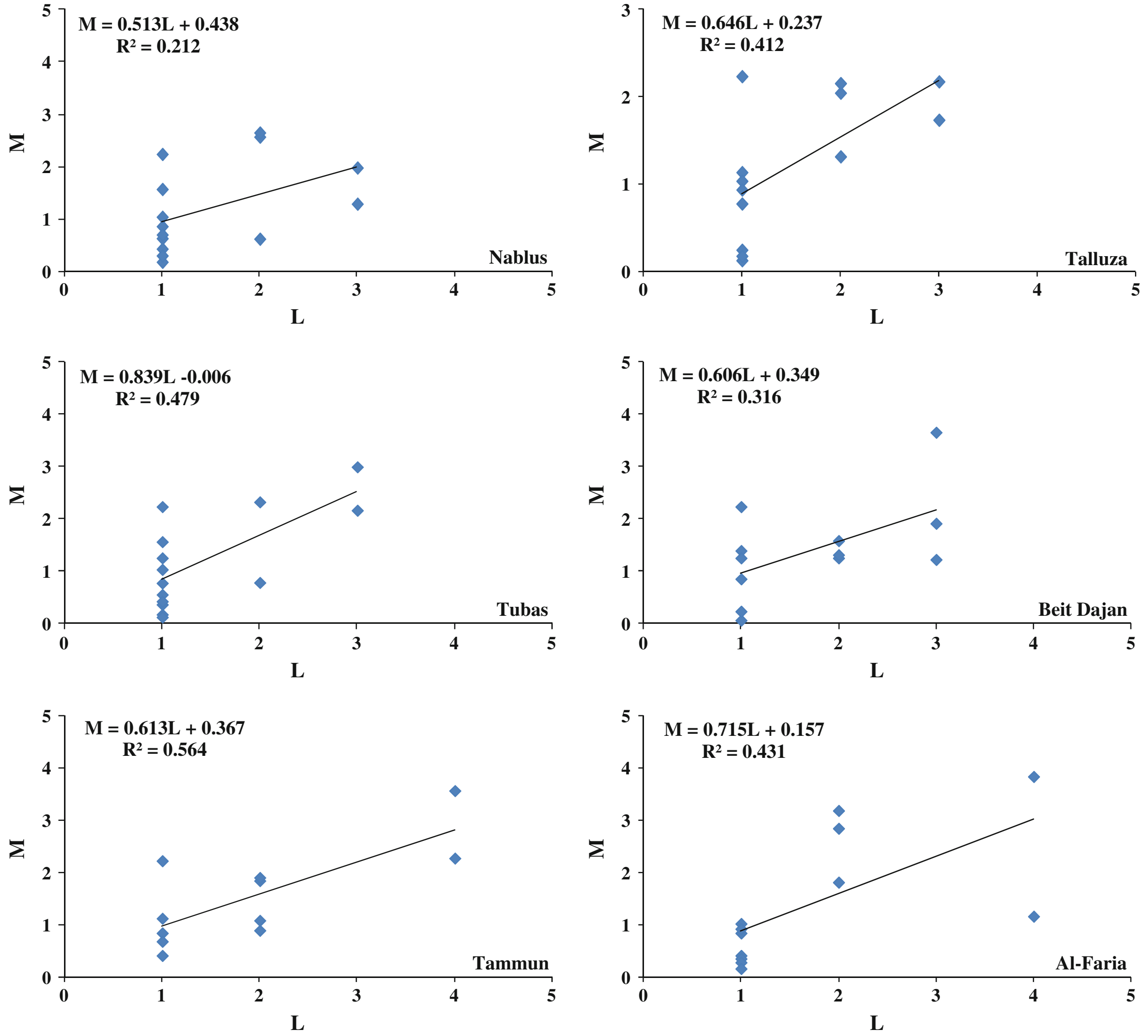

Fig. 9 Magnitude–duration curves for the rainfall station within the Faria catchment

Table 6 The real total water need in the critical drought period for different stations

Station	L	M	σ	$\overline{X}$	WD (mm)	WDa (mm)
Nablus	3	2.0	210	658	420	134
Taluza	3	2.2	191	627	420	165
Tubas	3	2.5	138	419	345	298
Beit Dajan	3	2.2	137	391	301	282
Tammun	4	2.8	102	322	285	335
Al- Faria	4	3.0	78	190	234	328

where values of WD obtained from Eq. 7 are negative. Consequently, the actual total water need in the critical period for each station is estimated and tabulated in Table 6.

Temporal drought analysis for each station in the Faria catchment facilitates the spatial assessment of drought in the catchment. For sustainable water resources management in the Faria catchment, the understanding of spatial extent of drought magnitudes is essential. According to the long term areal average annual rainfall, the resulting actual magnitude of water deficit for each station was mapped using the *SPLINE* technique within the GIS environment as shown in Fig. 10. For the period of 1960–2003, it was found that actual magnitude of water deficit is 275 mm averaged over the entire catchment. Though, considering the other threshold values (e.g. SPI = −1) to differentiate between drought and non-drought periods will end up with values of actual water deficit less than the estimated values in Table 6.

Another interesting result reached in the study, from the map of Fig. 10, is that the severity of drought increases in eastern and south-eastern parts of the catchment. That led us to think that while these parts of the catchment are more likely to be affected from agricultural drought with faster depletion of soil moisture (high evaporation rates), the other parts will suffer from meteorological drought, with consequent loss of water resources. In addition, the obtained map can provide us with the magnitude of actual water deficit at specific locations in the catchment. This corresponds to the water need in a critical drought period that should be met using "external" water resources, i.e. accumulated in other time periods (e.g. construct a long term reservoir to store excess water from a wet period to be used during dry period). Such information is necessary to develop proper management strategy to bridge the supply-demand gap in the Faria catchment under the extended dry conditions.

4 Conclusions

In this study, the overall meteorological drought vulnerability in the Faria catchment was assessed by reconstructing historical occurrences of drought at the annual time scale and drought categories by employing the SPI approach. The analysis of rainfall variability for 1960–2003 period showed that drought occurred in 21 out 43 years in the Faria catchment. The SPI approach is commonly used for the identification of various drought characteristics, such as duration, magnitude, and intensity. Basic formulae are given for these drought features and their applications are presented for rainfall records of the six rainfall stations located in the Faria catchment. The relationships between drought duration and magnitude are provided in the form of scatter diagrams with the best straight-line fits. It is estimated that the maximum drought duration is 3.3 years, averaged over the entire catchment. The spatial assessment indicated that the spatial extent of drought over the entire catchment is more or less belonged to mild and moderate droughts where the maximum negative SPI value is 2.23.

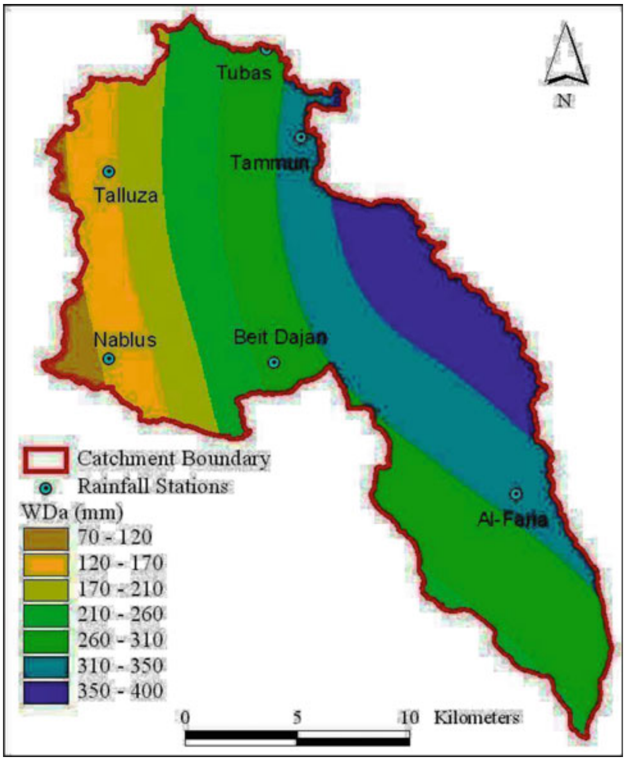

Fig. 10 Spatial extent of the actual magnitude of water (1-year time step) in the Faria catchment

The spatial patterns analyzed showed actual drought affected areas in the eastern and south-eastern parts of the catchment, with drought severity, which is associated with the pattern of rainfall, decreasing from moderately wet western to drier eastern areas of this region. The spatial and temporal analysis of drought using SPI was found useful in characterizing spatial patterns and temporal frequencies of drought, and in evaluating drought affected areas.

The conclusions reached in this study can be an essential step toward addressing the issue to drought vulnerability in the West Bank, Palestine and can guide drought management strategies for mitigation purposes. Identifying regional vulnerabilities can lead to adjustment in practices in water-dependent sectors to develop a proper management strategy to bridge the supply-demand gap and can help decision makers to take the drought into account from the hazard perspective, and include the concept of drought vulnerability into natural resource planning.

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