Dry events according a precipitation threshold value in the Mediterranean climate of northern Tunisia

Majid Mathlouthi (✉ Majid_Mathlouthi@yahoo.fr)

Research Laboratory in Sciences and Technology of Water at INAT, 43 avenue Charles Nicolle, 1082 Tunis, Tunisia

Fethi Lebdi

INAT: Institut National Agronomique de Tunis

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Abstract

Dry spells observed in Ichkeul basin Northern Tunisia using daily precipitation data were analyzed. Dry days were defined as having less than a threshold value of accumulated precipitation. Various values of the threshold were investigated. Analysis point dry spells occur randomly during the rainy season. The longest dry spells associated with various statistical recurrence periods are derived on the basis of the fitted Generalized Extreme Value (GEV) distributions. An extreme case (meteorological droughts) was analysed. From the drought return period analysis, the 1 September 1987 drought was found to be the most extreme with a 127-yr return period. The maximum number of seasonal dry events observed is inversely proportional to the threshold value. Longest observed in rainfall event duration is invariant to the rainfall threshold and displays 13 days. This study provides the foundation data for reducing Ichkeul's vulnerability to future droughts, and investigating the causes of droughts.

Introduction

Drought can be categorized into several types depending on its impact on the hydrological cycle (Heim, 2002). Lack of precipitation for an extended period, i.e., several months to years, leads to meteorological drought (Wilhite, 2000). Meteorological drought inevitably spreads through the hydrological cycle for a prolonged duration. This may cause crop yield reductions due to reduced soil moisture and is known as agricultural drought (Keyantash and Dracup, 2002; Jehanzaib and Kim, 2020). Extended meteorological drought may cause a streamflow shortage, called hydrological drought (Jehanzaib et al., 2020; Kim and Jehanzaib, 2020).

Drought is monitored using drought indices, which measure deviations from normal local conditions based on historical distributions (Dai, 2011). Standardized Precipitation Index (SPI) plays an important role in the analysis of drought characteristics because the income of precipitation does have a direct impact on the occurrence and evolution of drought (Lin et al., 2020). However, it should not be ignored that the water expenditure, such as the potential evapotranspiration (PET), also has a direct impact on the evolution of drought (Lin et al., 2020). Thus, some droughts indices, such as the Standardised Precipitation-Evapotranspiration Index (SPEI) and Humidity Index (HI), have been developed (Lin et al., 2020). Considering that drought depends on the water collection (such as precipitation) and expenditure (such as the PET loss), different drought indices may have differences in the description of drought in the same region (Lin et al., 2020). Standardized drought indices are widely used due to their versatility and simplicity over various time scales (Jehanzaib et al., 2020). However, they are based on the presumption of stationarity, which is not a valid assumption under changing climate conditions (Kim and Jehanzaib, 2020).

The stochastic models can be used to study dry spells. It can be subdivided into driven data models (e.g., the non-homogeneous Poisson model), which reproduce the primary characteristics of the available data series, and physically based models (e.g., the Markov chain model), which schematize the generating mechanisms of atmospheric precipitation (Sirangelo et al., 2019). The Markov chain probabilistic model is widely used to determine the relative chance of occurrence of a given rainfall to characterize a rainfall period as a dry or wet spell (Gregory et al., 1993; Sirangelo et al., 2019; Adane et al., 2020).

Reddy (1990) stated that 3mm rainfall depth per day is the minimum threshold value for crops to satisfy their crop water requirement during a growing season. In his study an average of 30 mm per decade (ten days sum) of precipitation depth was taken as a threshold value for evaluating whether a decade is in a dry or wet spell (Sifer et al., 2016). A decade with a depth of precipitation below this value as Markov chain model of first order was

considered as dry and vice versa for a decade with precipitation value of above the threshold level (Sifer et al., 2016). In his study Reddy (1990) described wet spell duration as a sequence of wet decades preceded and followed by the dry decades and correspondingly the dry spell duration is the sequence of dry decades followed and preceded by the wet ones (Sifer et al., 2016).

Droughts are expected to occur more frequently, caused by the predicted changes in the hydrologic cycle (Seidel et al., 2008; Caloiero et al., 2015). Many studies have been performed for the research of drought, such as the definition and evaluation of droughts, including the spatiotemporal structure and statistical characteristic analysis (Sirangelo et al., 2017; L'opez-Franca et al., 2014; Mishra and Singh, 2010, 2011; Rivoire et al. 2019) and the multivariable probability distributions jointly considering multiple drought variables such as duration, severity, and magnitude simultaneously (Shiau, 2006; Rajsekhar et al., 2015). Multiple researchers discussed the drought situation combining with weather/climate conditions, such as severe weather occurrence frequency (Dikici, 2020). Localized data analysis on dry spell occurrence and seasonal rainfall is important from the point of view of farmers (Gbangou et al., 2020). Farmers need information on these indicators, especially in the rainy season. However, for agricultural applications, these are critical seasons during crops' growing stages as they are highly sensitive to onset, dry spell occurrence and rainfall totals (Gbangou et al., 2019).

The phenomenon of drought in semi-arid countries is generally analyzed by considering the series of rainfall events (Alvalá et al., 2019; Mugari et al., 2020; Ahmed Suliman et al., 2020)

An analysis, which makes use the dry spell, particularly the extreme dry spell reflecting the variation of extreme drought condition, still needs to be further concerned and analyzed (Dunxian et al., 2016). This study uses the model by alternating wet/dry spell to analyze the drought according the variation of precipitation threshold. The dry event is the basic phenomenon.

The objective of this study is to use the daily rainfall data to represent and analyze the dry spell phenomenon regarding the regional frequency of extreme droughts in the studied region. Examining the spatial variations of extreme dry spell and estimate the potential risk of the region which will be more prone to prolonged dry spells is also undertaken. As supplementary objective, the evaluation of different dry spells behavior with five distingue thresholds value. This can be considered as an upgrade of the one proposed by Sirangelo et al. (2015) and Sirangelo et al., (2019) for the investigation of dry spells defined as the number of consecutive days without precipitation.

Data

The daily precipitation data used in this study were taken from rain gauges in Ichkeul lake basin northern Tunisia (Fig. 1) over the observation period. The climate is semi-arid to sub-humid. The average annual rainfall recorded is 450 to 626 mm. On the observed period, the coefficient of variation of the annual precipitation is 0.25. According the measurements in situ (Ghézala Dam), the mean annual evapotranspiration (ETP) is 1360 mm the average daily evapotranspiration is 3.6 mm day^{-1} .

Six major water resources of the region, with long term annual average flow rates of $134 \text{ m}^3 \text{ s}^{-1}$ to $550 \text{ m}^3 \text{ s}^{-1}$, have their outlets at Ichkeul lake. Fig. 1 depicts these major reservoirs operated for irrigation, flood control and domestic water supply purposes (Table 1). Agriculture is among the major economic sectors in the region where field crops

and livestock dominate. Also, a significant amount of watermelon and melon across the region are produced. Droughts can cause substantial crop failures in the region.

Table 1 Major Dam reservoirs within the region.

Name	Reservoir area (km ²)	Initial reservoir volume (hm ³)	Purpose	Irrigation land area (ha)
Tine	5.89	34	flood control, irrigation, domestic water supply	-
Joumine	6.60	129.9	flood control, irrigation, domestic water supply	1500
Ghézala	1.22	10.73	Irrigation	1100
Sejenane	7.90	137.5	Irrigation, domestic water supply	3402
Melah	3.03	48	Irrigation, domestic water supply	200
Douimis	3.15	45	Irrigation, domestic water supply	500

In this region, records of drought, based on precipitation, recorded in 1987. During this year, Ghézala Dam received only 408.6 mm of precipitation, or 60% of normal. The lowest recorded value is in 1968 (Fig. 2). The most severe droughts in Ichkeul Lake basin measured by lowest precipitation at Ghézala Dam occurred in 2001, 1993, and 1987.

Method

3.1. Homogeneity rainfall series

Homogeneity is an important issue to detect the variability of the data. In general, when the data is homogeneous, it means that the measurements of the data are taken at a time with the same instruments and environments. However, it is a hard task when dealing with rainfall data because it is always caused by changes in measurement techniques and observational procedures, environment characteristics and structures, and location of stations (Ho Ming and Yusof, 2012).

Pettit's test, Buishand test, Hubert test and Lee and Heghinian test were applied to study homogeneity on an annual time scale. The Khronostat software was used to perform these tests.

The change point detection test is the analysis of variance for data distribution, i.e., the shift in the mean of the variable in the time series. These methods assume a null hypothesis that there is no change in the variance of the series studied (Bougara et al., 2020).

3.2 Definition and concept of drought

Dry events consist of a series of dry days framed by rainfall events. The wet season is defined as a succession of rainfall events and dry events. Rainfall event themselves is defined as an uninterrupted series of rainy days including at least one day having received precipitation above a predetermined threshold value (Fig. 3). Here the 3.6 mm d⁻¹ has been selected such as it corresponds approximately to the expected daily evapotranspiration rate, thus marking the lowest physical limit for considering rainfall that may produce utilizable surface water resources

during the rainy season. A rainfall event is characterized by its duration, symbolizing the number of subsequent rainy days, and the total accumulated rainfall depth (see Fig. 3).

According to this definition, the dry event is therefore the time between the end of a rainfall event and the start of the succeeding rainfall event (in Fig. 3), defined by its duration.

3.3 Drought severity

According to Usman and Reason (2004), crops are more likely to do well with uniformly spread 'light' rains compared to a few 'heavy' rainfalls events interrupted by dry periods. So, the interruption of precipitation by dry spells in relation to the vegetative cycle of crops rather than in relation to the total seasonal rainfall is fundamental for the development of crops and the guarantee of their production (Gbangou et al., 2020). Since the alternating wet/dry spell method (variable time step) was used to study the dry events, and in order to consider the magnitude of droughts, and as then drought indices such as SPI, cannot used, a classification of the dry event duration with the accumulated rainfall depth was tested. The method refers to the cropping cycles of rain-fed crops (wheat, barley, and oats) among the study area. Assuming negligible soil water reserves at harvest time, the occurrence of the dry event, lasting longer than 20 days and between 10 and 20 days, will have a severe and moderate effect on a rainfed crop in the region, respectively.

Accordingly, the "drought range" of the duration indicates severe drought at dry event duration (DED) > 20 d, and moderate drought at 10 d < DED ≤ 20 d. Near-normal conditions are indicated by 1 d ≤ DED ≤ 10 d.

3.4 Return period

The statistical return period for Ichkeul lake basin was calculated using the method proposed by Kim *et al.* (2003). If variables are assumed to be distributed identically and independently (Chow et al. 1988), the return period of an event in any observation is the inverse of its exceedance probability:

$$T = \frac{1}{P(X > x_T)} = \frac{1}{1 - P(X \leq x_T)} \quad (1)$$

Where x_T is the scale of the event with return period T .

Previous work in Ichkeul Lake basin was showed that the GEV distribution was the most appropriate distribution when being fitted to the maximum dry event duration (Mathlouthi and Lebdi, 2021). The probability distribution function (PDF) is given by:

$$f(x) = \frac{1}{\alpha} \left[1 - \frac{k}{\alpha} (x - u) \right]^{\frac{1}{k} - 1} \exp \left\{ - \left[1 - \frac{k}{\alpha} (x - u) \right]^{\frac{1}{k}} \right\} \quad (2)$$

Where u is the location parameter, k is the shape parameter, and α is the scale parameter.

The univariate return period of a drought can be estimated by the univariate cumulative density function (CDF). Thus, the drought duration, given the return period, can be calculated from:

$$X_T = u + \frac{\alpha}{k} \left\{ 1 - \left[-\ln \left(1 - \frac{1}{T} \right) \right]^k \right\} \quad (3)$$

Where in this context, this statistic X_T is the drought of a return period of T . It is defined as the value whose probability of being exceeded is $1/T$, where T is a given time interval.

3.5 Effect of threshold value

The effect of the threshold value on the frequency and spatiotemporal distribution of wet/dry event and extreme dry events was studied according several thresholds value of precipitation, namely 1, 3, 3.6, 4 and 5 mm d⁻¹.

Results

4.1. Homogeneity tests results

Annual mean of each rain gauge is tested by the homogeneity tests (Pettitt, Hubert, Buishand, Leeand Heghinian) at $p = 0.01$ and 0.05 levels of statistical significance. Table 2 shows the results of the homogeneity tests for annual mean in all stations. The results showed that the Lee and Heghinian test rejected the null hypothesis (no break in time series) for all the stations and indicating the break point corresponding to 1968 for Ghézala Dam, O. El Gauss and Sidi Abdelbasset; 2001 for Wadi Joumine Antra and Cooperative Bakhrya, 1969 for Sidi Salem and 1999 for Fretissa. The others tests (Pettitt, Hubert and Buishand) did not detect any change for all rain gauges.

Thus, we can consider that these annual time series are homogeneous, however we will not retain O. el Gauss rain gauge since we only have eleven years of measurements and is no longer functional. Observations at this station ended in 1975. Similarly, the Cooperative Bakhrya series is discarded since it presents several data gaps that limited the assessment of drought during the periods from 1970 to 1974, 1975 to 1977, 1978, 1980, 1983 and 1997 to 2001. Furthermore, rain gauge measurements have been stopped since 2004.

Table 2
Results of the homogeneity test on annual rainfall.

Test/Rain gauge	Investigative Work	Ghézala Dam	O. el Gauss	Wadi J. Antra	Sidi Salem	Coopérative Bakhraya	Fretissa	Sidi Abdelbasset
Pettitt	Conclusion on H0	A	A	A	A	A	A	A
	Break date	-	-	-	-	-	-	-
Hubert	Conclusion on H0	A	A	A	A	A	A	A
	Break date	-	-	-	-	-	-	-
Buishand	Conclusion on H0	A	A	A	A	A	A	A
	Break date	-	-	-	-	-	-	-
Lee and Heghinian	Break probability	0.0777	0.2414	0.1880	0.0649	0.2807	0.1036	0.1228
	Conclusion on H0	R	R	R	R	R	R	R
	Break date	1968	1968	2001	1969	2001	1999	1968

A: accepted null hypothesis. R: rejected null hypothesis. * at $p = 0.05$ significant level, ** at $p = 0.01$ significant level.

4.2. Spatiotemporal characteristics of droughts

4.1.1 Rainfall depth per rainfall event

In the following analysis the negligible precipitation threshold was set at 3.6 mm per day. The descriptive statistics computed are maximum, mean and standard deviation of the rainfall depth per event for each rain gauge. Table 3 summarizes the main statistics found at the investigated rain gauges.

Table 3
Main statistics of the rainfall depth per event in Ichkeul lake basin.

Rain gauge	Ghézala-dam	O. J. Jebel Antra	Sidi Salem	Frétissa	Sidi Abd el Basset
Max value (mm)	182.8	199.6	180.5	188.5	149
Min value (mm)	4	4	4.2	4	4
Mean of rainfall depth/event (mm)	27.9	24.8	26.3	24.8	19.1
SD of rainfall depth/event (mm)	27.43	29.75	25.88	23.79	18.17
Coefficient Variation	0.983	1.199	0.984	0.959	0.951
R ² between rainfall event duration and rainfall depth/event	0.45	0.44	0.49	0.44	0.37
Legend: Max, maximum; SD, standard deviation; R ² : coefficient of determination.					

From this table, the mean for all the rain gauges lies between 19.1 mm per rainfall event (Sidi Abd el Basset) and 27.9 mm per rainfall event (Ghézala-dam).

The standard deviation for all the rain gauges is ranged from 18.17 mm per rainfall event to 29.75 mm per rainfall event. O. J. Jebel Antra records the highest standard deviation (29.75 mm) which indicates the large variation in the rainfall depth per event while Sidi Abd el Basset accuses the lowest standard deviation (18.17 mm) which implies the small variation in the rainfall depth per event. In addition, it is clear that the standard deviation for each station is always closer to the mean. Thus, high standard deviation indicates data are more spread out or above the mean.

The coefficient of variations for the rain gauges will represent the irregularity of the rainfall depth per event between stations. O. J. Jebel Antra displays the highest value of coefficient of variation, which is 1.199 while Sidi Abd el Basset has the smallest value of coefficient of variation, which is 0.951.

The maximum rainfall depth per rainfall event is ranged between 149 mm and 199.6 mm where O. J. Jebel Antra receives the highest maximum rainfall amount of 199.6 mm per rainfall event followed by Frétissa with the maximum rainfall depth of 188.5 mm per rainfall event. On the other hand, Sidi Abd el Basset acquires the lowest maximum rainfall depth per rainfall event which is 149 mm.

In order to investigate the interrelationship between the rainfall event duration and rainfall depth per event, regression analyses have been conducted. An average relationship is found between event duration and rainfall depth per event. In fact, the relationship between duration and rainfall depth per event should be strong; however, the results contradict this assumption (Fig. 4). This can be corroborated by the fact that the coefficient of determination (R^2) provides some useful insights regarding the regression model, but it does not disclose information about the causation relationship between the independent and dependent variables. Therefore, one should analyze the coefficient of determination together with other variables in a statistical model.

The coefficient of determination shows only association. As with linear regression, it is impossible to use R^2 to determine whether one variable causes the other. In addition, the coefficient of determination shows only the magnitude of the association, not whether that association is statistically significant.

Since regression analysis indicates the existence of a relationship between rainfall depth and duration, it is necessary to distinguish between the pdf's of the rainfall depth for different value of event duration. This is done by means of estimating conditional pdf's. The rainfall depths $H_{n,m}$ recorded during the events are grouped into class.

For events lasting at least 5 days, the statistical fitting showed that the gamma (3P) distribution was found to be superior to Log-Pearson 3 distribution when used to fit the depth per rainfall event duration (Fig. 5). The fitting results are obtained using Hyfran 1.1 software. The hypothesis H_0 (The sample comes from a generalized Gamma distribution) is accepted at the 5% significance level. The gamma (3P) distribution has successfully simulated daily precipitation. The gamma distribution is a popular choice, regardless of the observation time scale over which data are aggregated (Hanson et al., 2018). It has been used to model daily rain rates (Cho et al., 2004), as well as monthly and seasonal precipitation anomalies (Wilks and Eggleston, 1992). It adequately models the variation of precipitation amounts in wet periods with a scale parameter proportional to the number of days and a shape parameter independent of the length of the observation scale (Pavlides et al., 2021).

4.2.2 Dry event duration distribution

Statistical analysis allows for a quantitative investigation of relations between hydrological drought duration and deficit. Figure 6 shows the correlation structure between average duration and deficit of droughts in rainfall depth. Figure 6 indicates a moderate positive correlation. These correlations are based on Pearson correlation. The figure based on Spearman correlation coefficients to test for non-linearity showed a similar pattern. This indicates that we can assume that, in our case, linear models are not also suited to represent monotonic relationships, even if they are not imperfectly linear.

4.2.3 Severity of drought

The calculated drought range for each rain gauge was used to organize the frequency of droughts on the basis of severity and duration (Table 4). Fretissa indicated 569 droughts among which 406 were Near-normal and 109 were moderate; however, 54 severe droughts were found. The groups W. J. Antra–S. Salem had 984, 569, and 1078 droughts, respectively. Most of the droughts were Near-normal and these groups had severe droughts. In terms of duration, short-term droughts lasting less than 15 days represented 80% of the droughts in all rain gauges, whereas long-term droughts lasting more than 30 days composed only 4% of the droughts during the entire period. When the 5 rain gauges were both considered (Table 5), 8.5% of droughts were severe with an average occurrence rate of 68.6 per station. Overall, the average showed that any station in Ichkeul basin had droughts occurring approximately 21.55 times per year.

There is a high frequency of short-term droughts in Ichkeul basin because it is mostly in a sub-humid climate, as shown by the dry event distribution (Fig. 7); however, droughts often can last for a long period.

Table 4
Number of droughts by severity and duration.

		Fretissa	OJJ Antra	S. Abasset	S. Salem	Ghézala Dam
	Total No. of droughts	569	984	569	1078	895
Severity	Near-normal	406	757	394	838	700
	Moderate	109	154	115	155	124
	Severe	54	73	60	85	71
Duration	$D \geq 30$ days	23	26	24	34	26
	$15 \leq D < 30$ days	93	121	94	118	97
	$D < 15$ days	453	837	451	926	772

Table 5
Frequency and percentage of drought occurrence and severity over all stations. Also shown are the frequency of occurrence per one station and the annual mean drought occurrence frequency per one station.

Drought severity	No.	%	One station	1 yr
Near-normal	3095	75.5	619	16.29
Moderate	657	16	131.4	3.5
Severe	343	8.5	68.6	1.81
Total	4095	100	819	21.55

4.2. Return period

The return periods for droughts in Ichkeul lake basin, are shown in Fig. 8. The drought that occurred in 1 September 1987 has a 127-yr return period and was found to be the most extreme drought. This drought began in Sidi Abdelbasset. Subsequent droughts during 1 September 2001 (duration of 55 day) and 21 November 2006 (duration of 64 day) had return periods of 45 and 124 yr, respectively, and were found to be even more extreme than the drought in 25 April 2006 (duration of 44 day).

4.3. Effect of rainfall threshold value

The results analysis of the influence of rainfall threshold value (1, 3, 3.6, 4 and 5 mm day⁻¹), based on Ghézala Dam rain gauge observations, are shown in Table 6.

Table 6

Comparison of the variability of the number of droughts/season and that of the maximum seasonal event using different rainfall thresholds, Ghézala Dam rain gauge.

Rainfall threshold value (mm)	No. of droughts	Maximum no. of droughts	Mean of no. of droughts/rainy season	Standard deviation of no. of droughts/rainy season	Max duration (day)	Mean of the Max duration (day)	Standard deviation (day)
1	1199	45	32.59	4.75	42	24.72	6.90
3	902	33	23.74	4.57	45	26.68	7.64
3.6	816	31	21.5	4.67	57	30.2	9.68
4	816	30	21.47	4.52	56	30.24	9.55
5	743	28	19.55	4.44	56	32.79	9.50

The maximum number of observed seasonal dry events is inversely proportional to the precipitation threshold value. The mean follows this ascertainment also. Therefore, the maximum seasonal dry event duration increases as well as its average. The standard deviation does not vary much for either the number of events per rainy season or the duration of the maximum dry event (Table 6).

Furthermore, it can be concluded that the average duration of dry and rainfall events increases according to the selected threshold value. Standard deviations also fluctuate in the same direction, as do the observed maximum dry event durations. Longest observed in rainfall event duration do not differ significantly according to the rainfall threshold and displays 13 days. The coefficients of variation are practically stable (Tables 7 and 8). Unlike dry events, the variation is more pronounced (ie, 0.92 to 1.08), explaining that there is a significant dispersion of dry events which increases slightly depending on the threshold level.

Table 7

General drought characteristics using different rainfall thresholds, Ghézala-dam rain gauge.

Rainfall threshold value (mm)	Observation period	No. of data <i>n</i>	Longest observed in duration days	Arithmetic mean (day)	Standard deviation	Coefficient of variation
1	1968-2006	1199	42	6.12	5.64	0.92
3	1968-2006	902	45	6.57	6.89	1.05
3.6	1968-2006	816	57	7.3	7.91	1.08
4	1968-2006	816	56	7.36	7.97	1.08
5	1968-2006	743	56	8.25	8.92	1.08

Table 8
General rainfall event characteristics using variable threshold, Ghézala-dam rain gauge.

Rainfall threshold value (mm)	Observation period	No. of data n	Longest observed in duration days	Arithmetic mean (day)	Standard deviation	Coefficient of variation
1	1968-2006	1237	13	2.95	2.36	0.79
3	1968-2006	940	13	2.76	1.92	0.69
3.6	1968-2006	854	13	2.8	1.87	0.67
4	1968-2006	854	13	2.83	1.94	0.68
5	1968-2006	781	13	2.95	2.05	0.69

Discussion And Conclusions

This paper examines the frequency and severity of drought in Ichkeul lake basin using variable threshold value of precipitation from daily rainfall observations of rain gauges. Extreme values correspond to long spells of consecutive days with negligible precipitation that generate episodes of climatic drought. To date, the frequency analysis of these extreme values has been carried out using annual maximum series (AMS) adjusted to the Gumbel distribution (Perzyna 1994; Lana and Burgueño 1998). In this paper, we have used an AMS adjusted to the GEV distribution.

This analysis uses the hypothesis of the independence of successive events, and gives an alternative method to examine drought phenomena. It makes it possible to plan water resources on a different basis from that of observations made at regular time intervals.

In the Ichkeul Lake Basin, the most severe drought in a cinquantennal occurred during 1987 as the Ghézala Dam. Approximately 19% of the droughts were classified as short-term droughts that last 1 day, and long-term droughts last for more than 40 days. The maximum observation varies between 44 and 81 days. This short-term drought is attributed to the core of the rainy season. We also found that the long-term droughts were caused by a rainfall deficit during the beginning and end of rainy season. The 1990 and the 1987 were found to be the wettest and the driest year, respectively.

From the drought return period analysis, the 1 September 1987 drought was found to be the most extreme with a 127-yr return period. Subsequent droughts during 1 September 2001 (duration of 55 day) and 21 November 2006 (duration of 64 day) had return periods of 45 and 124 yr, respectively, and were found to be even more extreme than the drought in 25 April 2006 (duration of 44 day).

To evaluate the 1959–2010 droughts over a long term given a variable hydro-climate, different predetermined threshold values were selected. The procedure adopted allowed us to study the influence of climatic variation and the threshold value of precipitation in identifying dry events. The maximum number of seasonal dry events observed is inversely proportional to the rainfall threshold value. Longest observed in rainfall event duration does not vary with the rainfall threshold and displays 13 days. The coefficients of variation are practically stable. Dry events variation is more pronounced (ie, 0.92 to 1.08), a significant dispersion of dry events which increases slightly with the importance of the threshold.

Drought studies in Ichkeul lake basin have rarely been conducted in the past (Mathlouthi and Lebdi, 2008; 2020, 2021) Therefore, this study provides the foundation data for reducing Ichkeul's vulnerability to future droughts, and investigating the causes of droughts, introducing measures to deal with future droughts.

Declarations

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Conflicts of interest/Competing interests: The authors declare that they have no conflict of interest.

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability statement: The data are printed in paper documents stored (archived) in office of the General Directorate of Water Resources and the Division of Dam Operation of Extreme North and Ichkeul of the Ministry of Agriculture of Tunisia, (<http://www.agriculture.tn/>). These data are the property of this organization, and are available in situ.

Code availability: No software application or custom code.

Author Contributions: Discussed the results and contributed to the final version of the manuscript: **FL**; Developed and performed the design and implementation of the research, the computations, the analysis of the data and the results and the writing of the manuscript: **MM**.

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Figures

Figure 1

Localisation of the study zone.

Figure 2

Lowest 12-Month Precipitation (Totals taken at Ghézala Dam, 1968–2018).

Figure 3

Definition of threshold and drought characteristics.

Figure 4

Coefficient of determination between the rainfall event duration and the rainfall depth per event in Ichkeul lake basin.

Figure 5

Distribution of the rainfall depth per event (³ five-day long rainfall events) in Ichkeul lake basin.

Figure 6

Correlations between average duration and drought severity indices.

Figure 7

Frequency of the dry event duration at rain gauges.

Figure 8

Return periods, durations and observation dates of historical droughts. Long-duration droughts have a longer return period.