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Critical Drought Characteristics: A New Concept Based on Dynamic Time Period Scenarios

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Abstract: In research on monitoring drought events, analysis is often carried out using a single period as a reference. On the other hand, changing this default period in drought calculations causes the drought index values obtained from research to differ. As a gap in the literature, this point highlights the necessity of investigating the effect of various time periods on drought characteristics. It underscores the need to propose a new concept and methodology to address this gap effectively. This research aims to analyze critical drought characteristics through dynamic time period scenarios. For the first time in the literature, drought indices and potential and critical characteristics were analyzed for various (dynamic) time periods. Drought analysis was carried out for 13 time period scenarios with 10-year intervals from a meteorological station in Durham (1872–2021) by changing the initial time condition using the Standardized Precipitation Index (SPI). The results showed that in addition to the similarities, there are significant differences between drought characteristics. For example, in some time period scenarios, a drought event was recorded during a specific period, while in other scenarios (S5–S7, S10–S13), no drought was detected during the same period, like in SPI 1. Additionally, for SPI 12, the drought duration varied significantly, lasting between 20 and 29 months, and for SPI 6, the drought duration varied between 3 and 13 months. Regarding the intensity, SPI 1 ranged between −0.89 and −1.33, indicating a 33% difference, and the SPI 3 intensity ranged between −1.08 and −1.91, indicating a 50% increase in intensity. This research significantly contributes to the field by providing a novel approach using dynamic time period scenarios to determine critical drought characteristics, offering valuable insights for water resource management, drought mitigation planning, and design purposes.

Keywords: potential drought characteristics; critical drought; drought evaluation; standardized precipitation index (SPI); dynamic

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1. Introduction

Precipitation plays a crucial role in the hydrological cycle, impacting agricultural productivity, regional climate, and broader interactions within atmospheric and terrestrial systems [1,2]. It serves as a key indicator for evaluating the effects of climate change, directly affecting variables like soil moisture levels, streamflow, and groundwater replenishment [3–6]. Global climate changes, which are among the most significant environmental challenges, are resulting in the heightened frequency and severity of extreme weather events, notably droughts [7,8]. Recent research, such as that carried out by Gu et al. [9], anticipates a substantial increase in both the intensity and socioeconomic vulnerability of worldwide droughts under climates warmer by 1.5 and 2 °C, confirming the increasing imperative of understanding and mitigating drought effects. Droughts, observed in diverse climatic conditions, have extensive consequences in many sectors, such as agriculture, energy, water resources, and ecosystems [10,11]. A recent report from the United Nations on World Water Development [12] indicates that approximately four billion people worldwide experience water scarcity for at least one month annually. According to the World Economic Forum [13], economic losses from climate-related disasters, including droughts, amounted to nearly $1.5 trillion in the decade leading up to 2019. Also, Africa's drought-related economic losses in the past 50 years have been about 70 billion USD [14]. Considered among the most catastrophic natural events globally according to their widespread geographical impact [15], understanding the complex temporal patterns of droughts is vital for proficient water resource management and the formulation of strategies to mitigate their effects.

Various standardized drought indices have been employed to evaluate and assess drought. Each index relies on either a singular or multiple hydro-meteorological parameters determining a specific kind of drought, including the Standardized Precipitation Index (SPI) [16], the Standardized Precipitation Evapotranspiration Index (SPEI) [17], the Palmer Drought Severity Index (PDSI) [18], and the Reclamation Drought Index (RDI) [19]. Despite the challenge of determining a universal drought index, the SPI has wide acceptance because of its simplicity and its sole dependence on precipitation data, providing a more straightforward index compared to more complicated indices, and this simplicity makes the SPI particularly well suited to regions with restricted data availability [20]. Its efficiency across diverse time scales has been demonstrated in numerous studies, confirming the SPI's vital role in drought evaluation, particularly under the urgent considerations associated with global climate change [21–23].

After a thorough evaluation of the literature and the calculation and use of drought indices, it is noticed that these indices are generally used and performed for a single time period, determined by taking the available time period of the data as a reference [24–26]. Abu Arra and Şişman [24] analyzed the difference between the used time period and an acceptable time period using different statical metrics and indicated that, for meteorological droughts, a 10-year period and, for hydrological droughts, a 20-year period can be used with high confidence to yield acceptable results for the used time period. It is seen that these time periods vary in research conducted in the same or proximate study areas. For example, Gumus [27] evaluated drought in Türkiye using the SPI method for the period between 1970 and 2021, while Dabanlı et al. [28] evaluated drought in Türkiye using SPI for the period between 1931 and 2010, leading to different results. However, the research topics, study regions, and used methodologies overlap significantly. It is noticeable that this difference in basic assumptions, which is often ignored in analysis, calculations, and evaluations, brings incomplete and erroneous results. Therefore, the index calculations in drought analysis using a single time period selected in the classical way are insufficient for monitoring and evaluating potential and critical drought events that have been and/or may be seen. In order to solve this problem, instead of classical approaches in drought calculations, there is a need to define systematic, innovative concepts and frameworks in which datasets from different periods can be evaluated. Within the framework of the new concept(s) to be developed, potential drought characteristics should be determined according to dynamic time period scenarios, and critical drought characteristics should be determined according to these scenarios.

The aim of this research is to (1) analyze the effect of changing the initial time condition on the drought characteristics, (2) propose a new framework and concepts to identify critical drought characteristics by determining potential drought characteristics based on dynamic time period scenarios instead of the traditional method, and (3) compare the resulting drought characteristics based on different time period scenarios. The calculation of drought characteristics is based on individual drought events. Therefore, the characteristics must be determined for each specific drought event. For this purpose, in this study, drought analysis was carried out with the SPI method for different dynamic time period datasets, prepared by taking precipitation data from the Durham meteorological station

(1872–2021) as a reference and application; the drought characteristics were calculated for each period using SPI theory/definitions; and critical drought characteristics were determined for the region in the relevant years.

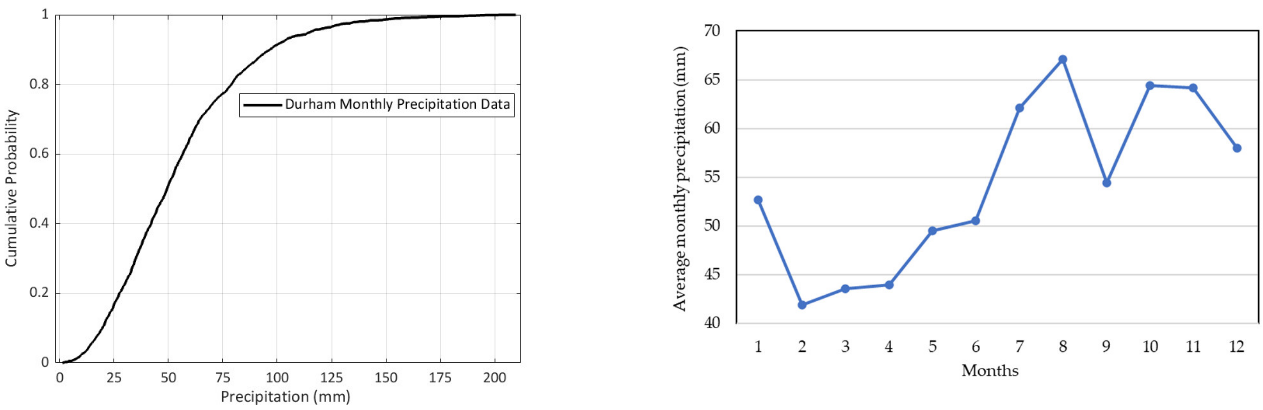
2. Materials and Methods

2.1. Application

The specified methods and determination of the critical drought characteristics using the SPI and dynamic time period scenarios are applied to Durham meteorological station. Durham City is situated in the northeastern part of the United Kingdom. It experiences a hybrid temperate maritime climate characterized by relatively mild summers and cool winters when viewed globally. Typically, July stands out as the warmest month during summer, while January is recognized as the coldest month in winter. The average temperature fluctuates between 5.2 °C (in winter) and 12.5 °C (in summer), with an annual average precipitation of 643 mm (Table 1). The meteorological data for total monthly precipitation (P) span from 1872 to 2021, covering 150 years and originating from the Durham University meteorological station, and have previously been obtained [29]. Notably, the Durham Observatory's weather records are the third longest continuous climate series in the United Kingdom. This dataset was selected because it is a continuous series with a long time period (150 years), it includes high-quality data, and more scenarios can be developed to answer and achieve the purposes of this research in the best way possible. Figure 1 shows the cumulative probability of the original monthly precipitation data and the average monthly time series of the precipitation dataset. Table 1 summarizes the main climatic information of the Durham station, including minimum, maximum, and average monthly precipitation, standard deviation and skewness, and the average and standard deviation of the temperature.

Table 1. Climatic information of the Durham station.

Station's Name	Lat. (N)	Lon. (W)	Average Monthly Precipitation (P)—mm	Standard Deviation (mm)	Min. Monthly Precipitation (mm)	Max. Monthly Precipitation (mm)	Skewness
Durham Station	54.77	1.59	54.37	31.74	1.30	209.70	1.14
			Monthly Temperature (T)—°C		Standard Deviation °C		
			8.6		4.46		



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

Figure 1. (**a**) Cumulative probability of monthly precipitation data for Durham station (1872–2021), (**b**) average monthly time series of the precipitation dataset between 1872 and 2021.

2.2. Homogeneity Tests

Variations within homogeneous data series are influenced by weather and climate changes. Thus, ensuring the homogeneity of time series data is essential for accurate climate and drought analysis. Using non-homogeneous data in climate research can lead to biased results. Therefore, this study will first test the homogeneity of the data before conducting drought analysis. To assess homogeneity, several absolute homogeneity tests are commonly used, including Pettitt [30], Buishand [31], and the Standard Normal Homogeneity Test (SNHT) proposed by Wijngaard et al. [32]. Homogeneity is evaluated based on the null hypothesis (H0), which assumes no changes within the data. Classifications are then assigned based on the number of tests that accept or reject the null hypothesis as follows:

1. Set 1 is labeled "Homogeneous" if all three methods accept the null hypothesis (H0).
2. Set 2 is labeled "Doubtful" if two of the homogeneity tests accept the null hypothesis (H0).
3. Set 3 is labeled "Suspect" if only one or none of the homogeneity tests accept the null hypothesis (H0).

2.3. The Standardized Precipitation Index (SPI)

The SPI calculates the drought index at several time scales, such as 1-month, 3-month, 6-month, and 12-month, depending on the monthly precipitation datasets. The selection of time scales plays a crucial role in determining different types of droughts. Short time scales, such as the commonly used 1-month and 3-month SPIs, indicate meteorological droughts. These shorter durations capture variations in weather patterns and highlight deviations from normal precipitation levels over a relatively brief period. On the other hand, longer time scales, spanning multiple months or even years, provide insights into hydrological droughts [16,20]. As for the method, the original monthly precipitation datasets are fitted to a suitable probability density function. The Gamma PDF has been determined as the best PDF for SPI calculations in most research, as stated by Wang et al. [33]. The selection process for a suitable PDF is carried out using goodness-of-fit tests for the original datasets (precipitation for SPI), including Chi-Square and Kolmogorov–Smirnov [34]. The probabilities are derived through computation of cumulative distribution functions applied to monthly precipitation datasets. Subsequently, these probabilities undergo a probabilistic standardization process, transforming them into a standard index value characterized by a mean of 0 and a standard deviation of 1, as shown in Figure 2. A critical point that must be mentioned is that the probabilistic standardization process differs from statistical standardization. The difference between them in SPI calculation has been studied in detail by Şen and Şişman [25].

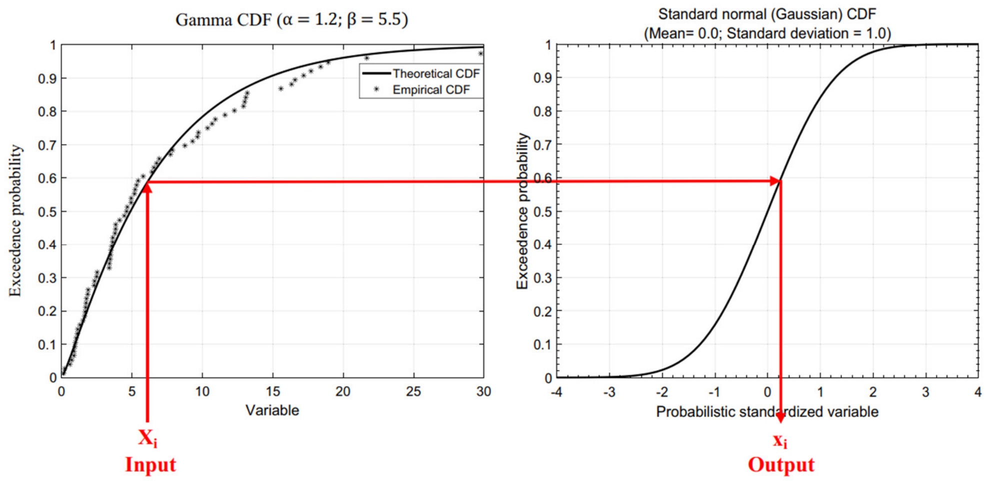


Figure 2. Probabilistic standardization process [25].

2.4. Drought Characteristics

The initial phase in drought analysis and evaluation involves computing the drought index. Subsequently, three key characteristics, namely duration (D), severity (S), and intensity (I), are derived based on this index. These drought characteristics are calculated using the drought index and based on the drought definition. The run theory introduced by Yavjevich [35] and the SPI theory developed by Mckee et al. [16] are two widely accepted definitions for drought characteristics. Yavjevich [35] states that a drought event commences when the drought index falls below zero and ends when it rises back above zero. Secondly, in identification, Mckee et al. [16] defined drought events (start) using -1 instead of 0 thresholds. A notable difference exists in the computation of drought characteristics between run theory and SPI theory. The run theory tends to yield more extreme duration values, while the SPI theory results in more extreme intensity values, as highlighted in [36]. This research uses SPI theory because the higher extreme intensity values are used to calculate the drought characteristics.

The main characteristic and parameter used in this research is drought duration (D), and based on the SPI theory, D is defined as the total number of months when the drought index is less than -1 until it returns to a positive value. The second parameter is the summation of the drought index over the drought duration (sum), and the biggest value of the drought indices is called the drought peak. Additionally, dividing (sum) by the drought duration gives the drought intensity. This research also calculates the average and median values for drought intensity for the first time to explore and compare the variations between different time period scenarios. Figure 3 shows the drought index values, drought duration for each drought theory, and drought peak values.

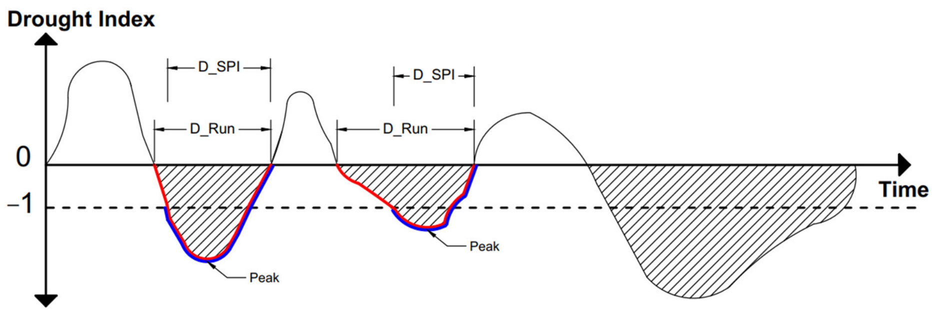


Figure 3. Drought duration based on SPI theory (D_SPI, blue line) and run theory (D_Run, red line) and drought index peak value (Peak) relying on drought index values [36].

The main drought characteristics and statistics used in this research are summarized as follows:

1. Drought duration (D) is defined as follows:

$$D_{SPI}\ \text{theory} = \text{Number of months between } DI1st_{month} < -1 \text{ and } DI_{\text{until any month returns positive.}} \quad (1)$$

2. Drought severity (sum): Summation of drought index values within the drought duration.
3. Drought intensity (I):

$$\text{Drought intensity} = \text{Drought severity/Drought duration} \quad (2)$$

4. Median and peak values for the drought event.

The potential drought characteristics are identified as the drought characteristics associated with each selected time period dataset scenario. It contains the drought duration (D), intensity (I), severity (sum), peak, and median values of DI. Considering and using these characteristics, scenarios will be used for specific hydraulic design purposes, such as dam design and water resource and drought management.

2.5. Dynamic Time Period Scenarios

To identify potential and critical drought characteristics, this research employs a methodological approach involving the generation of dynamic time period scenarios, with variations in the initial time conditions. The range of these time periods may include intervals such as 1, 5, or 10 years, changing based on the longest available time period for each condition, the purpose of the drought characteristics, and the climate of the study area. For each time period scenario, the drought index values and associated characteristics are meticulously calculated. Subsequently, a comparative analysis is conducted for specific drought events, considering their characteristics across different time periods. This comparative assessment aims to discern critical and potential drought characteristics by evaluating how the drought index and its related parameters evolve under diverse temporal conditions. Through this systematic exploration of varying time periods and associated drought characteristics, the research aims to contribute valuable insights into understanding the dynamics and critical factors influencing drought events, aiding in more effective drought management and mitigation strategies. Figure 4 shows the methodological approach in this research.

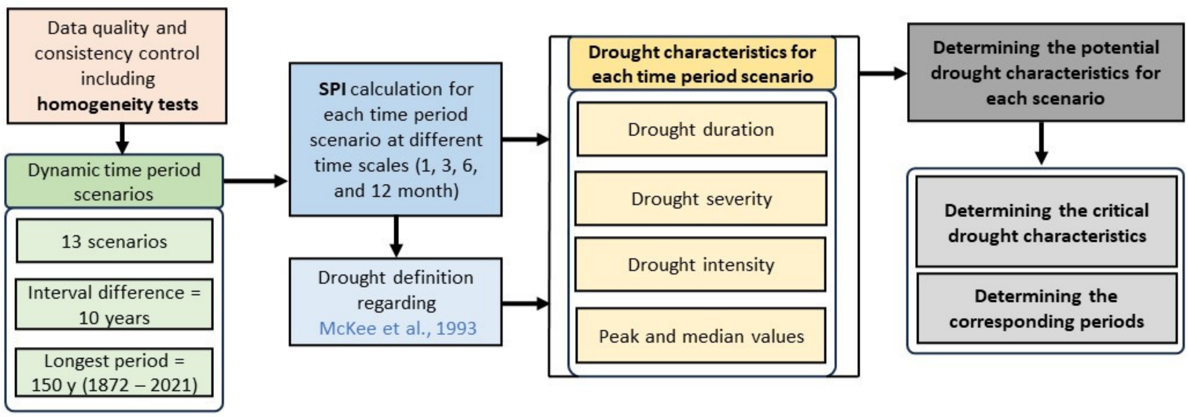


Figure 4. Methodological approach [16].

3. Results

This research study provides a comprehensive and detailed analysis of Durham station (1872–2021). The SPI drought index values and characteristics are calculated using SPI theory. Based on the longest available period (150 years) and the minimum (ideal) period (30 years), this period is divided into 13 time period scenarios, with 10 years as an interval. The 10-year interval reflects the practical use of the SPI in the literature and leads to 13 time period scenarios which can be analyzed and explained. In the analysis of potential drought characteristics across thirteen different time period scenarios, ranging from 30 to 150 years, and according to the framework of the proposed concept, the results demonstrate significant variability in the response of drought characteristics when assessed over different historical spans. The comparison focuses on the common last 30 years for all scenarios, utilizing the SPI to evaluate the drought duration, intensity, severity, median, and peak values during specific drought events. The time period scenarios with the start and end years for each scenario and the duration for each scenario are presented in Table 2. The results are organized into distinct sub-sections for each time scale to simplify and enhance clarity in the Results section.

Table 2. Time period dataset scenarios.

Scenario	Start and End Year	Time Period Duration (Years)
S1	1992–2021	30
S2	1982–2021	40
S3	1972–2021	50
S4	1962–2021	60
S5	1952–2021	70
S6	1942–2021	80
S7	1932–2021	90
S8	1922–2021	100
S9	1912–2021	110
S10	1902–2021	120
S11	1892–2021	130
S12	1882–2021	140
S13	1872–2021	150

3.1. Homogeneity Test Results

The monthly precipitation data from the Durham meteorological station were first subjected to absolute homogeneity tests using the two-stage approach suggested by Wijngaard et al. [32]. Three methods were employed: Pettitt, Buishand, and SNHT. The results were checked for homogeneity regarding a 95% confidence level. Table 3 summarizes the main homogeneity results, including the tests' names, test statistics, and the homogeneity results. As a result of these tests, the precipitation data were found to be homogenous.

Table 3. Homogeneity test results for precipitation data.

Test Name	Test Statistics	*p*-Value	Result	Homogeneity
Pettitt	48,958	0.378	Accept	Set 1: Homogenous
Buishand	47.583	0.629	Accept	
SNHT	6.671	0.328	Accept	

3.2. Drought Characteristics for SPI 1

The results of SPI 1 are interpreted and compared for thirteen different time period scenarios. Two drought events (Drought 1 (September 1996–October 1996) and Drought 2 (March 2011–June 2011)) are selected as examples and representative events, summarized in Table 4. Because SPI 1 is based on a 1-month time scale, the drought duration is generally low, ranging from 0 to 4 months. For the first drought event, increasing the time period above 110 years leads to no drought events (zero values), and the fifth, sixth, and seventh scenarios have no drought events. The duration in scenarios where the drought was recorded ranged consistently from 2 months upward across scenarios S1 through S4, S8, and S9, indicating a significant difference between these scenarios. The peak SPI values showed slight variability, ranging from −1.05 in Scenario S1 (30-year period) to −1 in Scenario S9 (110-year period), indicating a general uniformity in the peak drought experienced across these scenarios. In contrast, scenarios S5 through S13, which encompass longer historical records, did not record this drought event, possibly due to the changes in drought sensitivity over extended periods. The average SPI 1 (intensity) for the first drought event ranges between −0.73 and −0.78, showing a slight difference in intensities. However, the intensity for the second drought event ranges between −0.89 and −1.33, indicating a 33% difference; in this event, the maximum intensity is derived from S12 (140 years).

For Drought 2, a longer duration was observed, with all scenarios that recorded the drought showing durations from 2 to 4 months. The peak SPI values during this event were notably more severe, ranging from −2.41 in Scenario S1 to −2.35 in Scenario S13. This suggests a persistent severity in drought conditions when analyzed over a longer temporal frame. Notably, the severity, as measured by the sum of SPI, illustrated a marked increase in negative values. The median SPI values for drought events across all scenarios remained relatively consistent, underscoring the median as a robust measure of central drought tendency, less influenced by the extremities captured by the peak values. Because the number of drought months is low, the average and median values are relatively equal.

Figure 5 shows the variations in the drought index and characteristics for different time period scenarios (S1, S4, S7, S10, and S13). In Figure 5a, SPI 1 for S1 and S4 is less than −1, indicating the start of the drought event. However, for S7, S10, and S13, the SPI 1 values are more than −1, meaning no drought event has started. Figure 5b depicts the absolute values of peak SPI, intensity (average SPI), and median SPI for the abovementioned scenarios. Notably, the peak SPI values are relatively uniform across the scenarios, suggesting that the most intense phase of the drought is captured similarly regardless of the period. Figure 5c shows the duration of the drought alongside the absolute summation of SPI values, providing a measure of the cumulative severity of the drought across different scenarios. Based on the comprehensive analysis of all scenarios for the first drought event, the critical drought characteristics have been identified as an intensity of −0.78, a duration of 2 months, a peak SPI of −1.05, and a severity of SPI of −1.56.

Table 4. Summary of the drought characteristics for SPI 1 for different 13 time period scenarios.

Drought Characteristics SPI 1											
Years		Drought 1 (September 1996–October 1996)					Drought 2 (March 2011–June 2011)				
Scenario		D	P	S	A	M	D	P	S	A	M
S1—30 Y	1992–2021	2	−1.05	−1.56	−0.78	−0.78	4	−2.41	−3.9	−0.97	−0.71
S2—40 Y	1982–2021	2	−1.02	−1.49	−0.75	−0.75	4	−2.39	−3.77	−0.94	−0.67
S3—50 Y	1972–2021	2	−1.01	−1.48	−0.74	−0.74	3	−2.39	−2.73	−0.91	−0.32
S4—60 Y	1962–2021	2	−1.03	−1.51	−0.76	−0.76	4	−2.43	−3.82	−0.95	−0.68
S5—70 Y	1952–2021	0	-	-	-	-	3	−2.36	−2.67	−0.89	−0.30
S6—80 Y	1942–2021	0	-	-	-	-	3	−2.36	−2.66	−0.89	−0.30
S7—90 Y	1932–2021	0	-	-	-	-	3	−2.37	−2.71	−0.90	−0.32
S8—100 Y	1922–2021	2	−1.01	−1.48	−0.74	−0.74	4	−2.39	−3.74	−0.94	−0.66
S9—110 Y	1912–2021	2	−1	−1.47	−0.73	−0.73	3	−2.38	−2.72	−0.91	−0.32
S10—120 Y	1902–2021	0	-	-	-	-	3	−2.36	−2.67	−0.89	−0.30
S11—130 Y	1892–2021	0	-	-	-	-	2	−2.37	−2.66	−1.33	−1.33
S12—140 Y	1882–2021	0	-	-	-	-	2	−2.35	−2.64	−1.32	−1.32
S13—150 Y	1872–2021	0	-	-	-	-	3	−2.36	−2.66	−0.89	−0.89

D: duration, P: peak SPI, S: sum of SPI, A: average SPI (intensity), M: median SPI.

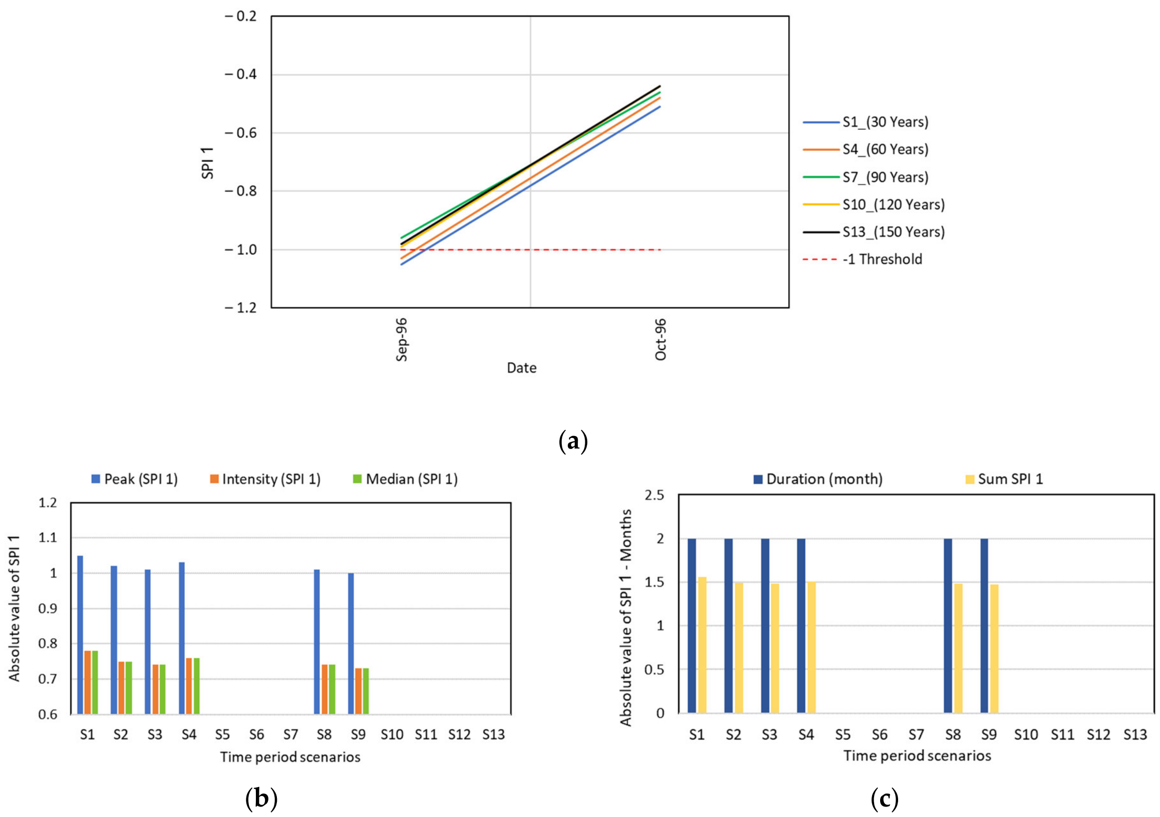


Figure 5. Potential drought characteristics for SPI 1 for the first selected drought event (September 1996–October 1996). (**a**) The difference between selected scenarios based on SPI 1, (**b**) the difference between all time period scenarios using the peak, intensity, and median values, (**c**) the difference between all time period scenarios using drought duration and the absolute summation of SPI 1 values.

Figure 6 presents the analysis of the potential drought characteristics for the second selected drought event (March 2011–June 2011) using the SPI. Figure 6a depicts the SPI values over the drought period for selected scenarios (S1, S4, S7, S10, and S13), highlighting consistent behavior but differentiating in the starting SPI index value. Figure 6b illustrates the absolute values of peak SPI, intensity (average SPI), and median SPI for each scenario. The peak SPI, representing the most severe point in the drought index, shows higher values for shorter time period scenarios (S1, S4) and slightly less severity in longer time frames (S10, S13), indicating that longer records have lesser peak values due to the longer climatic periods in the analysis. Conversely, the intensity and median values offer a clearer view of how the drought persists over its duration, with significant differences (Figure 6c). Based on the comprehensive analysis of all scenarios for the second drought event, the critical drought characteristics have been identified as an intensity of −1.33, a duration of 4 months, a peak SPI of −2.43, and a severity of the SPI of −3.9.

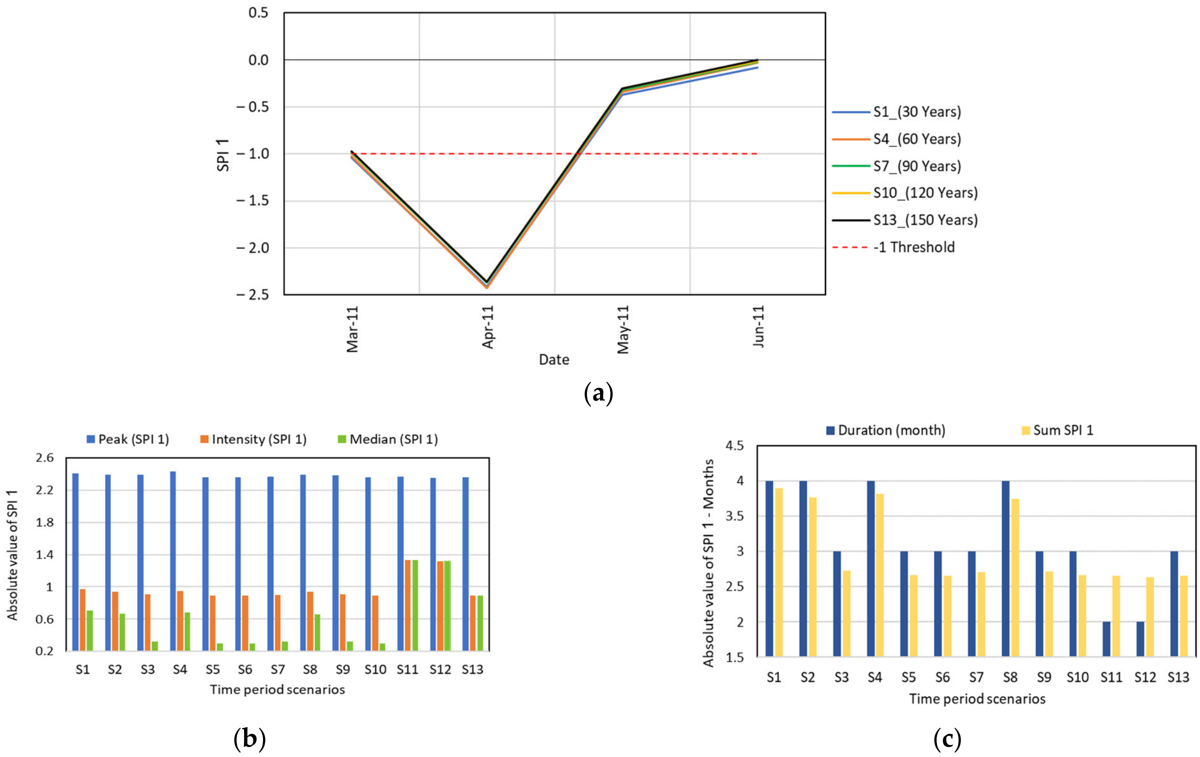


Figure 6. Potential drought characteristics for SPI 1 for the second selected drought event (March 2011–June 2011). (**a**) The difference between selected scenarios based on SPI 1, (**b**) the difference between all time period scenarios using the peak, intensity, and median values, (**c**) the difference between all time period scenarios using drought duration and the absolute summation of SPI 1 values.

3.3. Drought Characteristics for SPI 3

The results of SPI 3 are conducted on and compared for thirteen different time period scenarios. Two drought events (Drought 1 (November 2011–April 2012) and Drought 2 (July 2018–May 2019)) are selected as representative examples and events, summarized in Table 5 and presented in Figures 7 and 8. For Drought 1, the durations of the drought events varied between the scenarios, with longer durations observed in the 30-year, 40-year, and 60-year scenarios (S1, S2, and S4), at 6 months each, while the other scenarios found drought durations of 2 months. The peak SPI 3 values ranged from −2.55 in S1 to −2.42 in S6, indicating severe drought conditions across all scenarios. The sum of SPI values, representing the severity, also showed significant negative values, underscoring the intense nature of this drought event (first drought event). Notably, the absolute values of the median SPI and SPI intensity varied slightly, suggesting a consistent median drought condition across different historical time period scenarios but variable intensities, which were slightly more severe in longer period scenarios. The SPI intensity ranged between −1.08 (S2) and −1.91 (S12), indicating a 50% increase in intensity. Based on these results, the critical drought characteristics have been identified as an intensity of −1.91, a duration of 6 months, a peak SPI of −2.55, and a severity SPI of −6.74.

Table 5. Summary of the drought characteristics for SPI 3 for different 13 time period scenarios.

Drought Characteristics SPI 3											
Years		Drought 1 (November 2011–April 2012)					Drought 2 (July 2018–May 2019)				
Scenario		D	P	S	A	M	D	P	S	A	M
S1—30 Y	1992–2021	6	−2.53	−6.74	−1.12	−1.05	11	−1.60	−8.19	−0.74	−0.82
S2—40 Y	1982–2021	6	−2.51	−6.46	−1.08	−1.01	4	−1.56	−4.57	−1.14	−1.12
S3—50 Y	1972–2021	2	−2.45	−3.82	−1.91	−1.91	4	−1.52	−4.41	−1.1	−1.08

S4—60 Y	1962–2021	6	−2.55	−6.53	−1.09	−1.02	11	−1.58	−7.62	−0.69	−0.77
S5—70 Y	1952–2021	2	−2.45	−3.8	−1.9	−1.9	4	−1.50	−4.35	−1.09	−1.07
S6—80 Y	1942–2021	2	−2.42	−3.75	−1.88	−1.88	4	−1.48	−4.28	−1.07	−1.05
S7—90 Y	1932–2021	2	−2.46	−3.83	−1.92	−1.92	4	−1.52	−4.42	−1.1	−1.08
S8—100 Y	1922–2021	2	−2.47	−3.84	−1.92	−1.92	4	−1.53	−4.44	−1.11	−1.09
S9—110 Y	1912–2021	2	−2.49	−3.88	−1.94	−1.94	4	−1.54	−4.47	−1.12	−1.10
S10—120 Y	1902–2021	2	−2.46	−3.82	−1.91	−1.91	4	−1.51	−4.35	−1.09	−1.07
S11—130 Y	1892–2021	2	−2.46	−3.81	−1.9	−1.9	4	−1.5	−4.31	−1.08	−1.06
S12—140 Y	1882–2021	2	−2.47	−3.83	−1.91	−1.91	4	−1.51	−4.34	−1.08	−1.07
S13—150 Y	1872–2021	2	−2.45	−3.81	−1.9	−1.9	4	−1.5	−4.34	−1.08	−1.06

D: duration, P: peak SPI, S: sum of SPI, A: average SPI (intensity), M: median SPI.

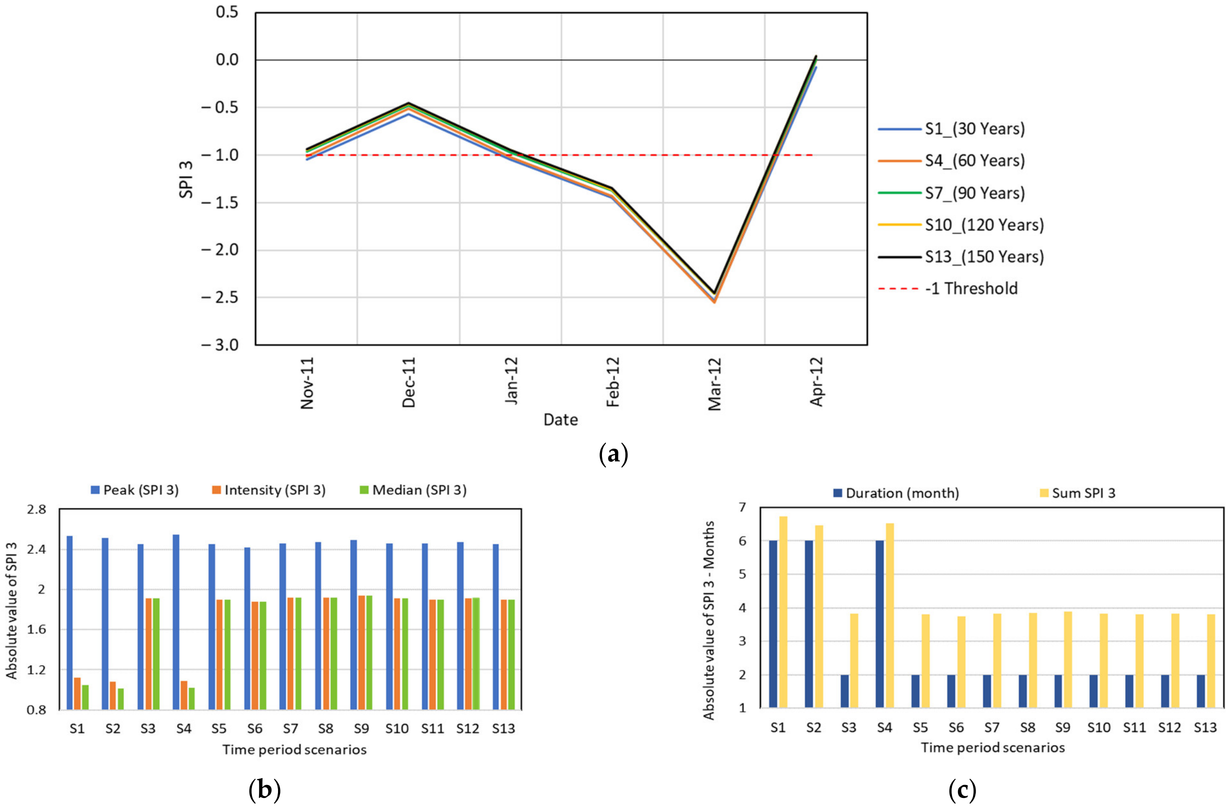


Figure 7. Potential drought characteristics for SPI 3 for the first selected drought event (November 2011–April 2012). (**a**) The difference between selected scenarios based on SPI 3, (**b**) the difference between all time period scenarios using the peak, intensity, and median values, (**c**) the difference between all time period scenarios using drought duration and the absolute summation of SPI 3 values.

Figure 8 presents a detailed analysis of the potential drought characteristics for SPI 3 during the second selected drought event (July 2018–May 2019) across multiple time period scenarios. Figure 8a shows the SPI 3 values for five selected scenarios (30, 60, 90, 120, and 150 years), where S1, S2, and S4 fell below −1 in July 2018, and the other scenarios fell below −1 in February 2019. Figure 8b, a box-and-whisker plot, displays the distribution of SPI values across all scenarios during the drought event, highlighting variability in the central tendency and SPI values. Figure 8c shows each scenario's peak, intensity, and median SPI value, illustrating how these characteristics differ across various historical time period scenarios. Figure 8d compares the duration and severity of the drought across all scenarios, revealing that while the duration of the drought is relatively consistent, the total severity varies, with shorter scenarios tending to accumulate higher negative SPI values, leading to more intense drought conditions. For S1, S2, and S4, the duration is 11 months.

Based on these results, the critical drought characteristics have been identified as an intensity of −1.14, a duration of 11 months, a peak SPI of −1.60, and a severity SPI of −8.19.

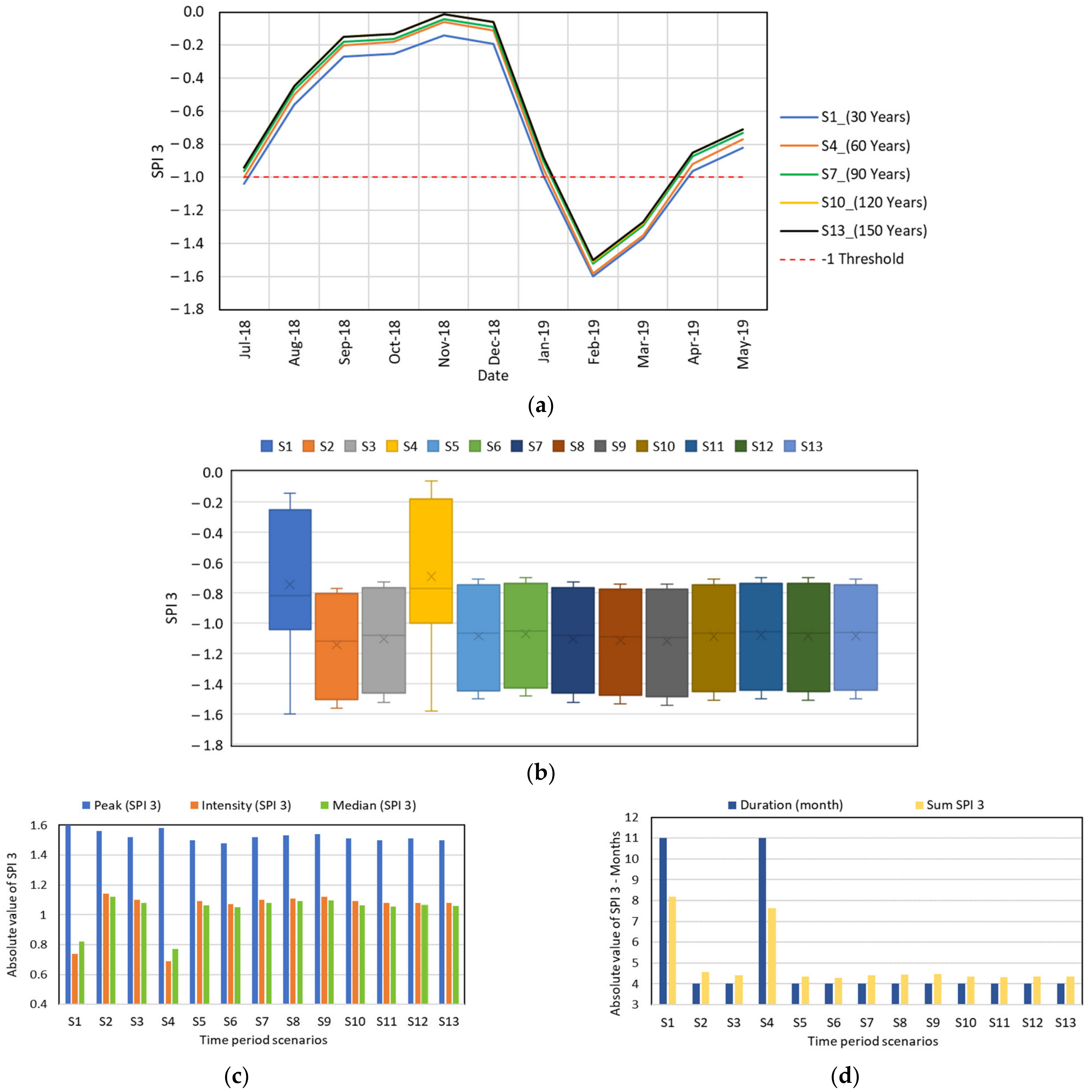


Figure 8. Potential drought characteristics for SPI 3 for the second selected drought event (July 2018–May 2019). (**a**) The difference between selected scenarios based on SPI 3, (**b**) the box-and-whisker plot for SPI 3 values, (**c**) the difference between all time period scenarios using the peak, intensity, and median values, (**d**) the difference between all time period scenarios using drought duration and the absolute summation of SPI 3 values.

3.4. Drought Characteristics for SPI 6

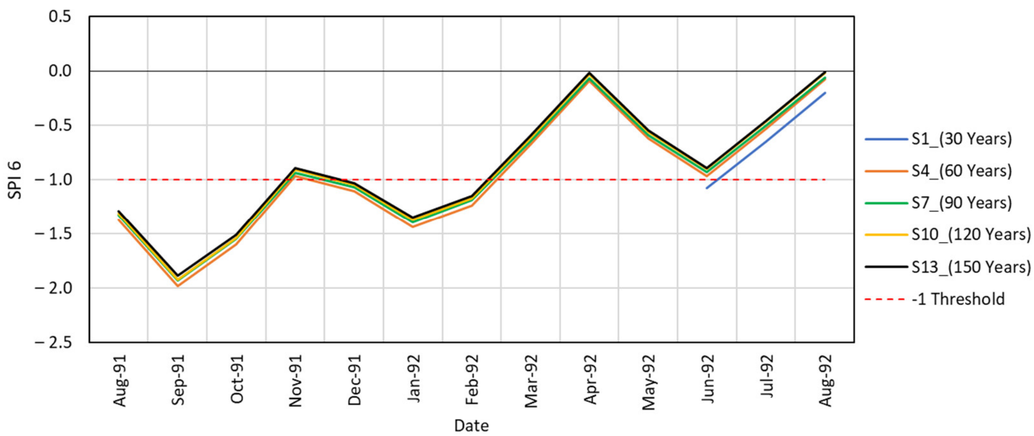
For a 6-month time scale, two drought events were used to compare the results obtained for thirteen scenarios using 150 years of precipitation data from Durham station. The first drought event occurred in 1991–1992 and the second in 2017. Drought indices and detailed drought characteristics obtained from the classical SPI analysis for each scenario are summarized in Table 6 and Figures 9 and 10. For the first drought event, the durations varied significantly across scenarios, with longer durations generally observed in longer scenarios (40 to 150 years), where drought lasted 12 to 13 months. This contrasts with the shortest scenario (S1, 30 years), which recorded a duration of only 3 months. The peak SPI values during this event were notably severe across all scenarios, ranging from −2.53 in S1 to −1.86 in S6, highlighting that this drought event was consistently captured as intense across different time period scenarios. The maximum intensity was observed in S2 (40 years) with a value of −1 and 13 months of drought.

In Figure 9a, the SPI values for selected scenarios showed that all the scenarios went below the −1 threshold during the drought event, except the first scenario, which started in June 1992. The box-and-whisker plot in Figure 9b provides a distribution of the SPI values during this drought event across all scenarios, illustrating the variability in the drought index values captured in different time periods. This visualization highlights that while the median SPI values are fairly consistent, the range of peak and average values can vary, reflecting different perceptions of drought analysis based on the different time period scenarios. The bar charts in Figure 9c,d depict the absolute values of peak SPI, intensity, median, and drought duration and severity. Based on these results, the critical drought characteristics have been identified as an intensity of −1, a duration of 13 months, a peak SPI of −2.02, and a severity SPI of −13.06.

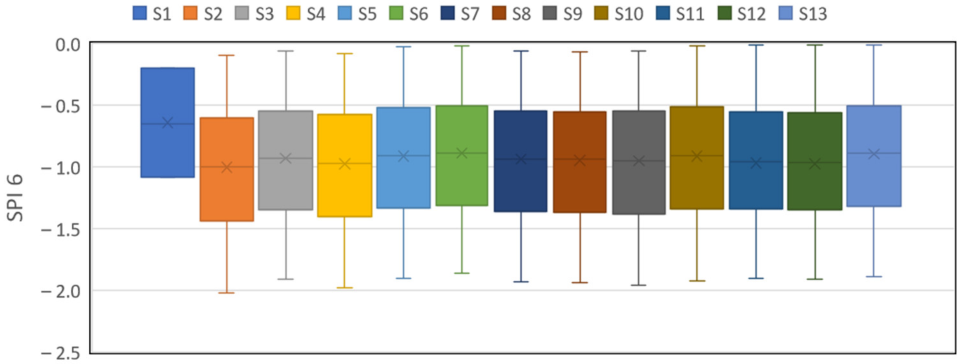
Table 6. Summary of the drought characteristics for SPI 6 for different 13 time period scenarios.

Drought Characteristics SPI 6											
Years		Drought 1 (August 1991–August 1992)					Drought 2 (May 2017–August 2017)				
Scenario		D	P	S	A	M	D	P	S	A	M
S1—30 Y	1992–2021	3	−1.08	−1.94	−0.65	−0.65	4	−1.42	−2.44	−0.61	−0.45
S2—40 Y	1982–2021	13	−2.02	−13.06	−1	−1	4	−1.35	−2.07	−0.52	−0.35
S3—50 Y	1972–2021	13	−1.91	−12.08	−0.93	−0.93	2	−1.26	−1.72	−0.86	−0.86
S4—60 Y	1962–2021	13	−1.98	−12.69	−0.98	−0.97	4	−1.32	−1.96	−0.49	−0.32
S5—70 Y	1952–2021	13	−1.90	−11.86	−0.91	−0.91	2	−1.25	−1.69	−0.84	−0.84
S6—80 Y	1942–2021	13	−1.86	−11.59	−0.89	−0.89	2	−1.22	−1.65	−0.82	−0.82
S7—90 Y	1932–2021	13	−1.93	−12.19	−0.94	−0.94	2	−1.27	−1.74	−0.87	−0.87
S8—100 Y	1922–2021	13	−1.94	−12.31	−0.95	−0.94	2	−1.28	−1.76	−0.88	−0.88
S9—110 Y	1912–2021	13	−1.96	−12.37	−0.95	−0.95	2	−1.29	−1.76	−0.88	−0.88
S10—120 Y	1902–2021	13	−1.92	−11.84	−0.91	−0.91	2	−1.25	−1.68	−0.84	−0.84
S11—130 Y	1892–2021	12	−1.90	−11.62	−0.97	−0.96	2	−1.23	−1.65	−0.82	−0.82
S12—140 Y	1882–2021	12	−1.91	−11.68	−0.97	−0.97	2	−1.24	−1.66	−0.83	−0.83
S13—150 Y	1872–2021	13	−1.89	−11.65	−0.90	−0.96	2	−1.23	−1.65	−0.83	−0.83

D: duration, P: peak SPI, S: sum of SPI, A: average SPI (intensity), M: median SPI.



(**a**)



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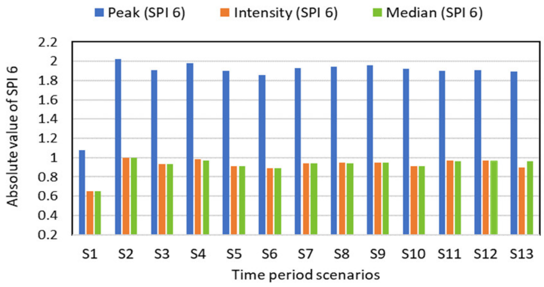

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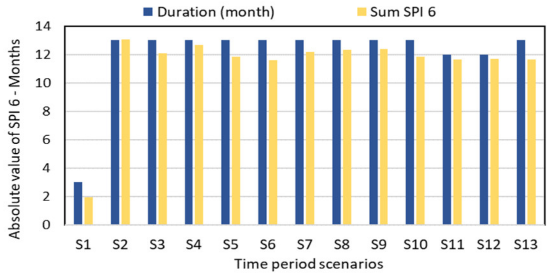
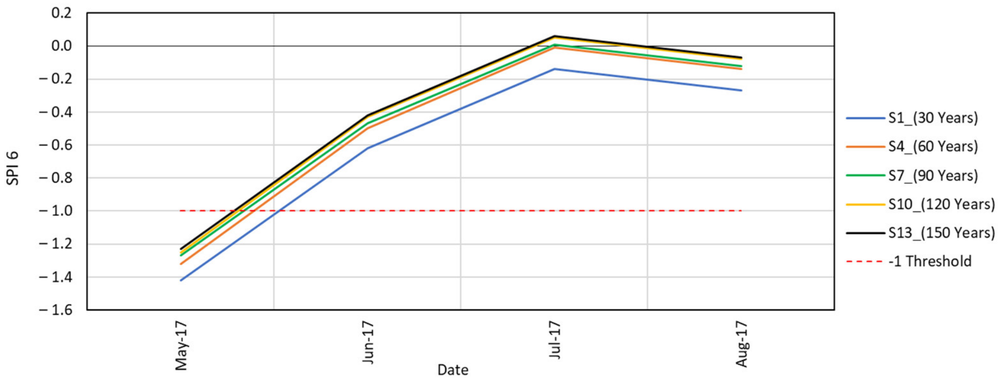


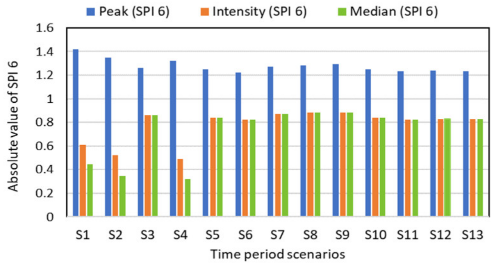
(**d**)

Figure 9. Potential drought characteristics for SPI 6 for the first selected drought event (August 1991–August 1992). (**a**) The difference between selected scenarios based on SPI 6, (**b**) the box-and-whisker plot for SPI 6 values, (**c**) the difference between all time period scenarios using the peak, intensity, and median values, (**d**) the difference between all time period scenarios using drought duration and the absolute summation of SPI 6 values.

Figure 10 presents the analysis of potential drought characteristics for the second selected drought event (May 2017–August 2017). Figure 10a depicts the SPI values over the drought period for selected scenarios, highlighting a difference in duration between these scenarios. For S1 and S4, the duration is 4 months; for other scenarios, the duration is 2. However, all the scenarios started in the same month, but the SPI value in the third and fourth months was the main reason for the change in the duration. Figure 10b illustrates the absolute peak SPI, intensity, and median values for each scenario. Figure 10c shows the duration and the absolute values of the severity. Based on the comprehensive analysis of all scenarios for the second drought event, the critical drought characteristics have been identified as an intensity of −0.88, a duration of 4 months, a peak SPI of −1.42, and a severity of SPI of −2.44.



(**a**)



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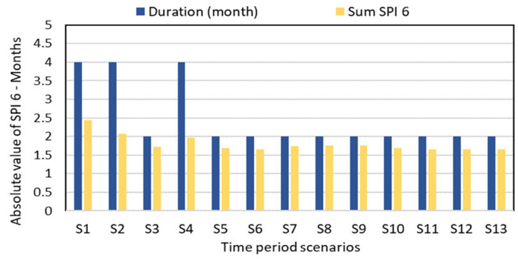

(**c**)

Figure 10. Potential drought characteristics for SPI 6 for the second selected drought event (May 2017–August 2017). (**a**) The difference between selected scenarios based on SPI 6, (**b**) the difference between all time period scenarios using the peak, intensity, and median values, (**c**) the difference between all time period scenarios using drought duration and the absolute summation of SPI 6 values.

3.5. Drought Characteristics for SPI 12

This section explains the findings from an analysis of SPI 12 across 13 different time period scenarios for a prolonged drought event that occurred from August 1995 to December 1997, as summarized in Table 7 and shown in Figure 11. The analysis reveals considerable variations in the drought's characteristics based on the time period scenarios used. The duration of the drought event ranged widely, with the shortest period (S1, 30 years) experiencing the longest drought duration at 29 months, while most other scenarios had durations of about 20 to 23 months. This variability in duration highlights how the selected time period can influence the drought characteristics. Also, the intensity ranged between −0.93 and −1.09. The maximum duration, severity, and intensity were observed in S1.

Figure 11a shows that while the SPI values fluctuated, the start and end years differed for the time period scenarios. For example, S4, S7, S10, and S13 ended in July 1997. In contrast, S1 ended in January 1998. The box-and-whisker plot in Figure 11b visualizes the distribution of SPI values for each scenario during the drought. Figure 11c quantifies the peak, intensity, and median SPI values for each time period scenario, indicating some consistency in these metrics across the scenarios. Figure 11d compares the duration and severity of the drought across all scenarios. There is a noticeable difference in how the duration of droughts and severity are perceived, with shorter scenarios tending to record longer durations and a higher cumulative severity. Based on the comprehensive analysis of all scenarios for the second drought event, the critical drought characteristics have been identified as an intensity of −1.09, a duration of 29 months, a peak SPI of −2.21, and a severity of SPI of −31.48.

Table 7. Summary of the drought characteristics for SPI 12 for different 13 time period scenarios.

Drought Characteristics SPI 12						
Years		Drought 1 (August 1995–December 1997)				
Scenario		D	P	S	A	M
S1—30 Y	1992–2021	29	−2.21	−31.48	−1.09	−1.15
S2—40 Y	1982–2021	23	−2	−24.89	−1.08	−1.03
S3—50 Y	1972–2021	23	−1.85	−22.43	−0.98	−0.92
S4—60 Y	1962–2021	23	−1.91	−23.3	−1.01	−0.96
S5—70 Y	1952–2021	21	−1.83	−19.82	−0.94	−0.89
S6—80 Y	1942–2021	21	−1.81	−19.53	−0.93	−0.88
S7—90 Y	1932–2021	23	−1.88	−22.56	−0.98	−0.87
S8—100 Y	1922–2021	23	−1.91	−23.06	−1	−0.95
S9—110 Y	1912–2021	23	−1.92	−22.99	−1	−0.88
S10—120 Y	1902–2021	20	−1.84	−19.66	−0.98	−0.90
S11—130 Y	1892–2021	20	−1.83	−19.26	−0.96	−0.88
S12—140 Y	1882–2021	20	−1.85	−19.49	−0.97	−0.89
S13—150 Y	1872–2021	20	−1.84	−19.57	−0.98	−0.89

D: duration, P: peak SPI, S: sum of SPI, A: average SPI (intensity), M: median SPI.

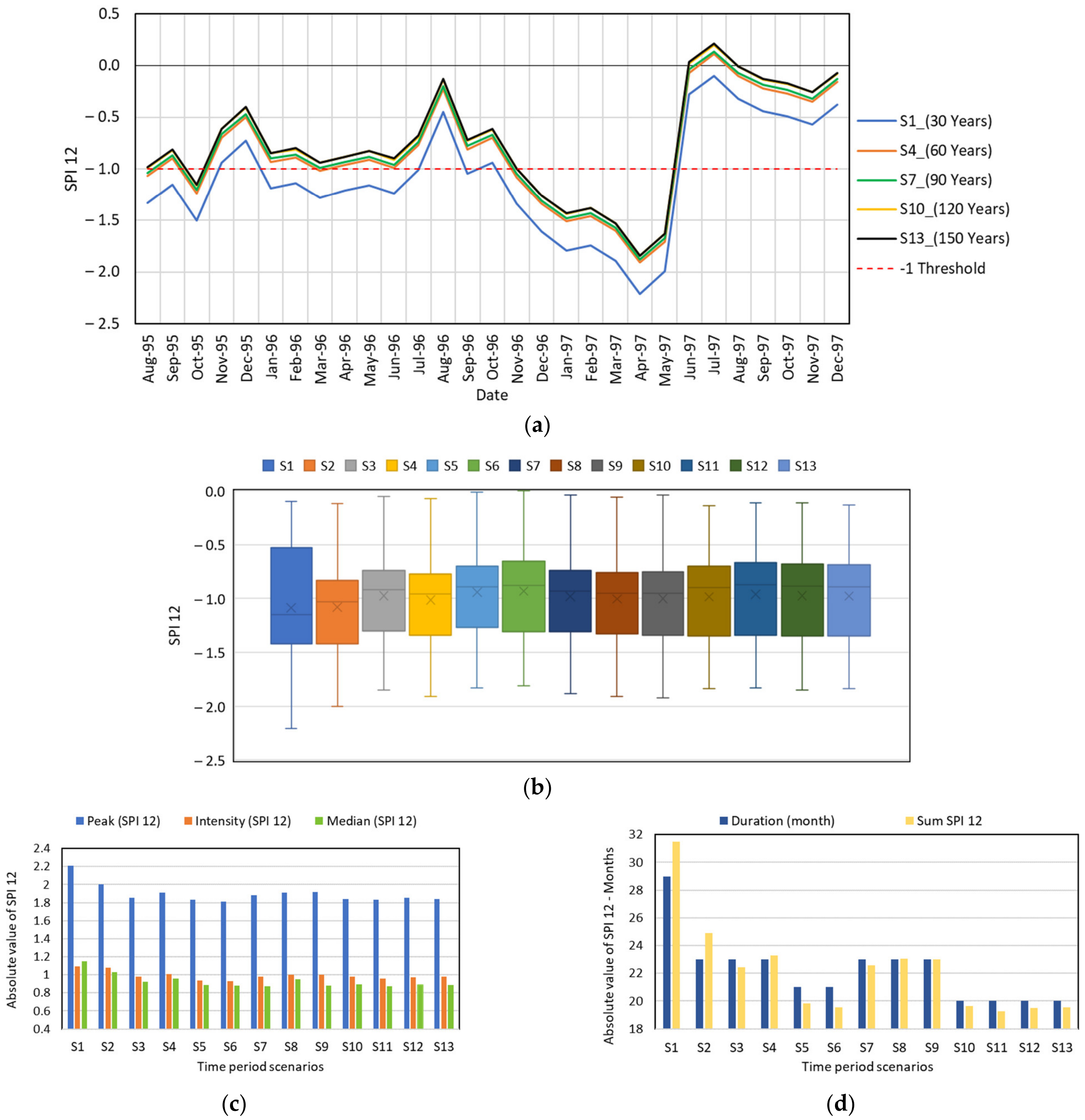

Figure 11. Potential drought characteristics for SPI 12 for the first selected drought event (August 1995–December 1997). (**a**) The difference between selected scenarios based on SPI 12, (**b**) the box-and-whisker plot for SPI 12 values, (**c**) the difference between all time period scenarios using the peak, intensity, and median values, (**d**) the difference between all time period scenarios using drought duration and the absolute summation of SPI 12 values.

4. Discussion

4.1. Initial Time Condition and Dynamic Time Period Scenarios

The determination of the initial time conditions and dynamic time period scenarios plays a pivotal role in calculating the drought characteristics, particularly in critical drought assessments. This step, as a first step, is crucial, as the results heavily depend on it. Dynamic time period scenarios are established based on the available data, the specific purpose of the drought characteristics analysis, and the climate conditions of the study area. This study utilized 10-year intervals, resulting in 13 time period scenarios. However, for more precise and localized studies, shorter intervals, such as one year, may be necessary. Therefore, the selection of dynamic time period scenarios should be tailored to both the available data and the objectives of the drought characteristics analysis. For example, for more accurate and microscale studies, smaller intervals are recommended. Additionally, in arid regions where drought events have significant impacts, smaller intervals are recommended to capture finer-scale variations in drought severity and duration.

4.2. Drought Definition and Critical Drought Characteristics

The definition of drought and its relationship to drought characteristics is a fundamental aspect of drought analysis. In this study, we used the drought definition proposed by the original article on SPI theory [16], which sets the threshold for drought initiation at an SPI value of −1. However, it is important to recognize that alternative definitions, such as those based on run theory [35], or different definitions such as −1.0 or 0 [37], can lead to different results. This highlights the need for further research to understand the impact of the selected drought definition and threshold on drought characteristics and critical drought assessments. McKee et al. [16] emphasized the use of a threshold of −1, arguing that values between 0 and −1 may still reflect normal or wet conditions and thus do not signify the onset of a drought event. This choice is pivotal, as the SPI provides a versatile and universally applicable method that is adaptable to different time scales and sensitive to changes in precipitation patterns [38,39]. Furthermore, employing a threshold of −1 instead of 0 results in shorter drought durations and a higher intensity, providing a more conservative approach to identifying critical drought characteristics. Clarifying the implications of different drought definitions and thresholds is essential for enhancing the accuracy and reliability of drought assessments and management strategies.

4.3. Comparison between Critical and Traditional Drought Characteristics

In terms of the drought characteristics obtained in this research, the analysis reveals noteworthy insights across dynamic time period scenarios and SPI time scales. For SPI 1, the intensity ranges between −0.89 and −1.33, indicating a 33% difference, with the maximum intensity derived from the longest time period (S12, 140 years). This suggests that increasing the time period for short time scales yields more critical and conservative results. Additionally, variations in drought duration are observed, with some scenarios showing no drought events, particularly in longer time period scenarios, implying that increasing the time period decreases the duration. Conversely, for SPI 3, there is a positive relationship between time period and drought intensity, while duration exhibits an inverse relationship, similar to SPI 1, where shorter time periods yield longer durations. Decreasing the time period leads to longer durations, consequently resulting in reduced intensity, as intensity is inversely proportional to severity divided by drought duration. However, for SPI 6, no consistent relationship is observed between duration and intensity, necessitating careful consideration, especially for short time scales. In contrast, for longer time scales like SPI 12, an adverse relationship between time period and intensity and duration is observed, with increasing time periods resulting in decreased intensity and duration. Therefore, utilizing shorter time periods, such as 30 years, is deemed more conservative. For instance, the duration decreases from 29 months for a 30-year time period to 20 months for a 150-year time period, while the intensity decreases from −1.09 to −0.98. This trend may be attributed to the increased impact of climate change over the last 30 years. These findings underscore the importance of considering both the time period and SPI time scales in drought analysis for effective drought management and decision-making.

4.4. Critical Drought Characteristics and Various Sectors

Utilizing critical drought characteristics, which offer a more nuanced and precise understanding of drought characteristics and impacts compared to traditional drought characteristics, can significantly enhance decision-making and design across various sectors. For instance, in water resource management, critical drought characteristics provide insights into the most severe and prolonged drought events, enabling more effective allocation of water resources and infrastructure planning [40,41]. For example, reservoir design and operation plans may incorporate critical drought characteristics to ensure a sufficient water supply during prolonged dry periods. Agricultural stakeholders can benefit from critical drought characteristics by identifying specific crop water requirements and implementing targeted irrigation strategies to mitigate the impacts of extreme drought conditions [42]. Moreover, critical drought characteristics are invaluable in ecosystem management, guiding conservation efforts to protect vulnerable ecosystems and biodiversity from the adverse effects of severe droughts. By incorporating critical drought characteristics into decision-making processes and design considerations, stakeholders can enhance resilience to drought and better adapt to the challenges posed by water scarcity.

4.5. Previous Studies

Previous studies, such as those conducted by Wang et al. [43] and Laimighofer and Laaha [44], have extensively investigated drought uncertainties, including the effect of the selected time periods. Both studies underscored the observation period as one of the most significant sources of uncertainty in drought analysis. However, despite acknowledging this, they primarily focused on drought index values without delving into analysis or quantification of the observation period's impact on the drought characteristics and their corresponding applications. Furthermore, these studies did not provide any perspective or suggestions on determining the critical drought conditions arising from these uncertainties. For instance, Laimighofer and Laaha [44] highlighted that the observation period can account for up to 49% of the uncertainty in SPI calculations. Conversely, Wang et al. [43] stated that the uncertainty in SPI calculation decreases with an increase in the time scale and record length. These findings align with previous literature. Also, in terms of critical drought characteristics and their corresponding applications, there is no universally preferable time period. Instead, each drought event and its critical characteristics have an event-based critical time period. However, our research delved further, aiming to uncover the nuanced effects of the time period on drought characteristics, particularly focusing on identifying critical drought characteristics essential for effective drought management and adaptation strategies.

4.6. New Parameters for Drought Characterization

This study extends beyond the classical drought characteristics traditionally used in drought analysis, such as duration, severity, and intensity, to incorporate additional parameters that offer a more accurate understanding of drought dynamics. Drought characteristics offer detailed insights into droughts' temporal and quantitative aspects, allowing for a nuanced understanding of their progression and mitigation [35–37]. Specifically, this research calculates the peak and median values of the drought index during each identified drought event and scenario. The peak value represents the maximum drought index, providing insight into the most severe point of precipitation deficiency experienced during the event. This metric is crucial for understanding the potential stress on ecological and agricultural systems. Similarly, the median value of the drought index serves as a robust measure of the typical drought conditions over the event's duration, offering a more stable indicator that is less influenced by extreme values than the mean. This helps in ensuring that the assessment is not skewed by unusually wet or dry values within the drought period.

4.7. Limitations and Future Opportunities

Like any research, this study has certain limitations. One significant limitation is the use of data from only a single meteorological station, chosen for its long and continuous data records. The inclusion of additional stations might yield new insights, potentially enhancing the robustness and generalizability of the findings. However, given that this article proposes new concepts and methods regarding selecting the time periods, temporal drought evaluation, and critical drought characteristics, an application to one station is sufficient. One station is enough to demonstrate the effectiveness and applicability of the proposed methodologies. Another limitation is the reliance on a single drought definition, specifically the one introduced by McKee et al. [16]. Future research could benefit from exploring various drought definitions and different time period scenarios to provide a more comprehensive understanding of critical drought characteristics. By addressing these limitations, subsequent studies can build on this work to refine and expand the applicability of the proposed methods.

5. Conclusions

This research significantly advances the field of drought analysis by examining the impact of various time period scenarios on drought characteristics and introducing a novel methodology that employs dynamic time periods to identify critical drought characteristics. Through the analysis of drought indices across different time periods, this study underscores the importance of temporal variability in understanding drought and provides a novel approach to filling this gap. The proposed methodology enhances the precision of identifying critical drought characteristics and offers valuable insights for water resource management, drought mitigation planning, and infrastructure design. This study lays a solid foundation for future work to improve the accuracy and adaptability of drought assessments and management strategies. The key findings can be summarized as follows:

1. Significant differences in drought characteristics were observed across different time period scenarios.
2. The duration of drought events varied notably when different time periods were considered. For example, for SPI 12, the drought duration varied significantly from 20 to 29 months, and for SPI 6, the drought duration varied between 3 and 13 months.
3. The intensity of SPI 1 ranged between −0.89 and −1.33, indicating a 33% increase, and the SPI 3 intensity ranged between −1.08 and −1.91, indicating a 50% increase.
4. The proposed methodology using dynamic time period scenarios instead of one time period enhances the precision of identifying critical drought characteristics.
5. The selection of a definition of droughts significantly impacts the resulting drought characteristics, highlighting the need for careful selection and further research to understand the implications of different definitions on drought assessments.

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References

1. Muhammad, W.; Yang, H.; Lei, H.; Muhammad, A.; Yang, D. Improving the regional applicability of satellite precipitation products by ensemble algorithm. *Remote Sens.* **2018**, *10*, 577.
2. Kesgin, E.; Yaldız, S.G.; Güçlü, Y.S. Spatiotemporal variability and trends of droughts in the Mediterranean coastal region of Türkiye. *Int. J. Climatol.* **2024**, *44*, 1036–1057.
3. Kharyutkina, E.; Loginov, S.; Martynova, Y.; Sudakov, I. Time series analysis of atmospheric precipitation characteristics in Western Siberia for 1979–2018 across different datasets. *Atmosphere* **2022**, *13*, 189.
4. Vaheddoost, B.; Mohammadi, B.; Safari, M.J.S. The Association between Meteorological Drought and the State of the Groundwater Level in Bursa, Turkey. *Sustainability* **2023**, *15*, 15675.
5. Merabti, A.; Meddi, M.; Martins, D.S.; Pereira, L.S. Comparing SPI and RDI applied at local scale as influenced by climate. *Water Resour. Manag.* **2018**, *32*, 1071–1085.
6. Nassaj, B.N.; Zohrabi, N.; Shahbazi, A.N.; Fathian, H. Evaluating the performance of eight global gridded precipitation datasets across Iran. *Dyn. Atmos. Ocean.* **2022**, *98*, 101297.
7. IPCC. Summary for policymakers. In *Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*; Core Writing Team, Lee, H., Romero, J., Eds.; IPCC: Geneva, Switzerland, 2023; pp 1–34. https://doi.org/10.59327/IPCC/AR6-9789291691647.001.
8. Zhao, X.; Xia, H.; Liu, B.; Jiao, W. Spatiotemporal comparison of drought in Shaanxi–Gansu–Ningxia from 2003 to 2020 using various drought indices in google earth engine. *Remote Sens.* **2022**, *14*, 1570.
9. Gu, L.; Chen, J.; Yin, J.; Sullivan, S.C.; Wang, H.M.; Guo, S.; Zhang, L.; Kim, J.S. Projected increases in magnitude and socioeconomic exposure of global droughts in 1.5 and 2 °C warmer climates. *Hydrol. Earth Syst. Sci.* **2020**, *24*, 451–472.
10. Zhao, Q.; Chen, Q.; Jiao, M.; Wu, P.; Gao, X.; Ma, M.; Hong, Y. The temporal-spatial characteristics of drought in the Loess Plateau using the remote-sensed TRMM precipitation data from 1998 to 2014. *Remote Sens.* **2018**, *10*, 838.
11. Brito, C.S.; da Silva, R.M.; Santos, C.A.G.; Neto, R.M.B.; Coelho, V.H.R. Monitoring meteorological drought in a semiarid region using two long-term satellite-estimated rainfall datasets: A case study of the Piranhas River basin, northeastern Brazil. *Atmos. Res.* **2021**, *250*, 105380.
12. Water, U.N. Water and climate change. In *The United Nations World Water Development Report*; Water UN: Geneva, Switzerland, 2020.
13. World Economic Forum. *This Is What Climate Change Costs Economies around the World*; World Economic Forum: Cologny, Switzerland, 2023. Available online: www.weforum.org (accessed on 25 March 2024).
14. World Meteorological Organization. *State of the Global Climate 2022*; World Meteorological Organization: Geneva, Switzerland, 2022. Available online: www.public.wmo.int (accessed on).
15. Thomas, T.; Jaiswal, R.K.; Galkate, R.; Nayak, P.C.; Ghosh, N.C. Drought indicators-based integrated assessment of drought vulnerability: A case study of Bundelkhand droughts in central India. *Nat. Hazards* **2016**, *81*, 1627–1652.
16. McKee, T.B.; Doesken, N.J.; Kleist, J. The relationship of drought frequency and duration to time scales. In Proceedings of the 8th Conference on Applied Climatology, Anaheim, CA, USA, 17–22 January 1993; Volume 17, pp. 179–183.
17. Vicente-Serrano, S.M.; Beguería, S.; López-Moreno, J.I. A multiscalar drought index sensitive to global warming: The standardized precipitation evapotranspiration index. *J. Clim.* **2010**, *23*, 1696–1718.
18. Palmer, W.C. Meteorological drought. US. Weather Bureau Res. Paper, 1965. 45, 1–58.
19. Tsakiris, G.; Pangalou, D.; Vangelis, H. Regional drought assessment based on the Reconnaissance Drought Index (RDI). *Water Resour. Manag.* **2007**, *21*, 821–833.
20. World Meteorological Organization. *Standardized Precipitation Index User Guide*; World Meteorological Organization: Geneva, Switzerland, 2012; p. 1090.
21. Mahmoudi, P.; Rigi, A.; Miri Kamak, M. A comparative study of precipitation-based drought indices with the aim of selecting the best index for drought monitoring in Iran. *Theor. Appl. Climatol.* **2019**, *137*, 3123–3138.
22. Wable, P.S.; Jha, M.K.; Shekhar, A. Comparison of drought indices in a semi-arid river basin of India. *Water Resour. Manag.* **2019**, *33*, 75–102.
23. Şen, Z. Fuzzy standardized precipitation index (FSPI) for drought early warning procedure. *Theor. Appl. Climatol.* **2023**, *155*, 1281–1287.
24. Abu Arra, A.; Şişman, E. Innovative Drought Classification Matrix and Acceptable Time Period for Temporal Drought Evaluation. *Water Resour. Manag.* **2024**, *38*, 2811–2833.
25. Şen, Z.; Şişman, E. Probabilistic standardization index adjustment for standardized precipitation index (SPI). *Theor. Appl. Climatol.* **2023**, *155*, 2747–2756.
26. Elouissi, A.; Benzater, B.; Dabanli, I.; Habi, M.; Harizia, A.; Hamimed, A. Drought investigation and trend assessment in Macta watershed (Algeria) by SPI and ITA methodology. *Arab. J. Geosci.* **2021**, *14*, 1329.
27. Gumus, V. Evaluating the effect of the SPI and SPEI methods on drought monitoring over Turkey. *J. Hydrol.* **2023**, *626*, 130386.
28. Dabanlı, İ.; Mishra, A.K.; Şen, Z. Long-term spatio-temporal drought variability in Turkey. *J. Hydrol.* **2017**, *552*, 779–792.
29. Burt, S.; Burt, T. *Durham Weather and Climate since 1841*; Oxford University Press: Oxford, UK, 2022; 580p.
30. Pettitt, A.N. A non-parametric approach to the change-point problem. *Appl. Stat.* **1979**, *28*, 126–135.
31. Buishand, T.A. Some methods for testing the homogeneity of rainfall records. *J Hydrol.* **1982**, *58*, 11–27. https://doi.org/10.1016/0022- 1694(82)90066-X.

32. Wijngaard, J.; Tank, A.; Können, G. Homogeneity of 20th Century European Daily Temperature and Precipitation Series. *Int. J. Climatol.* **2003**, *23*, 679–692. https://doi.org/10.1002/joc.906.
33. Wang, H.; Chen, Y.; Pan, Y.; Chen, Z.; Ren, Z. Assessment of candidate distributions for SPI/SPEI and sensitivity of drought to climatic variables in China. *Int. J. Climatol.* **2019**, *39*, 4392–4412.
34. Stephens, M.A. Use of the Kolmogorov–Smirnov, Cramer–Von Mises and related statistics without extensive tables. *J. R. Stat. Soc. Ser. B: Stat. Methodol.* **1970**, *32*, 115–122.
35. Yevjevich, V.M. Objective Approach to Definitions and Investigations of Continental Hydrologic Droughts. Ph.D. Thesis, Colorado State University, Collins, CO, USA, 1967.
36. Abu Arra, A.; Şişman, E. Investigation of the main difference between the run and SPI theories regarding drought characteristics. In Proceedings of the AHI EVRAN 3rd International Congress on Scientific Research, 2023; Volume 2, pp. 124–134. (03 – 04 May 2023, Baku Azerbaijan)
37. Abu Arra, A.; Şişman, E. Characteristics of hydrological and meteorological drought based on intensity-duration-frequency (IDF) curves. *Water* **2023**, *15*, 3142.
38. Peng, Y.; Peng, T.; Li, Y. Spatiotemporal Characteristics of Drought in Northwest China Based on SPEI Analysis. *Atmosphere* **2023**, *14*, 1188.
39. Tigkas, D.; Vangelis, H.; Tsakiris, G. Implementing crop evapotranspiration in RDI for farm-level drought evaluation and adaptation under climate change conditions. *Water Resour. Manag.* **2020**, *34*, 4329–4343.
40. Tsakiris, G. Drought risk assessment and management. *Water Resour. Manag.* **2017**, *31*, 3083–3095.
41. Şişman, E. Self-similar characteristics of drought duration, total deficit, and intensity curves. *Arab. J. Geosci.* **2020**, *13*, 8.
42. Tigkas, D.; Vangelis, H.; Tsakiris, G. Drought characterisation based on an agriculture-oriented standardised precipitation index. *Theor. Appl. Climatol.* **2019**, *135*, 1435–1447.
43. Wang, W.; Wang, J.; Romanowicz, R. Uncertainty in SPI calculation and its impact on drought assessment in different climate regions over China. *J. Hydrometeorol.* **2021**, *22*, 1369–1383.
44. Laimighofer, J.; Laaha, G. How standard are standardized drought indices? Uncertainty components for the SPI & SPEI case. *J. Hydrol.* **2022**, *613*, 128385.