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Spatiotemporal Characteristics and Trends of Meteorological Droughts in the Wadi Mina Basin, Northwest Algeria

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Abstract: Drought has become a recurrent phenomenon in Algeria in the last few decades. Significant drought conditions were observed during the late 1980s and late 1990s. The agricultural sector and water resources have been under severe constraints from the recurrent droughts. In this study, spatial and temporal dimensions of meteorological droughts in the Wadi Mina basin (4900 km^2) were investigated to assess vulnerability. The Standardized Precipitation Index (SPI) method and GIS were used to detail temporal and geographical variations in drought based on monthly records for the period 1970–2010 at 16 rainfall stations located in the Wadi Mina basin. Trends in annual SPI for stations in the basin were analyzed using the Mann–Kendall test and Sen's slope estimator. Results showed that the SPI was able to detect historical droughts in 1982/83, 1983/84, 1989/90, 1992/93, 1993/94, 1996/97, 1998/99, 1999/00, 2004/05 and 2006/07. Wet years were observed in 1971/72, 1972/73, 1995/96, 2008/09 and 2009/10. Six out of 16 stations had significant decreasing precipitation trends (at 95% confidence), whereas no stations had significant increasing precipitation trends. Based on these findings, measures to ameliorate and mitigate the effects of droughts, especially the dominant intensity types, on the people, community and environment are suggested.

Keywords: drought; trends; SPI; mina basin; Algeria

1. Introduction

Drought is a recurring phenomenon that affects a wide variety of sectors, making it difficult to develop a single definition of it. According to a water-resource-oriented definition, which takes into account the water requirements related to biological, economic and social characteristics of a region, drought refers to a condition of severe reduction of water supply availability (compared to a normal value), extending along a significant period of time over a large region [1]. Drought is a complex phenomenon that involves different human and natural factors that determine the risk and vulnerability to it [2].

The particularly strong influence of drought on many sectors is visible in arid and semiarid regions, where water is scarce [3]. Water scarcity can strongly impact the agricultural sector in such regions [4]. In the case of the Mediterranean Basin, much of which is arid or semiarid, the extremely variable precipitation across temporal and spatial scales is influenced by geographical position of the region between two contrasting masses of water: the Atlantic Ocean and the Mediterranean Sea [5–7]. An additional feature determining high variability of precipitation in this region is the presence of various mountain ranges distributed along the coastal areas from east to west [7]. To avoid water scarcity, increased knowledge about variability of meteorological conditions could be used to mitigate the effect of drought, as well as guide various irrigation scheduling and water productivity strategies in arid sandy soils. According to Rossi [8] the drought mitigation measures can be divided into three main categories: (1) water-supply oriented, such as using additional sources of low quality water and improvement of existing water system efficiency, (2) water-demand reduction: restriction of municipal uses and irrigation, pricing, dual distribution system, water recycling and (3) minimalization of drought impact by temporal relocation of water resources, tax relief, and development of warning systems. Knowledge about drought phenomena can also help with sustaining reforestation programs under an eventual increase in aridity [9] and with water resources planning and management via reservoirs to overcome scarcity [10].

Meteorological drought can be assessed using many indicators. For example, Weighted Anomaly Standardized Precipitation Index (WASP) was developed by Lyon [11] to monitor precipitation in the tropical regions. Crop Moisture Index (CMI) is commonly calculated weekly along with the Palmer Drought Severity Index (PDSI) output as a short-term drought indicator of impact on agriculture [12]. Drought Reconnaissance Index (DRI) [13] is based on a simplified water balance equation considering precipitation and potential evapotranspiration. Effective Drought Index (EDI) as a good index for operational monitoring of both meteorological and agricultural drought [14]. Hydro-thermal Coefficient of Selyaninov (HTC) developed by Selyaninov, Bokwa et al. [15] uses temperature and precipitation values, and is sensitive to dry conditions specific to the climate regime being monitored. RPI (Relative Precipitation Index) is the ratio of precipitation sum for the given period and the long-term average for the same period expressed in percent [15]. NOAA Drought Index (NDI) is a precipitation-based index in which the actual precipitation measured is compared with normal values during the growing season [16]. Palmer Drought Severity Index (PDSI) [17] uses monthly temperature and precipitation data along with information on the water-holding capacity of soils. SPEI (Standardized Precipitation Evapotranspiration Index) is a standardized monthly climatic balance computed as the difference between the cumulative precipitation and the potential evapotranspiration [18]. The Standardized Precipitation Index (SPI), developed by McKee et al. [19] in the 1990s, is robust and effective for evaluating meteorological drought and remains a very popular choice among researchers to reveal drought and to estimate duration and intensity of drought events [19]. The SPI has several advantages, as discussed by [20] and [21], over many other drought indices, such as some of those mentioned above. Firstly, it is based only on rainfall, so that in the absence of other hydro-meteorological measurements, drought assessment is still possible. Secondly, SPI can be used to quantify precipitation deficit for multiple timescales, which enables it to assess drought conditions in meteorological, hydrological and agriculture applications. Finally, standardization of the SPI index ensures that the frequency of extreme drought events at any location and any timescale is approximately constant.

Due to its robustness and convenience, SPI has already been widely used to characterize dry and wet conditions in many countries in the Mediterranean region, such as Turkey [22,23], Spain [24,25], Italy [26–30], Iran [31–33], Greece [34–36], Iraq [37–39], and Palestine [40].

In particular, many researchers in North Africa have studied meteorological drought using SPI indices, including in Algeria [41–45], in Morocco [46], and in Tunisia [47–49]. So far, there has not been a study on spatial and temporal variations of meteorological drought, expressed by SPI, in the region of the Wadi Mina basin of northwest Algeria, which is characterized by high intensities of agriculture and presence of forest cover. According to [50], renewable water resources in Algeria are quite low and can be approximated as 19 billion cubic meters per year. In the other words, the water resources are equal 450 cubic meters (m^3) per capita per year and are slightly below the 500 m^3 per capita per year that is recommended as the scarcity threshold indicating a water crisis. Moreover, the water resources have high variability and projections are that rainfall could decrease by more than

20% by 2050, which would result in greatly worsening water shortages in different basins of Algeria [51]. Knowledge on extreme dry conditions is also very important because these can influence not only on water scarcity for agriculture but also on natural ecosystems, mainly forest in the case of the studied basin. For example, Mensah et al. [52] showed that elevated temperatures will further exacerbate the drought impacts on forest ecosystems at sites with precipitation levels equal or smaller than the atmospheric evaporative demand and strong influence of vapor pressure deficits on carbon uptake, and can worsen the decline in soil moisture.

In this work, the objective was to better characterize annual-scale drought patterns over the Wadi Mina basin in order to aid water resource planning. The main objectives are to (1) map characteristics of drought patterns over the basin during 1970–2010, (2) identify any trends in precipitation or in drought characteristics, (3) identify drought years over the observation period, and (4) estimate the return periods for severe drought across the basin.

2. Study Area and Data

2.1. Study Area

The Wadi Mina basin, with an area of 4900 km^2, is located in the northwest of Algeria (Figure 1). The Wadi Mina involves four major tributaries: Wadi Mina, Wadi Haddad, Wadi Abd and Wadi Taht. The climate is continental, with cold winters and hot summers. Mean annual precipitation ranges from about 220 to 400 mm, and most precipitation occurs between November and March. Mean annual temperatures are about 16 °C to 19.5 °C. Almost half the basin is covered by a varying density of vegetation, with in particular 32% of scrub, 35.8% of forests and 20% cereal crops [53].

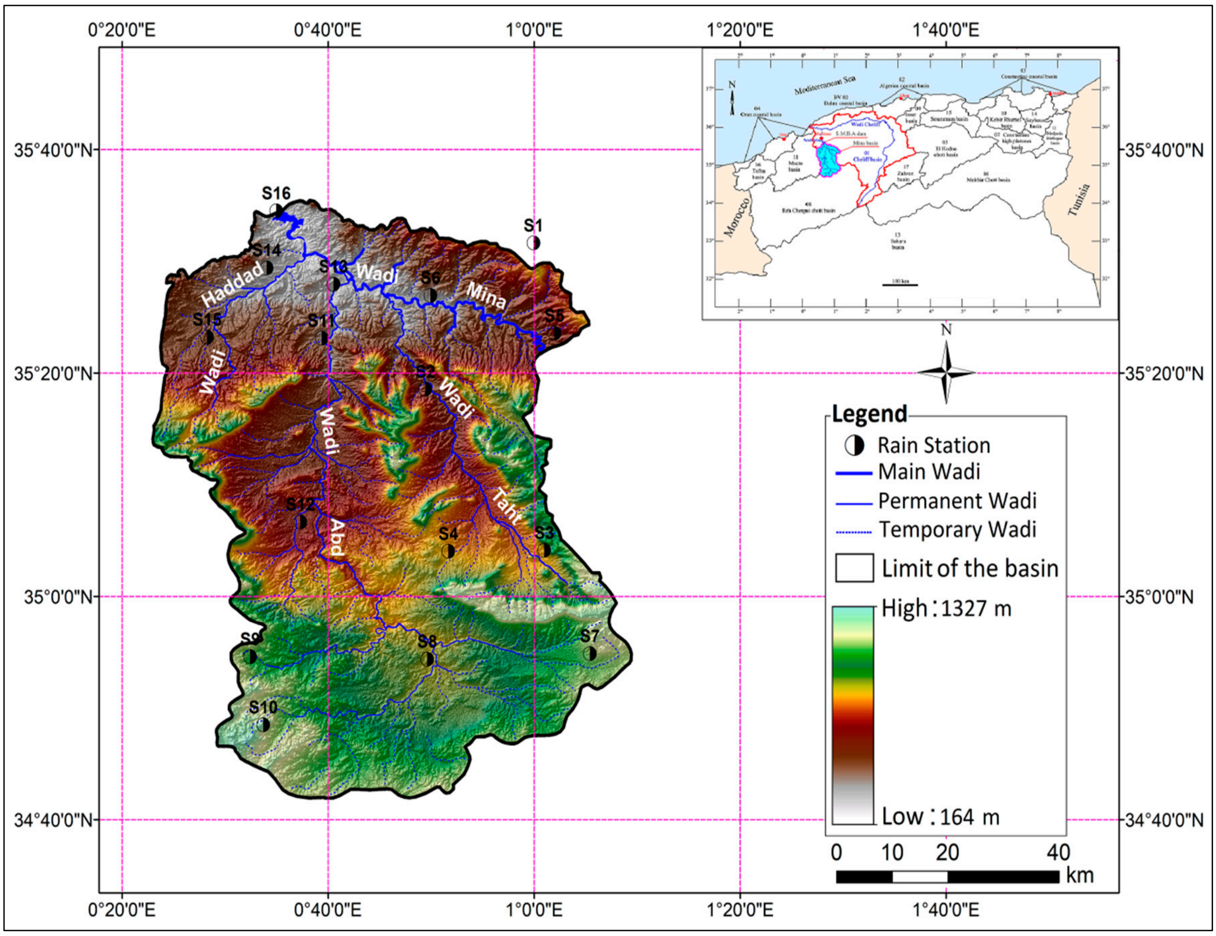


Figure 1. Topography and station distribution for the Wadi Mina basin in northern Algeria.

2.2. Data Used

Monthly precipitation records for a 40-year observation period (September 1970 to August 2010, using water years that go from September to August) are compiled for 16 stations from the Algeria National Agency of Water Resources (Figure 1 and Table 1). These stations constitute a relatively well-distributed network with acceptable spatial density over the basin. To assure quality, data was checked for inhomogeneities using the double mass curve, linear regression and Mann-Whitney test methods. The procedure detected a few inhomogeneities, for which the irregular data were adjusted using data of nearby reliable stations. Rainfall data of these 16 stations were analyzed statistically to evaluate rainfall variability in the study area (Table 2). These preliminary statistical analyses included measure of central tendency (mean, and median), dispersion (standard deviation SD, coefficient of variation CV) and distribution (skewness Cs and kurtosis Ck) (Table 3).

Table 1. Characteristics of rain gauge stations used in the analysis.

			Geographical Coordinates		Elevation	Period of Observation
Rain Station	ID	Name	Longitude (E)	Latitude (N)		
			(°)	(°)	(m)	
S1	12702	Rahuia	1°00′	35°31′	650	Septmber 1970–August 2010
S2	13001	Kef Mahboula	0°49′	35°18′	475	
S3	13002	Frenda	1°01′	35°04′	990	
S4	13004	Ain El Haddid	0°51′	35°04′	829	
S5	13101	Mechra Safa	1°02′	35°23′	655	
S6	13102	Djilali Benamar	0°49′	35°27′	300	
S7	13201	Ain Kermes	1°05′	34°55′	1162	
S8	13202	Rosfa	0°49′	34°54′	960	
S9	13203	Tiricine	0°32′	34°54′	1070	
S10	13204	Sidi Youcef	0°33′	34°48′	1100	
S11	13302	Ain Hamara	0°39′	35°23′	288	
S12	13304	Takmaret	0°37′	35°06′	655	
S13	13306	Oues El-Abtal	0°40′	35°28′	354	
S14	13401	Sidi A.E.K Djilali	0°34′	35°29′	225	
S15	13407	El Hachem	0°28′	35°23′	417	
S16	13410	SMBA	0°35′	35°34′	145	

Table 2. Descriptive statistics of annual rainfall series in the Wadi Mina basin (1970/71–2009/10 water years).

N°	Min (mm)	Max (mm)	Mean (mm)	Median (mm)	SD (mm)	Cv (%)	Cs	Ck
S1	210.00	524.70	352.53	333.10	89.27	25.32	−0.87	0.19
S2	143.00	672.20	343.63	326.85	106.90	31.11	1.06	0.88
S3	221.00	672.90	396.42	388.00	11203	28.26	0.09	0.61
S4	194.80	610.00	312.83	302.65	102.92	32.90	1.60	1.23
S5	197.70	734.40	378.03	366.40	119.22	31.54	1.02	0.88
S6	158.60	645.10	345.38	314.35	120.84	34.99	0.15	0.75
S7	155.70	580.20	323.70	320.80	107.93	33.34	0.25	0.83
S8	77.70	557.00	218.40	187.80	113.76	52.09	2.18	1.55
S9	115.20	561.50	306.84	306.75	104.40	34.02	0.11	0.54
S10	159.20	631.00	294.89	270.40	99.59	33.77	1.76	1.15
S11	164.80	506.40	265.10	260.55	74.97	28.28	3.13	1.51
S12	120.50	413.10	254.25	241.65	73.14	28.77	−0.34	0.57
S13	129.60	558.00	278.65	266.10	84.84	30.45	2.12	1.18
S14	135.60	474.20	254.13	239.55	72.12	28.38	1.33	1.08
S15	152.60	517.00	291.01	276.25	78.85	27.10	0.21	0.57
S16	141.00	436.60	237.97	226.95	63.09	26.51	1.86	1.15

To test for stationarity, the Kwiatkowski–Phillips–Schmidt–Shin test (KPSS) was used [54]. The results of the stationarity test for monthly, seasonal and yearly series are shown in Table 3. All the monthly, seasonal and annual series of the rainfall stations are indicated as showing stationarity (p-value is more than 0.05).

Table 3. Results of stationarity tests for the monthly, seasonal and yearly series.

Station	Monthly Series *p*-Value	Seasonal Series *p*-Value	Yearly Series *p*-Value
S1	0.576	0.427	0.412
S2	0.459	0.529	0.425
S3	0.756	0.871	0.345
S4	0.842	0.777	0.310
S5	0.912	0.867	0.610
S6	0.956	0.569	0.524
S7	0.875	0.784	0.459
S8	0.758	0.657	0.351
S9	0.910	0.741	0.301
S10	0.986	0.891	0.295
S11	0.886	0.741	0.287
S12	0.782	0.625	0.254
S13	0.975	0.412	0.210
S14	0.754	0.541	0.354
S15	0.621	0.459	0.311
S16	0.524	0.567	0.421

3. Methodology

3.1. SPI

The standardized precipitation index (SPI) is commonly used to detect meteorological drought. Each drought is characterized by drought intensity (Di), a drought magnitude (Dm) and drought duration (Dd). Run intensity can be either the value of the SPI at any moment (Dint) or the minimum SPI value during a drought event (Dmi) The drought magnitude (Dm) is equal to the accumulated values of below-threshold SPI during each drought event (Figure 2).

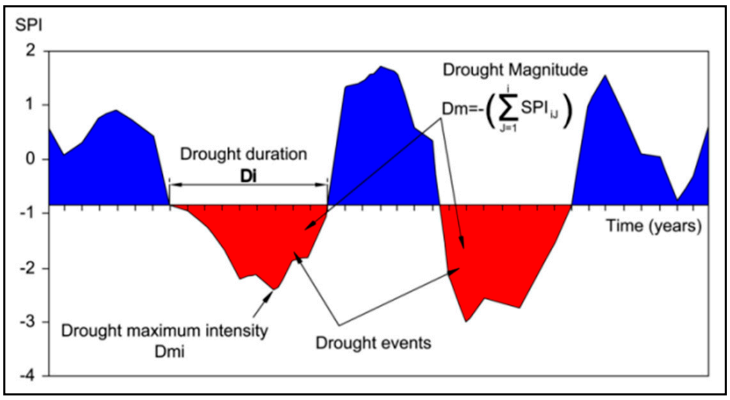


Figure 2. Definition of drought properties based on the SPI index [55].

SPI is mathematically based on the cumulative probability of monthly precipitation amount recorded at the observation post [56,57]. No evaporation estimate is considered, unlike other drought indices such as SPEI. SPI = 0 denotes average (climatological) precipitation, SPI = 1 denotes 1 standard deviation wetter than average, and SPI = −1 denotes 1 standard deviation drier than average. In the case of the presented analysis, the monthly precipitations were aggregated over water years, and finally a yearly SPI (12-month timescale) for each water year was calculated. SPI periods (years) with SPI below the defined threshold are considered drought years, and consecutive drought years are grouped into droughts. The whole period of observation at a meteorological station is used to determine the parameters of a precipitation probability density function, taken to be in the form of a gamma distribution:

$$g(x) = \frac{1}{\beta^{\alpha}\Gamma(\alpha)} x^{\alpha-1} e^{-x/\beta} \quad (1)$$

where α and β are the shape and scale parameters respectively. x is consecutively precipitation and $\Gamma(\alpha)$ is the gamma function. The gamma function defined by the following:

$$\Gamma(a) = \int_0^{\infty} y^{a-1} e^{-y} dy \quad (2)$$

The alpha and beta parameters of the gamma distribution are estimated from the precipitation time series as

$$\propto = \frac{1}{4A}\left(1 + \sqrt{1 + \frac{4A}{3}}\right), A = ln(x) - \frac{\sum ln(x_i)}{n}, \beta = \frac{x}{\propto} \quad (3)$$

where x is the mean value of precipitation quantity; n is the precipitation measurement number; x_i is the quantity of precipitation in a sequence of data.

The cumulative probability can be presented as:

$$G(x) = \int_0^x g(x)dx = \frac{1}{\hat{\beta}^{\hat{a}}\,\Gamma\left(\hat{\alpha}\right)} \int_0^x x^{\propto_{pro}-1} e^{-x/\beta_{pro}} dx \quad (4)$$

To allow for the possibility that the precipitation may be zero, a mixture probability distribution is used, for which the cumulative probability becomes

$$H(x) = q + (1-q)G(x) \quad (5)$$

where q is the probability that the quantity of precipitation equals zero.

The calculation of the SPI is presented on the basis of the following equation [20,58]:

$$\text{SPI} = \begin{cases} -\left(t - \frac{c_0+c_1t+c_2t^2}{1+d_1t+d_2t^2+d_3t^3}\right). \ 0 < H(x) \leq 0.5 \\ +\left(t - \frac{c_0+c_1t+c_2t^2}{1+d_1t+d_2t^2+d_3t^3}\right). \ 0.5 < H(x) \leq 1.0 \end{cases} \quad (6)$$

where t is determined as

$$t = \begin{cases} \sqrt{ln\left(\frac{1}{(H(x))^2}\right)}. \ 0 < H(x) \leq 0.5 \\ \sqrt{ln\left(\frac{1}{1-(H(x))^2}\right)}. \ 0.5 < H(x) \leq 1.0 \end{cases} \quad (7)$$

and c_0. c_1. c_2. d_1. d_2 and d_3 are coefficients whose values are:

$$c_0 = 2.515517.\ c_1 = 0.802853.\ c_2 = 0.010328$$

$$d_1 = 1.432788.\ d_2 = 0.189269.\ d_3 = 0.001308$$

According to McKee et al. [18] different categories and approximate probabilities of wet and dry spells can be considered based on SPI for the timescale of interest, as shown in Table 4. SPI is expected to follow a near-normal (bell curve) distribution, with SPI values near 0 being the most common and high positive or negative SPI (corresponding to very wet or very dry periods, respectively) being rare.

Table 4. Drought classification based on SPI value and corresponding event probabilities based on the approximation that SPI values follow a standard normal distribution.

SPI Values	Drought Category	Probability (%)
2.00 or more	Extremely wet	2.3
1.50 to 1.99	Very wet	4.4
1.00 to 1.49	Moderately wet	9.2
−0.99 to 0.99	Near normal	68.2
−1.00 to −1.49	Moderate drought	9.2
−1.50 to −1.99	Severe drought	4.4
−2.00 or less	Extreme drought	2.3

These probabilities shown in Table 4 are estimates, assuming that SPI is normally distributed. Achieving an approximately standard normal probability distribution is the main motivation behind the transformation of precipitation to SPI.

3.2. Trend Analysis

Trend analysis determines whether the measured values of a variable show a consistent increase or decrease during a time period. Many statistical methods can be used for trend detection in a time series of meteorological and hydrological records. In this study we used simple and accepted methods for evaluating trends, the Mann–Kendall test and Sen's estimator of slope.

The Mann–Kendall method is a widely used non-parametric test for detecting trends in climatological and hydrological time series. It has been suggested by many authors to assess trends in environmental data time series because, unlike least-squares linear regression, it is robust to outlying and extreme values.

The Mann–Kendall test statistic S is given by [59]:

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^{n} sgn\left(x_j - x_k\right) \tag{8}$$

where n is the number of data. x are the data values at times j and k ($j > k$) and the sign function is

$$sgn\left(x_j - x_k\right) = sgn\left(R_j - R_i\right) = \begin{cases} +1,\ if\left(x_j - x_k\right) > 0 \\ 0,\ if\left(x_j - x_k\right) = 0 \\ -1,\ if\left(x_j - x_k\right) < 0 \end{cases} \tag{9}$$

The variance of S is computed by

$$Var(S) = \frac{[n(n-1)(2n+5)] - \sum_{i=1}^{m} t_i(t_i - 1)(2t_i + 5)}{18} \tag{10}$$

where t_i is the number of ties of extent i and m is the number of tied rank groups. For n larger than 10, a Z test statistic that, under the null hypothesis of no correlation, approximates a standard normal distribution is computed as the Mann–Kendall test statistic as follows:

$$Z = \begin{cases} \frac{S-1}{\sqrt{Var(S)}},\ if\ S > 0 \\ 0,\ if\ S = 0 \\ \frac{S-1}{\sqrt{\ Var(S)}},\ if\ S < 0 \end{cases} \tag{11}$$

If a linear trend is present in a time series, then the true slope (change per unit time) can be estimated by using a simple non-parametric procedure developed by Sen [60]. The slope estimates of the $n(n-1)/2$ unique pairs of data are first computed by:

$$Q(i,j) = \frac{X_j - X_i}{j-i} \text{ for } i,\ j = 1,\ 2.\ldots.\text{n} \tag{12}$$

where x_j and x_i are data values at time *j* and *i* (*j* > *i*). respectively. The median of these *N* values of *Q* is Sen's estimator of slope. After sorting the *Q* values, if *N* is even, then Sen's estimator is calculated by:

$$Q_{med} = \frac{1}{2}\left(Q_{\frac{N}{2}} + Q_{\frac{N+2}{2}}\right) \tag{13}$$

If *N* is odd, then Sen's estimator is computed by:

$$Q_{med} = \left(Q_{\frac{N+1}{2}}\right) \tag{14}$$

Sen's estimator Q_{med} provides the rate of change and enables determination of the total change in any variable during the analysis period. Sen's slopes are expressed here as rate of change per 40 years (1970–2010) in mm.

3.3. Drought Charcateristics

3.3.1. Frequency Analysis

Drought frequency (F_i) is the chance of a station being in drought in a given year. This was estimated empirically based on the following formula:

$$F_i = \frac{n}{N}100\% \tag{15}$$

where *n*—number of years of drought (SPI equal 0 or less), *N*—number of analyzed years.

3.3.2. Drought Intensity (DI)

Drought intensity (DI) is used to represent the severity of the drought. The drought intensity of a site within a certain period is usually reflected by the SPI value. The more negative the SPI value, the more serious the drought is. Its formula is as follows:

$$D_i = \left(\frac{1}{m}\sum_{i=1}^{m}|SPI_i|\right)j \tag{16}$$

3.3.3. Drought Magnitude (DM)

DM corresponds to the cumulative water deficit over a drought period. DM is the sum of the absolute values of all SPI values (0 or less) during a drought event (Equation (16)):

$$\text{DM} = -\sum_{j=1}^{i} SPI_{i,j} \tag{17}$$

3.3.4. Drought Duration (DD)

DD equals the number of time periods between the drought start and its end. In our case, we consider all SPI values below 0 as drought years.

3.4. Return Period of Drought

In addition to computing drought frequencies as empirical probabilities in the 40-year observation record, return periods of severe drought were also computed in this study using the annual maximum series (AMS) approach. The AMS here is based on the time series of SPI values for drought years. A drought was described as an SPI value less than zero. Drought-free years were given a zero value. The number of years for which

SPI values are available is used to calculate the duration of the sequence. Only non-zero values were used in the drought frequency calculation. To account for the number of zero values, a correction was made using nonexceedance likelihood (F') according to the following expression [55,61]:

$$F' = q + (1 - q)F \tag{18}$$

where F is the non exceedance probability value obtained by using frequency analysis on the non zero values and q is the probability of zero values which can be calculated as the ratio of the number of time intervals without drought occurrences to the total number of time intervals in the recording period [55,61].

To estimate the return period of drought severity that may go beyond the values observed over the 40-year period for which we have data, we fitted a probability distribution to the derived AMS. In this case, the drought event time series were fitted with gamma distributions. The return period of drought with particular severity was then calculated as:

$$F'(s) = \frac{1}{1 - F'(x)} \tag{19}$$

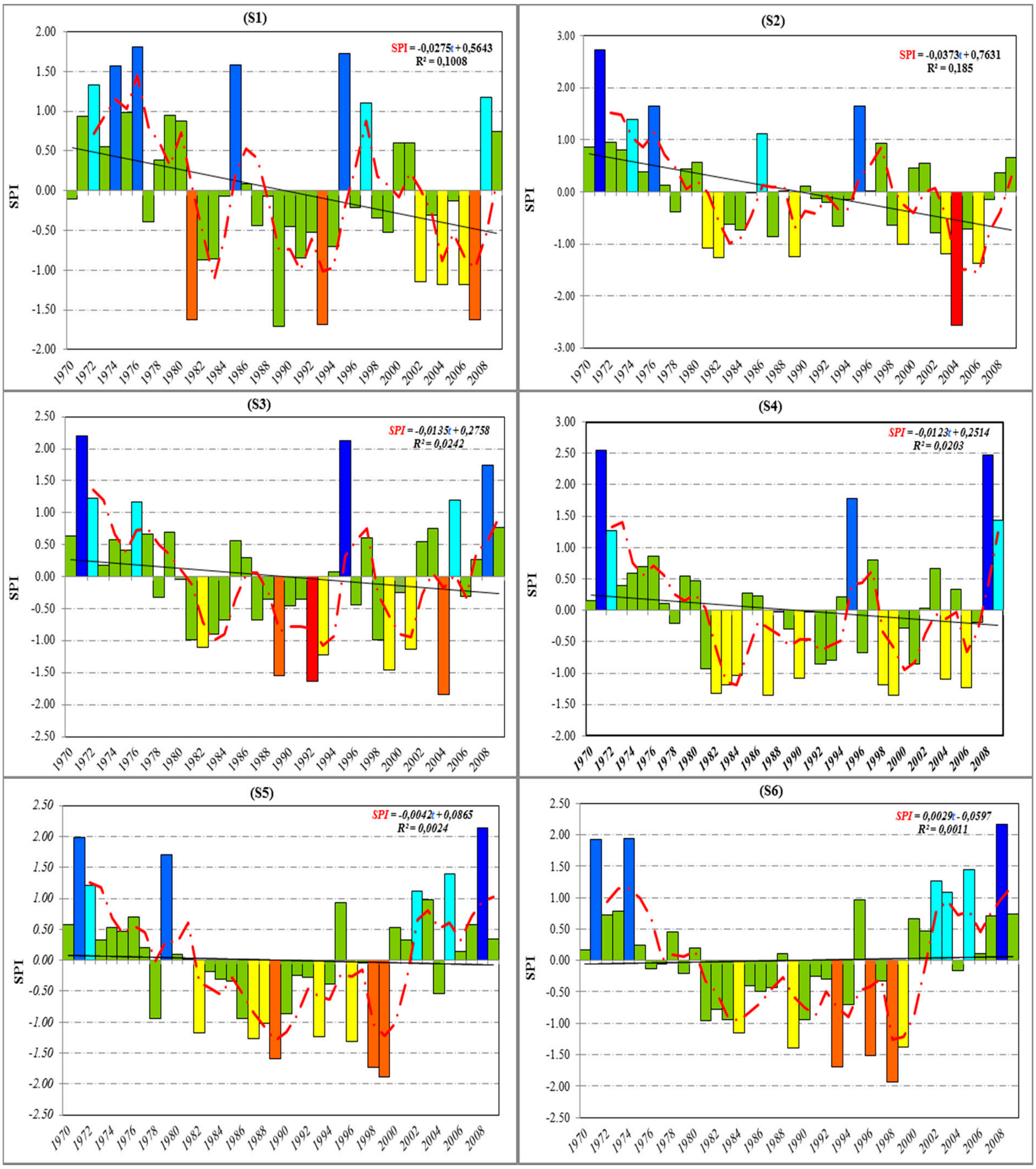
4. Results and Discussion

4.1. Temporal Variability

The SPI was used to provide an indicator of drought severity in this study. The temporal characteristics of droughts in Wadi Mina basin was analyzed based on the 12-month timescale water-year SPI computed for each station (Figure 3). Analysis of the computed SPI series shows the basin has experienced droughts of high severity and duration in the 1980s and 1990s. A drought is defined whenever the SPI reaches a value of 0.00 and continues until the SPI becomes positive again.

The main historical droughts observed in the study area were in 1982/83, 1983/84, 1989/90, 1992/93, 1993/94, 1996/97, 1998/99, 1999/00, 2004/05 and 2006/07. Wet years were observed in 1971/72, 1972/73, 1995/96, 2008/09 and 2009/10. A decreasing trend of SPI, implying a likely increased frequency and intensity of drought, was observed on 13 of 16 rain gauge stations. Most of the stations with the strongest decreasing SPI trend are observed in the lower part of the Wadi Mina basin where are observed relatively lower sums of precipitation (Table 2). Increase of trend of SPI and likely decreased intensity of drought is observed on three rain gauge stations located mainly in upper part of the basin, in the Wadi Abd tributary. Spatio-temporal changes of SPI is caused by change of precipitation. Elouissi et al. [62] detected similar decreasing trends of precipitation in the northern part of the Macta basin (Algeria), close to the Mediterranean coast, and increasing trends in the southern part. The changes of precipitation and SPI can be affected by geographical position of the area in relation to the Atlantic Ocean, the Mediterranean Sea and the Atlas mountain ranges [63]. We can also see from Figure 3 that dry periods have tendency to cluster over long stretches of years. Clustering is especially visible in station S8 during 1975–1993, S5 (1981–1999), S6 (1981–1999) and S13 (1996–2007). Figure 3 also shows that at station S3 located in the upper part of the Wadi Taht subbasin, and S6 and S5 in the upper Wadi Mina, intensity of meteorological drought since 2000, expressed by SPI, was small, with wet years being more common.

Trend analysis determines whether the measured values of a variable show a significant increase or decrease during a time period. In this study, we used a simple method for evaluating trends, Mann-Kendall test and annual and seasonal Sen's slopes of trend values are expressed as rate of change per 40 years (1970–2010) in mm. The result of this analysis is shown in Table 5. At 7 of 16 rain gauge stations, or 44% all stations, there was a significant negative trend ($p < 0.1$). The significance level of trend in 6 cases was $p < 0.05$, and in the case of S13 station the p value was under 0.01. At most stations, from 1996 onward there were mainly severe droughts. Significant decreasing trends were observed at stations located in the upper part of the Wadi Mina and middle part of the Wadi Taht tributary. A significant increasing trend was not detected at any of the Wadi Mina basin stations.



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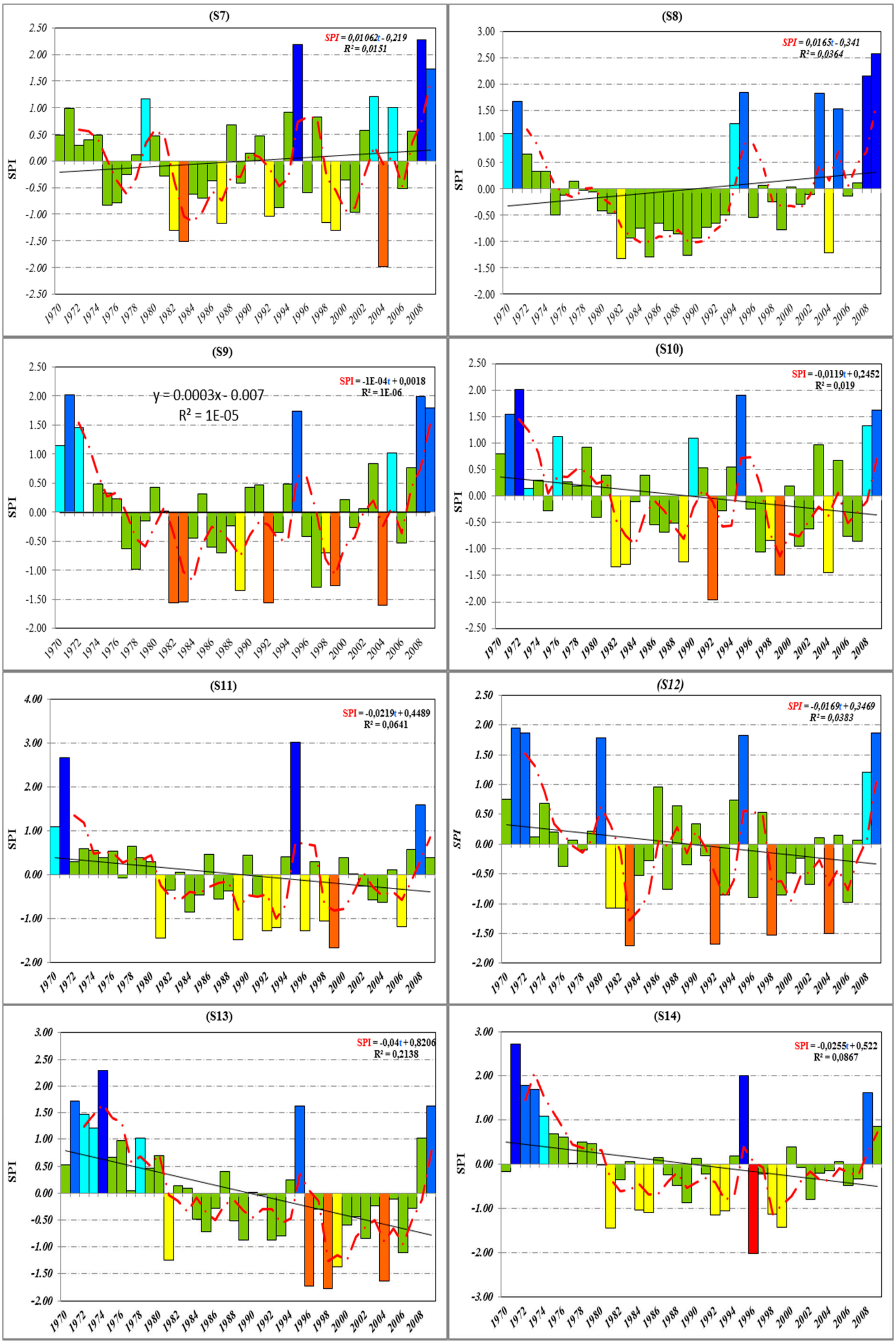


Figure 3. *Cont.*

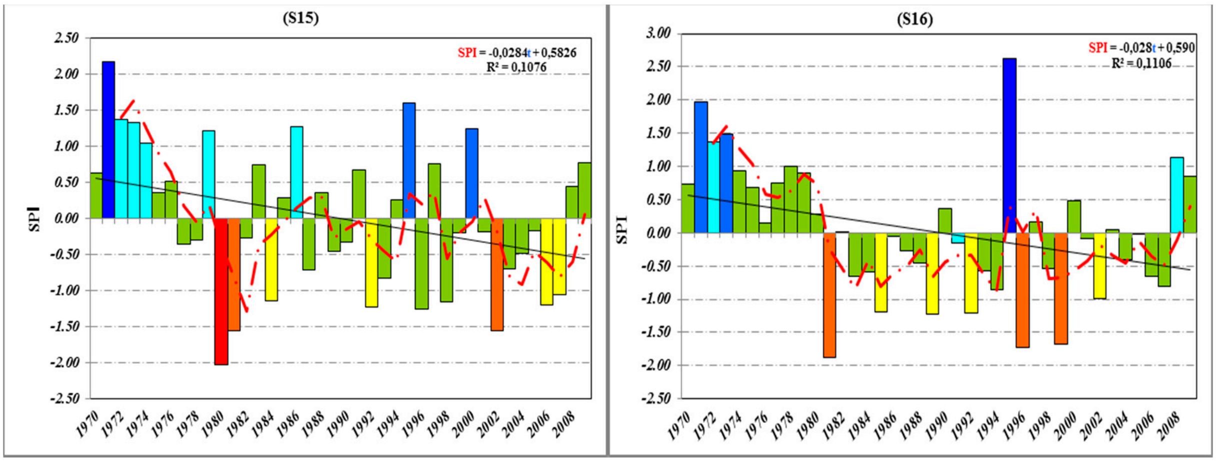


Figure 3. Annual SPI time series and its linear trend and 3 year moving average of the pluviometric stations of Wadi Mina basin. Note that colors are linked with drought classification based on Table 4. Number in branches above figures is number of station.

Table 5. Values of statistics b, Z of the Mann–Kendall test for the annual SPI series (1970–2010).

Stations	Area (km^2)	Z	Sen's Slope	Describtion
S1	57.40	−1.969	−0.031	Significant at 95% level of confidence or p = 0.05
S2	413.10	−2.540	−0.038	Significant at 95% level of confidence or p = 0.05
S3	160.60	−1.037	−0.015	
S4	560.20	−1.340	−0.02	
S5	150.30	−0.722	−0.012	
S6	254.60	0.011	0.001	
S	165.20	0.163	0.002	
S8	607.40	0.524	0.063	
S9	398.90	0.000	0.080	
S10	534.40	−1.002	0.334	
S11	261.70	−2.005	0.455	Significant at 95% level of confidence or p = 0.05
S12	568.90	−1.270	−0.019	
S13	193.30	−3.251	−0.906	Significant at 99% level of confidence or p = 0.01
S14	205.40	−1.969	−0.554	Significant at 95% level of confidence or p = 0.05
S15	300.40	−1.899	−0.653	Significant at 90% level of confidence or p = 0.1
S16	68.30	−2.237	−0.650	Significant at 95% level of confidence or p = 0.05

Table 1 presents drought classification for the 16 rain gauge stations in each year. The most common SPI category overall was near normal (NN). For several years (1971, 1972, 1995, 2008 and 2009) most stations were in wet categories (EW, VW and MW). For 1971, 1995 and 2008 only 2–5 out of 16 stations were dry, and no severe or extreme drought was observed. The highest number of stations with severe or extreme drought (SD and ED) was observed in the years 1981, 1983, 1989, 1992, 1996, 1998, 1999 and 2004. The highest number of years with unusually wet conditions (MW, VW and EW) were observed on stations S13 and S15-8 cases. These stations were located in the lower part of the Wadi Mina. The most cases of intense drought (ED, SD and ED) were observed at station S9-9 cases, and the highest number of years with severe and extreme drought were observed at stations S1, S9 and S12-4 cases.

4.2. Spatial Variability

To visualize the distribution of droughts in the basin, the study area is divided using Theissen Polygon tool in Arc GIS 10.2 into 16 polygons corresponding to the 16 rainfall stations. Stations that are closely spaced are assigned less area and vice versa (Figure 4). Lee et al. [64] showed that the spatial distribution of the rain gauge networks and the density have a significant influence on accurately calculating areal precipitation and Thiessen method gave good results when the spatial distribution of the rain gauge networks was even, as was the case here. Moreover, the weights assigned to the different stations do not vary with time, and thus it is easy to map the precipitation falling during each period. Geostatistical methods offer more sophisticated approaches to making maps based on station data, but the uncertainty of areal precipitation is in any case high if there are relatively few stations, like in this basin [65]. Even though some stations may show drought conditions, a regional drought is acknowledged only when some major portion of the total study area is under drought. Regional drought is determined by the intra-annual precipitation distribution, which can be affected by teleconnection patterns [66,67], and the North Atlantic Oscillation indices [68]. Moreover, regional-scale influence on the rainfall conditions in North Africa could result from the response of the African summer monsoon to oceanic forcing, amplified by land-atmosphere interaction [69].

The spatial distribution of drought intensity is shown (Figure 4) in each analyzed year. In 1971, 1995, and 2008, wet conditions prevailed over almost all the Wadi Mina basin (SPI $\geq$ 1.0). Less widespread wet conditions were seen in 1972 (east and central part of basin in wet condition) and 2009 (upper and middle part of basin). No droughts were seen between 1970 and 1979 in the region. The year 1980 is an example of intra-basin variability: almost all area of basin had near normal conditions, but particular areas had either very wet conditions (middle part of the Wadi Abd catchment) or extreme drought (upper part of the Wadi Haddad tributary). The years where a large part of the Wadi Mina basin was in drought were 1982, 1989, 1999, 2004 and 2006, but the worst situation was in 2004, where all the upper and middle parts of the basin had moderate to extreme drought. Spatial patterns of drought within the basin varied unpredictably during the study period, which could be due to the complex interaction of storm tracks with orographic features.

4.3. Drought Evaluation Indicators

4.3.1. Frequency Analysis

Drought frequency calculated for all analyzed stations is presented in Table 6. Near normal (NN) conditions occurred most frequently at all stations (57.5% to 72.5% of the time, depending on station). The extreme categories—extreme wetness (EW) and extreme drought (ED)—were the least frequently observed. Extreme drought only occurred at 3 of 16 rainfall gauge stations over the 40-year observation period. However, all but 2 rainfall gauge stations (S4 and S8) observed either ED and SD.

Table 2 shows drought duration, magnitude and intensity, as well as average, maximum and minimum SPI at annual time scale for the meteorological stations considered in this study area. All drought indicators have strong variability over the study area. Drought duration (DD) varied between 1 to 16 years, and most frequently was only 1 year. The highest DD of 12, 13 and 16 years were observed at stations S13, S6 and S5, respectively. The highest drought intensity was observed at S16 station and lowest at S8. The largest drought magnitude was observed at S5 and the smallest at S11. Extreme drought was observed in 1980/81, 1996/97 and 2004/05 in stations located in the lower part of basin.

Table 6. Frequency of each drought and wetness class for the considered stations, %.

	S1	**S2**	**S3**	**S4**	**S5**	**S6**	**S7**	**S8**	**S9**	**S10**	**S11**	**S12**	**S13**	**S14**	**S15**	**S16**
EW	0	2.5	5	5	0	2.5	5	5	2.5	2.5	5	0	2.5	5	2.5	2.5
VW	10	5	2.5	2.5	5	5	2.5	10	7.5	7.5	2.5	13	7.5	7.5	2.5	5
MW	7.5	5	7.5	5	7.5	7.5	7.5	5	7.5	7.5	2.5	2.5	10	2.5	15	5
NN	65	73	70	65	65	70	68	70	65	65	70	70	65	65	58	73
MD	7.5	13	7.5	23	13	7.5	13	10	7.5	13	18	5	7.5	18	15	7.5
SD	10	0	7.5	0	7.5	7.5	5	0	10	5	2.5	10	7.5	2.5	5	7.5
ED	0	2.5	0	0	2.5	0	0	0	0	0	0	0	0	0	2.5	0
Sums	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100

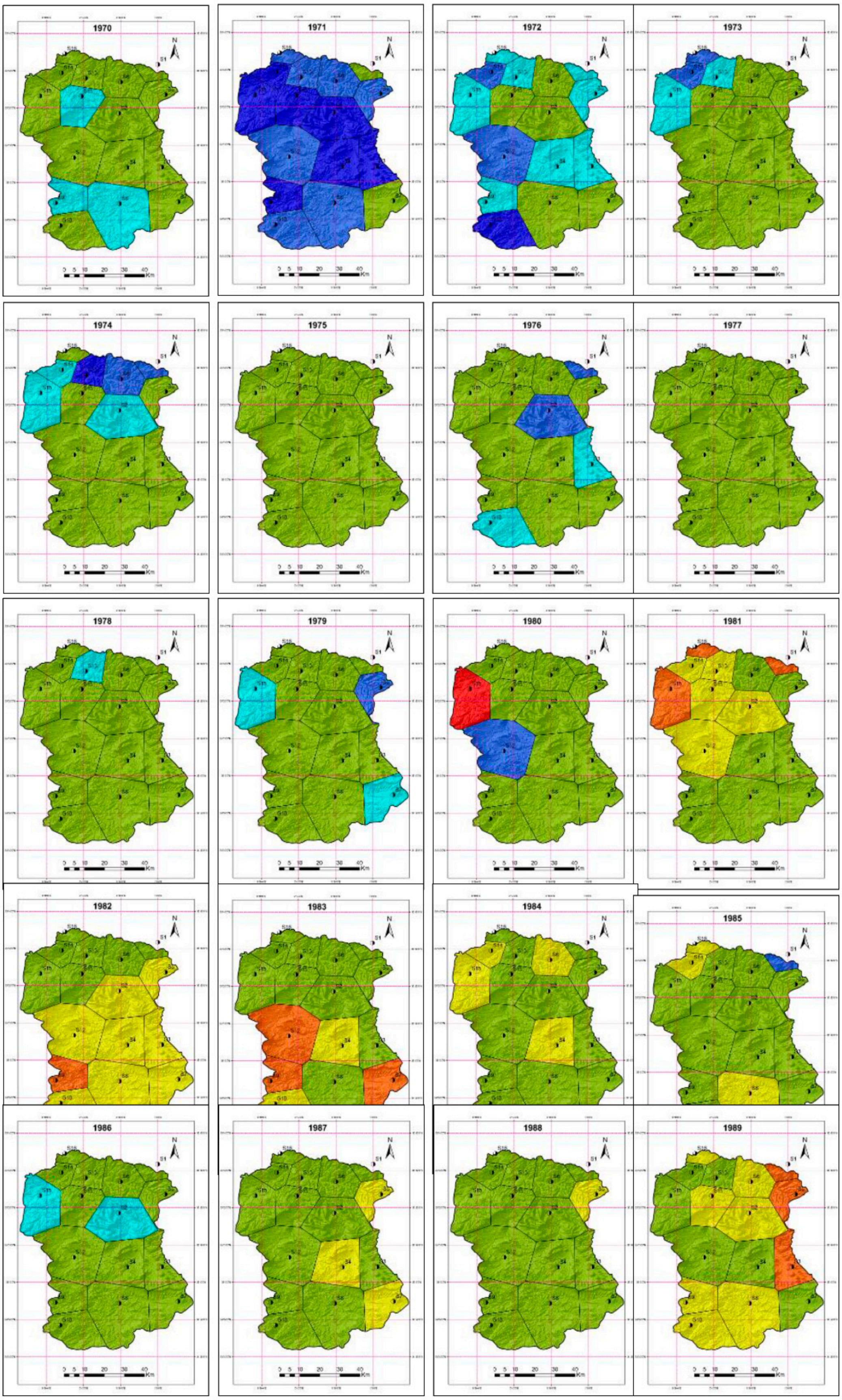


Figure 4. *Cont*.

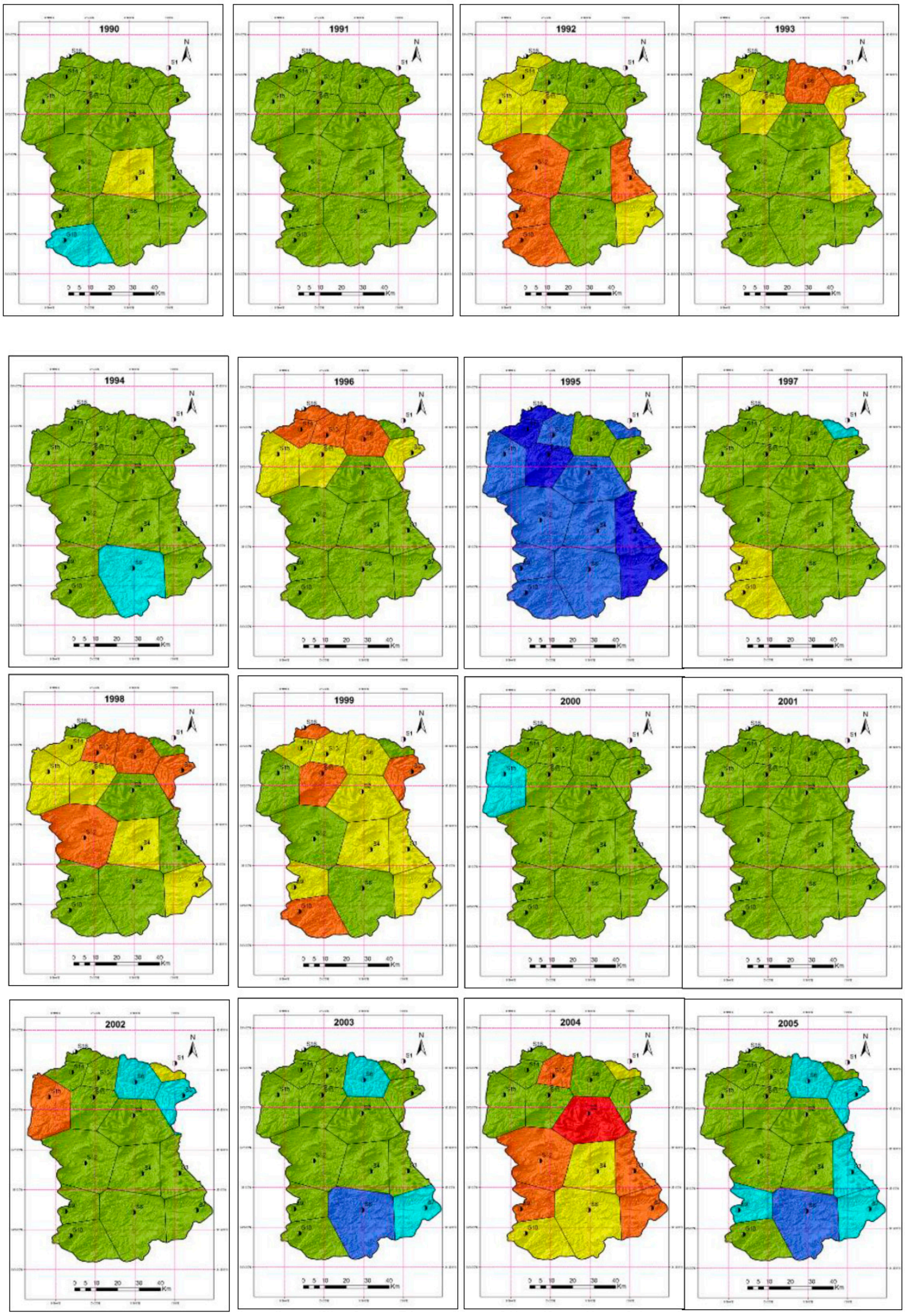


Figure 4. *Cont.*

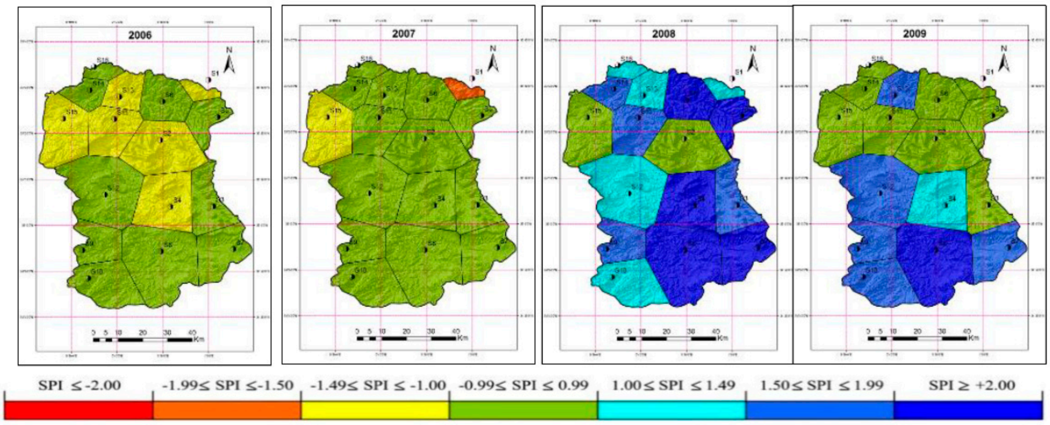


Figure 4. Spatial variability of meteorological drought in the wadi Mina basin.

4.3.2. Calculation of Return Period and the Severity-Area-Frequency (SAF) Curve

The Severity-Area-Frequency (SAF) curve is a very useful method for showing the spatial extent of different types of drought in a given area. This technique has been undertaken by several researchers around the world, for example in India [70]; China [71]; Southern Africa [72] and in Iraq [39]. Figure 5 illustrates the drought Severity-Area-Frequency curves of SPI annual scale time for 10-, 25-, 50-, 100-year exceedance periods, along with the curves for the four most severe drought years of 1984/85, 1993/94, 1998/99 and 2004/05 that affected the region.

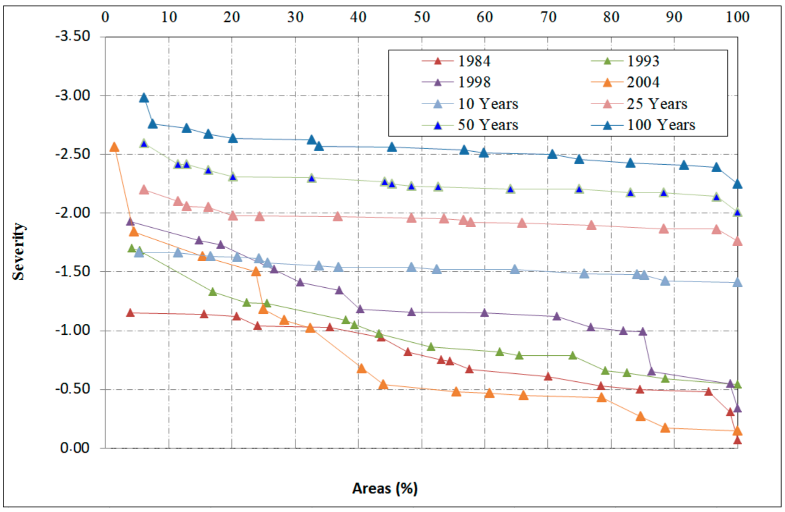
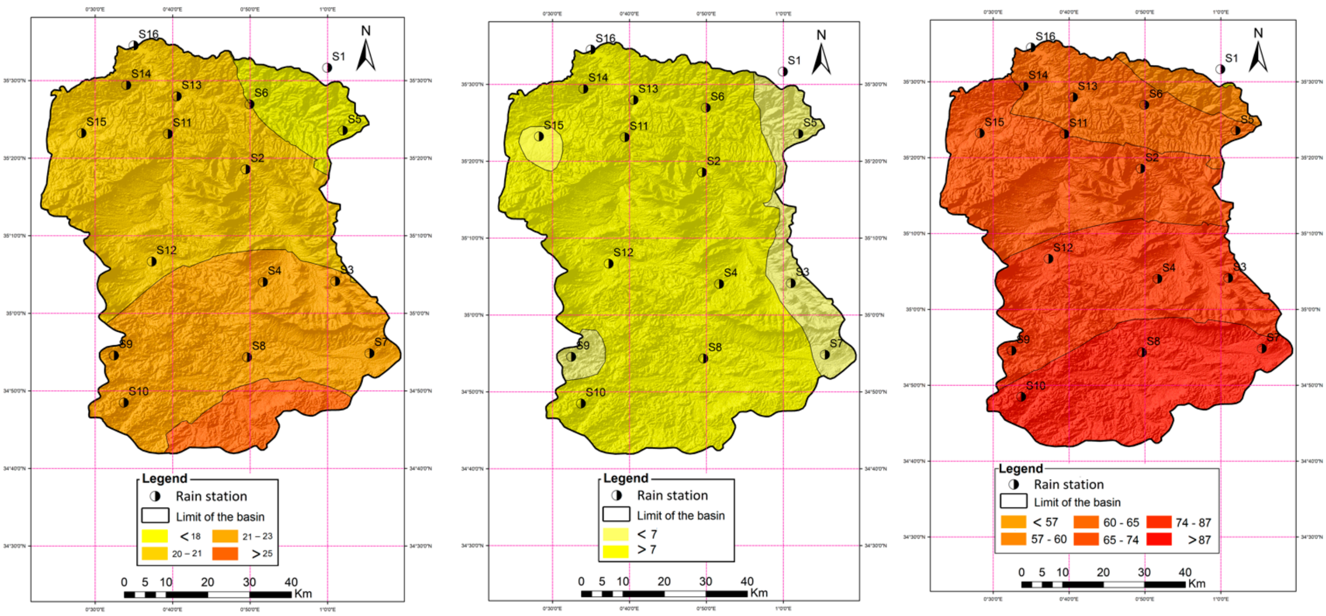


Figure 5. Estimated drought severity—area—frequency curves for the annual SPI values for the Wadi Mina basin, as compared those seen in historical droughts.

The severity analysis shows that all selected droughts have smaller severity than for return periods 10, 25, 50 and 100 years. Moreover, the high drought severity occurred on relatively small areas, less than 20% of analyzed basin and is observed mainly on the north part of the basin—Figure 4. Moderate or near normal years are observed on the most parts of the basin.

4.3.3. Spatial Pattern of Return Periods of Droughts

The return periods of moderate, severe and extreme droughts at all stations were calculated and the values were then used to prepare the corresponding maps by using inverse distance weighted (IDW) interpolation method analysis tool of ArcMap (Figure 6). The presentation of these maps shows spatial variability of the drought for the different classes, with extreme drought more likely (shorter return period) in the north and east, apparently modulated by the high heterogeneity of the spatial distribution of the rainfall [45,73]. Assessing vulnerability to drought across the Wadi Mina basin is important, considering that, as shown by Henchiri et al. [74], grasslands and croplands in the northern region of the Africa are highly vulnerable to drought risk.



(**a**) (**b**) (**c**)

Figure 6. Return periods of meteorological droughts in Wadi Mina with (**a**) moderate; (**b**) severe; and (**c**) extreme severities.

To mitigate risks of drought, proper water management techniques must be adopted. One of these techniques is supplemental irrigation, which is an efficient practice used for increasing agricultural production under limited water resources in areas affected by drought [75].

5. Conclusions

This study was focused on analyzing temporal and spatial extents of droughts in the Wadi Mina basin, Algeria, using SPI as an indicator of drought severity. The aim of this study was to investigate spatial and temporal dimensions of meteorological droughts in the Wadi Mina basin. Meteorological drought was expressed by the Standardized Precipitation Index (SPI) method and GIS was used to detail temporal and geographical variations in the drought vulnerability based on severity of drought events at annual time steps. This study is applied to rainfall monthly records for the period 1970–2010 at 16 rainfall stations located in the Wadi Mina basin.

The results showed that the SPI was able to detect historical droughts of 1982/83, 1983/84, 1989/90, 1992/93, 1993/94, 1996/97, 1998/99, 1999/00, 2004/05 and 2006/07. Wet years were observed in 1971/72, 1972/73, 1995/96, 2008/09 and 2009/10. Decreasing SPI was observed on 13 of 16 rain gauge stations, with six showing statistically significant ($p < 0.05$) decreases. Most of the stations with the greatest decreasing trend were observed in the lower part of the Wadi Mina basin, where average precipitation is already low. As expected given the process used to construct SPI, near normal conditions dominated at all stations, and severe and extreme drought categories were uncommon. The spatial variability of the drought showed that extreme drought is more likely (shorter return period) in the north and east.

Severity-Area-Frequency curves that can aid the development of a drought preparedness plan were developed for Wadi Mina basin, so as to ensure sustainable water resource planning within the basin.

One limitation of the study is that we used only SPI to detect drought intensities. In the future, we plan to add evapotranspiration and calculate the SPEI indicator, which can give more complex information about meteorological conditions influencing drought events, particularly for agricultural and forestry applications. Moreover, in this study only annual sum of precipitation was used and thus seasonal variability of drought was not detected. While this is to some extent justified for this region given that precipitation is concentrated in only a few months per year, in a future study monthly and seasonal precipitation variations could also be explored. Moreover, as a future study, we plan to compare drought analyses based on different sources of rainfall data, including the Soil Moisture to Rainfall (SM2RAIN) [76] algorithm to estimate rainfall based on soil moisture time series.

The SM2RAIN is based on the inversion of the hydrological water balance, for estimation of rainfall from soil moisture observations. In this approach the soil is assumed as reservoir used for measuring the amount of rainfall [77]. This method gives independent rainfall product with a different error structure and allows integration with other satellite-based rainfall products. According to [76], the SM2RAIN method can be useful in regions for which satellite rainfall data are affected by higher errors or not available. Because Northwest Algeria is the region where water scarcity is high, we will perform analysis that can show potential use of SM2RAIN as indirect source of rainfall to detect meteorological drought, including seasonal variations.

Author Contributions: Conceptualization, M.A.; methodology, M.A., A.W., H.M. and N.K.; software, M.A. and A.K.T.; formal analysis, M.A., A.W.; validation: M.A., A.W. and N.K.; investigation, M.A., A.K.T., A.W. and H.M.; data curation, M.A.; writing—original draft preparation, M.A., A.W. and N.K.; writing—review and editing, M.A., A.W. and N.K.; visualization, A.W.; supervision, M.A., A.W. and N.K. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement: The data presented in this study are available on request from the Corresponding authors.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table 1. Drought classification in the Wadi Mina basin.

Years	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12	S13	S14	S15	S16
1970	NN	NN	NN	NN	NN	NN	NN	MW	MW	NN	MW	NN	NN	NN	NN	NN
1971	NN	EW	EW	EW	VW	VW	NN	VW	EW	VW	EW	VW	VW	EW	EW	VW
1972	MW	NN	MW	MW	MW	NN	NN	NN	MW	EW	NN	VW	MW	VW	MW	MW
1973	NN	NN	NN	NN	NN	NN	NN	NN	NN	NN	NN	NN	MW	VW	MW	VW
1974	VW	MW	NN	NN	NN	VW	NN	NN	NN	NN	NN	NN	EW	MW	MW	NN
1975	NN	NN	NN	NN	NN	NN	NN	NN	NN	NN	NN	NN	NN	NN	NN	NN
1976	VW	VW	MW	NN	NN	NN	NN	NN	NN	MW	NN	NN	NN	NN	NN	NN
1977	NN	NN	NN	NN	NN	NN	NN	NN	NN	NN	NN	NN	NN	NN	NN	NN
1978	NN	NN	NN	NN	NN	NN	NN	NN	NN	NN	NN	NN	MW	NN	NN	NN
1979	NN	NN	NN	NN	VW	NN	MW	NN	NN	NN	NN	NN	NN	NN	MW	NN
1980	NN	NN	NN	NN	NN	NN	NN	NN	NN	NN	NN	VW	NN	NN	ED	NN
1981	SD	MD	NN	NN	NN	NN	NN	NN	NN	NN	MD	MD	MD	MD	SD	SD
1982	NN	MD	MD	MD	MD	NN	MD	MD	SD	MD	NN	MD	NN	NN	NN	NN
1983	NN	NN	NN	MD	NN	NN	SD	NN	SD	MD	NN	SD	NN	NN	NN	NN
1984	NN	NN	NN	MD	NN	MD	NN	NN	NN	NN	NN	NN	NN	MD	MD	NN
1985	VW	NN	NN	NN	NN	NN	NN	MD	NN	NN	NN	NN	NN	MD	NN	MD
1986	NN	MW	NN	NN	NN	NN	NN	NN	NN	NN	NN	NN	NN	NN	MW	NN
1987	NN	NN	NN	MD	MD	NN	MD	NN	NN	NN	NN	NN	NN	NN	NN	NN
1988	NN	NN	NN	NN	MD	NN	NN	NN	NN	NN	NN	NN	NN	NN	NN	NN
1989	SD	MD	SD	NN	SD	MD	NN	MD	MD	MD	MD	NN	NN	NN	NN	MD
1990	NN	NN	NN	MD	NN	NN	NN	NN	NN	MW	NN	NN	NN	NN	NN	NN
1991	NN	NN	NN	NN	NN	NN	NN	NN	NN	NN	NN	NN	NN	NN	NN	NN
1992	NN	NN	SD	NN	NN	NN	MD	NN	SD	SD	MD	SD	NN	MD	MD	MD
1993	SD	NN	MD	NN	MD	SD	NN	NN	NN	NN	MD	NN	NN	MD	NN	NN
1994	NN	NN	NN	NN	NN	NN	NN	MW	NN	NN	NN	NN	NN	NN	NN	NN
1995	VW	VW	EW	VW	NN	NN	EW	VW	VW	VW	EW	VW	VW	EW	VW	EW
1996	NN	NN	NN	NN	MD	SD	NN	NN	NN	NN	MD	NN	SD	SD	MD	SD
1997	MW	NN	NN	NN	NN	NN	NN	NN	MD	MD	NN	NN	NN	NN	NN	NN
1998	NN	NN	NN	MD	SD	SD	MD	NN	NN	NN	MD	SD	SD	MD	MD	NN
1999	NN	MD	MD	MD	SD	MD	MD	NN	MD	SD	SD	NN	MD	MD	NN	SD
2000	NN	NN	NN	NN	NN	NN	NN	NN	NN	NN	NN	NN	NN	NN	MW	NN
2001	NN	NN	NN	NN	NN	NN	NN	NN	NN	NN	NN	NN	NN	NN	NN	NN
2002	MD	NN	NN	NN	MW	MW	NN	NN	NN	NN	NN	NN	NN	NN	SD	NN
2003	NN	NN	NN	NN	NN	MW	MW	VW	NN	NN	NN	NN	NN	NN	NN	NN
2004	MD	ED	SD	MD	NN	NN	SD	MD	SD	MD	NN	SD	SD	NN	NN	NN
2005	NN	NN	MW	NN	MW	MW	MW	VW	MW	NN	NN	NN	NN	NN	NN	NN
2006	MD	MD	NN	MD	NN	NN	NN	NN	NN	NN	MD	NN	MD	NN	MD	NN
2007	SD	NN	NN	NN	NN	NN	NN	NN	NN	NN	NN	NN	NN	NN	MD	NN
2008	MW	NN	VW	EW	EW	EW	EW	EW	VW	MW	VW	MW	MW	VW	NN	MW
2009	NN	NN	NN	MW	NN	NN	VW	EW	VW	VW	NN	VW	VW	NN	NN	NN

EW—extremely wet, VW—very wet, MW—moderately wet, NN—near normal, MD—moderate drought, SD—severe drought, ED—extreme drought.

Table 2. Average and maximum annual SPI values during drought years for the meteorological stations considered.

Stations	Events	Duration DD (Years)	Intensity DI	Magnitude DM	SPI Values				
					Average	Maximum	Year	Minimum	Year
S1	1	1	−0.11	−0.11	−0.74	−1.71	1989/90	−0.07	1984/85
	2	1	−0.39	−0.39					
	3	4	−0.86	−3.42					
	4	8	−0.80	−6.42					
	5	1	−0.21	−0.21					
	6	2	−0.43	−0.86					
	7	6	−0.93	−5.58					
S2	1	1	−0.39	−0.39	−0.79	−2.56	2004/05	−0.01	1985/86
	2	5	−0.74	−3.71					
	3	1	−0.86	−0.86					
	4	1	−1.25	−1.25					
	5	4	−0.29	−1.14					
	6	2	−0.83	−1.66					
	7	6	−1.13	−6.76					
S3	1	1	−0.32	−0.32	−0.84	−1.84	2004/05	−0.04	1980/81
	2	5	−0.74	−3.71					
	3	7	−0.89	−6.24					
	4	1	−0.44	−0.44					
	5	4	−0.96	−3.84					
	6	1	−1.84	−1.84					
	7	1	−0.31	−0.31					
S4	1	1	−0.21	−0.21	−0.80	−1.36	1999/00	−0.02	1991/92
	2	4	−1.12	−4.48					
	3	7	−0.63	−4.43					
	4	1	−0.67	−0.67					
	5	4	−0.92	−3.67					
	6	1	−1.09	−1.09					
	7	2	−0.71	−1.42					
S5	1	1	−0.94	−0.94	−0.86	−1.88	1999/00	−0.05	1997/98
	2	13	−0.76	−9.84					
	3	4	−1.25	−4.98					
	4	1	−0.54	−0.54					
S6	1	2	−0.10	−0.19	−0.77	−1.93	1989/99	−0.06	1977/78
	2	1	−0.21	−0.21					
	3	7	−0.74	−5.16					
	4	6	−0.88	−5.30					
	5	4	−1.29	−5.15					
	6	1	−0.17	−0.17					

Table 2. *Cont.*

Stations	Events	Duration DD (Years)	Intensity DI	Magnitude DM	SPI Values				
					Average	Maximum	Year	Minimum	Year
S7	1	3	−0.62	−1.87	−0.97	−1.98	2004/05	−0.26	1977/78
	2	7	−0.85	−5.97					
	3	1	−0.41	−0.41					
	4	2	−0.95	−1.90					
	5	1	−0.59	−0.59					
	6	4	−0.94	−3.77					
	7	1	−1.98	−1.98					
	8	1	−0.52	−0.52					
S8	1	2	−0.31	−0.62	−0.62	−1.33	1983/84	−0.02	1978/79
	2	16	−0.73	−11.67					
	3	1	−0.55	−0.55					
	4	2	−0.51	−1.02					
	5	2	−0.20	−0.40					
	6	1	−1.22	−1.22					
	7	1	−0.14	−0.14					
S9	1	1	−0.01	−0.01	−0.81	−1.60	2004/05	−0.01	1973/74
	2	3	−0.59	−1.77					
	3	3	−1.19	−3.56					
	4	8	−0.49	−3.91					
	5	4	−0.92	−3.69					
	6	1	−0.27	−0.27					
	7	1	−1.60	−1.6					
	8	1	−0.53	−0.53					
S10	1	1	−0.28	−0.28	−0.85	−1.96	1992/93	−0.11	1984/85
	2	1	−0.41	−0.41					
	3	3	−0.91	−2.74					
	4	4	−0.75	−2.98					
	5	2	−1.12	−2.24					
	6	4	−0.91	−3.65					
	7	2	−0.79	−1.57					
	8	1	−1.45	−1.45					
	9	2	−0.81	−1.61					

Table 2. *Cont.*

Stations	Events	Duration DD (Years)	Intensity DI	Magnitude DM	SPI Values				
					Average	Maximum	Year	Minimum	Year
S11	1	1	−0.07	−0.07	−0.85	−1.67	1999/00	−0.07	1977/78
	2	2	−0.90	−1.80					
	3	2	−0.66	−1.32					
	4	3	−0.81	−2.42					
	5	3	−1.00	−2.99					
	6	1	−1.29	−1.29					
	7	2	−1.37	−2.73					
	8	3	−0.49	−1.47					
	9	1	−0.19	−0.19					
S12	1	1	−0.37	−0.37	−0.8	−1.70	1983/84	−0.10	1978/79
	2	1	−0.10	−0.10					
	3	5	−0.93	−4.65					
	4	1	−0.76	−0.76					
	5	1	−0.34	−0.34					
	6	3	−0.91	−2.73					
	7	1	−0.90	−0.90					
	8	5	−0.75	−3.76					
	9	1	−1.50	−1.50					
	10	1	−0.98	−0.98					
S13	1	1	−1.25	−1.25	−0.77	−1.77	1998/99	−0.04	1991/92
	2	3	−0.49	−1.48					
	3	2	−0.69	−1.38					
	4	3	−0.57	−1.70					
	5	12	−0.87	−10.42					
S14	1	1	−0.17	−0.17	−0.68	−2.02	1996/97	−0.02	1980/81
	2	3	−0.61	−1.83					
	3	2	−1.07	−2.13					
	4	3	−0.54	−1.62					
	5	3	−0.81	−2.42					
	6	5	−0.56	−2.79					
	7	4	−0.31	−1.22					
	8	2	−0.42	−0.83					

Table 2. *Cont.*

Stations	Events	Duration DD (Years)	Intensity DI	Magnitude DM	SPI Values				
					Average	Maximum	Year	Minimum	Year
S15	1	2	−0.32	−0.64	−0.81	−2.03	1980/81	−0.17	2005/06
	2	3	−1.29	−3.86					
	3	1	−1.14	−1.14					
	4	1	−0.71	−0.71					
	5	2	−0.39	−0.78					
	6	2	−1.03	−2.05					
	7	1	−1.25	−1.25					
	8	2	−0.68	−1.35					
	9	7	−0.76	−5.32					
S16	1	1	−1.88	−1.88	−0.76	−1.88	1981/82	−0.01	2005/06
	2	7	−0.63	−4.43					
	3	4	−0.70	−2.80					
	4	1	−1.73	−1.73					
	5	2	−1.11	−2.21					
	6	2	−0.54	−1.07					
	7	4	−0.47	−1.87					

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