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Detection of Drought Events in Setúbal District: Comparison between Drought Indices

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Abstract: Due to the lack of a general drought definition, water users and managers have developed and used different indices. Many studies using drought indices have been made so as to detect drought events or just to compare their results and assess their advantages and disadvantages. In Portugal, these studies have been done for common drought indices; however, an integrated evaluation and comparison using recent data is needed. Therefore, this study is intended to give an updated overview of the behaviour of the proposed indices. This study proposes the usage of PDSI, scPDSI, SPI and SPEI. With the exception of the PDSI, all indices have been calculated through R packages. The results for the studied regions in mainland Portugal suggest that the drought situations are, in general, most significant and frequent than the wet periods. From our results, we can conclude that the SPI model is more sensitive to extreme drought events and can detect them earlier. The PDSI, scPDSI and SPEI are more reliable for drought monitorization at medium and long spells, which might represent the environmental interactions more closely to the reality. Also, the scPDSI tends to reduce the importance of short period recovering. It is then advisable that impact and scientifical studies consider all of these indices or at least some of them to have a broader and complete understanding of the drought situations to be studied.

Keywords: SPI; SPEI; PDSI; scPDSI

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1. Introduction

Drought is a natural phenomenon that has no singular definition [1–3]. However, it can be understood as a slow, deceptive, hazardous and complex phenomenon which occurs due to the lack of precipitation compared to what is normal, affecting both environmental and human demands [2,4–6] at different time and spatial scales [2,5]. Hence, Wilhite and Glantz [1] grouped droughts into four categories: meteorological, hydrological, agricultural and socioeconomical.

Due to its complex definition, detection and difficulty in its quantification regarding duration, spatial extension and intensity [2,7–9], it should be viewed as a relative phenomenon instead of an absolute one [2]. Because of its complexity and different meaning for different water users and managers, several indices able to monitor drought events have been developed [2,6–8]. Some of them are the Palmer Drought Severity Index (PDSI) [10,11], the Standardized Precipitation Index (SPI) [9,12] and the Standardized Precipitation-Evaporation Index (SPEI) [13].

The usage of PDSI and SPI is justifiable in the sense that both indices are used by the entities responsible for the Portuguese Drought Prevention, Monitoring and Contingency Plan [14]. In this study, besides these indices, we decided to use the self-calibrated Palmer Drought Severity Index (scPDSI) and the SPEI. Regarding the scPDSI and SPEI, they have been chosen because the former is a modification from the original PDSI and the latter was created as an alternative to the SPI; therefore, this study is a good opportunity to compare them.

The PDSI was proposed by Palmer [15] and is one of the most successful and used at quantifying the severity of droughts [16,17]. It is based on a water balance model, which, in turn, needs a water supply-demand budget that is developed through precipitation, soil characteristics [18,19], potential evapotranspiration and runoff [18]. The scPDSI is a variation of the original PDSI and was proposed by Wells et al. [16]. This index was proposed to solve some of the PDSI issues; for example, the constants calibration, which was turned into a dynamic process [8,19], the spatial comparability and the match between drought conditions and the index's values [8,20]. Furthermore, the scPDSI reduces the value range and the excessive frequency of extreme events [17,21]. The SPI was proposed by Mckee et al. [22] as a normalized index, adjusted to a gamma function, able to quantify the probability's relationship of precipitation deficit or surplus for different timescales, most commonly between 1 and 48 months [3,22,23]. These different timescales represent different stages of the hydrological cycle [22,23] and are proxies for the different water resources (e.g., soil moisture, groundwater, river discharge and reservoir storage). The SPI calculation is simple since it only requires monthly precipitation data as an input [3,21]. Due to its simple calculation and its versatility on the comparation between different areas and periods, the Lincoln Declaration on Drought Indices recommends the use of SPI by all national meteorology and hydrology services [3,24]. The SPEI was proposed by Vicente-Serrano et al. [7] as an alternative drought index derived from the SPI [7,8]. Its main difference over SPI is the introduction of water demand estimation through the introduction of potential evapotranspiration into the calculation [7]. Therefore, this index combines both the sensitivity of the PDSI and the versatility of the SPI, enabling it to be compared with the scPDSI [7,8].

Several studies have been made worldwide with these indices for different reasons so as to understand its advantages and disadvantages on different applications like drought monitoring, impacts on agriculture, the prediction of forest fires, among other objectives [5]. Consequently, some studies have been conducted to compare the usage of drought indices, like, for example, Sousa et al. [17], Zargar et al. [25], Paulo et al. [12], Vicente-Serrano et al. [8], Naumann et al. [26], Silva [27], Cota et al. [28], Pathak et al. [29], Yang et al. [21], Wang et al. [13], Adnan et al. [30], Bayissa et al. [31], Fırat et al. [32], Li et al. [33], Lu et al. [6], Wang et al. [20], Katipoglu et al. [34], among others. Vicente-Serrano et al. [8] found that the SPI and SPEI have a superior capability to assess drought impacts compared to Palmer indices for monitoring drought impacts on hydrological, agricultural, and ecological areas. Vicente-Serrano et al. [8] also found that SPI and SPEI have small differences, although SPEI has the best responses to drought during the summer season. Wang et al. [13] observed that the SPI, SPEI and scPDSI correlated well with each other. Furthermore, Wang et al. [13] found that scPDSI is better than SPI and SPEI at representing water deficits at medium periods. Yang et al. [21] discovered that the drought index presenting the best results for China was the scPDSI for representing long-term trends of wet or dry spells, despite reducing the value range compared to the PDSI. Besides, Yang et al. [21] found that the SPI and SPEI usage is more recommendable for humid areas than arid or semiarid ones, because the SPI does not take into account the contributions of temperature's variation to drought, while SPEI overestimates its contribution. In Adnan et al. [30], the authors found for Pakistan that the SPI and SPEI are more suitable than scPDSI to monitor droughts. Li et al. [33] and Katipoglu et al. [34] concluded that SPEI is a more complete index than SPI, mostly because it takes into account evapotranspiration. Lu et al. [6] discovered that the scPDSI and SPEI have a better response than the SPI, SPEI being the best between the three at identifying drought events. Wang et al. [20] discovered that, on an annual timescale, the SPI have the best response for steppe and desert biomes, and on a seasonal and monthly timescale, the scPDSI have the greatest sensitivity on summer and on vegetated areas, respectively. The texts presented by Zargar et al. [25] and WMO&GWP [16] are very complete and detailed regarding the characteristics, advantages and disadvantages of most (if not all) of the drought indices.

In Portugal, there are studies comparing the different drought indices and also studies using only one drought index to analyse drought-related events. For example, Pires et al. [10] characterized the historical evolution of droughts in mainland Portugal using only Palmer Drought Severity Index—PDSI. Sousa et al. [17] have shown that the scPDSI behaviour is more reliable and realistic than the PDSI, taking into consideration the temporal sequence and magnitude of drought events, described in the literature. Paulo et al. [12] concluded that SPI and SPEI correlate well with each other and have similar results regarding occurrence and severity of drought events. Paulo et al. [12] have also found that the PDSI is more accurate at identifying earlier drought events and severe drought events than SPI and SPEI. Silva [27] correlated the SPI with the Vegetation Health Index and found that the SPI for 3 months has a good correlation with VHI from May to July and in October. This author concluded that SPI for 3 and 6 months can detect a higher number of drought events than the VHI. Cota et al. [28] assessed that the SPI and SPEI are both useful indices at identifying and monitoring both drought and extreme precipitation events and that they present a good correlation. Cota et al. [28] have also identified a decrease in the value range of the SPI. The texts of Silva et al. [35,36], De Lima et al. [37] and Santo et al. [38] are some of the studies that have been done in Portugal in which they mostly use SPI to assess drought events in Portugal. Generally, they conclude that this index is a very important tool in detecting and monitoring drought situations and extreme precipitation events. Furthermore, Silva et al. [35] found an increase in the extent of dry events and a non-significant decrease in the extent of wetter events, according to SPI. Santo et al. [38] also found a decrease in the SPI range value and that the values' variation for this index, between October and March in all timescales, is associated with North Atlantic Oscillation (NAO). Páscoa et al. [39] have used SPI and SPEI to assess drought situations in the Iberian Peninsula over the last 112 years and found that, with the exception of the northwestern area, there is an increased trend of drought events. These authors have also concluded that SPEI identified dryer conditions than SPI. Russo et al. [40] have assessed the impact of drought events, using SPEI and SPI, on burned areas in the Iberian Peninsula. Ribeiro et al. [41] have found that SPEI and the number of hot days is dependent of each other, which suggests a strong association between hot and dry extreme values.

In this regard, this study had as a main objective the evaluation and comparison of the aforementioned drought indices using an up-to-date time period of data. Another important objective is the testing of the behaviour of these indices so as to understand which present better results and detecting major drought events in the study area (Setúbal district) between 1979 and 2020. The SPEI, SPI and scPDSI were computed using Rstudio packages, while the PDSI was calculated and made available by IPMA. The defined objectives were particularly important in the context of the Climpest project. This project aims to analyze drought situations and the pine trees' resilience to these events. Ultimately, this project will try to recreate the past emergence of certain pests in pine trees, namely *Thaumetopoea pityocampa*, comparing two pine trees; one hosting the larvae and the other not hosting the larvae, but both must have the same climatic response to drought situations (more information about the project can be found at: https://doi.org/10.1016/j.foreco.2021.119548). The project will contribute to better forest management. Thus, within the project, this study represents an important historical drought assessment in the Setúbal district, which has not been the specific target of drought studies, even though it is particularly affected by drought spells.

2. Study Area and Data

2.1. Setúbal District

Setúbal district is located in the southern west coast of mainland Portugal, south of Lisbon (Figure 1a). The study area was chosen within the context of the ClimPest project because, according to the report from the World Resources Institute, several Portuguese districts, mainly in the south of the country, face "extremely high" water scarcity (Figure 2). Among the districts indicated by the document is Setúbal.

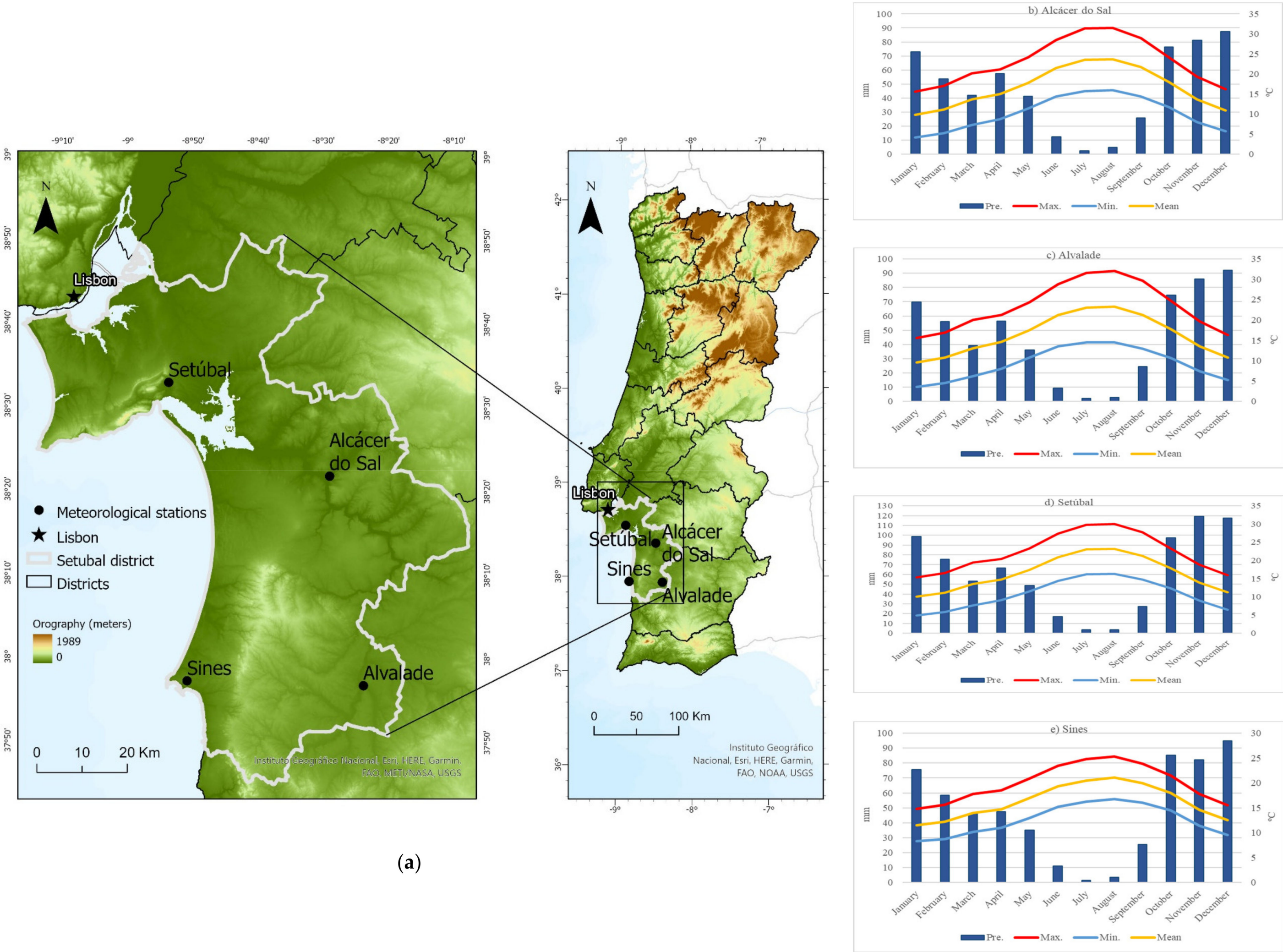

Figure 1. Study area geographical location (**a**), and climatic characterization. The letters (**b**–**e**) represent the meteorological stations, namely, Alcácer do Sal, Alvalade, Setúbal and Sines, respectively. In the graphics are represented for the 1981–2010 period the average values of precipitation, "Pre" (blue columns), maximum temperature, "Max." (red line), minimum temperature, "Min." (blue line) and mean temperature, "Mean" (yellow line).

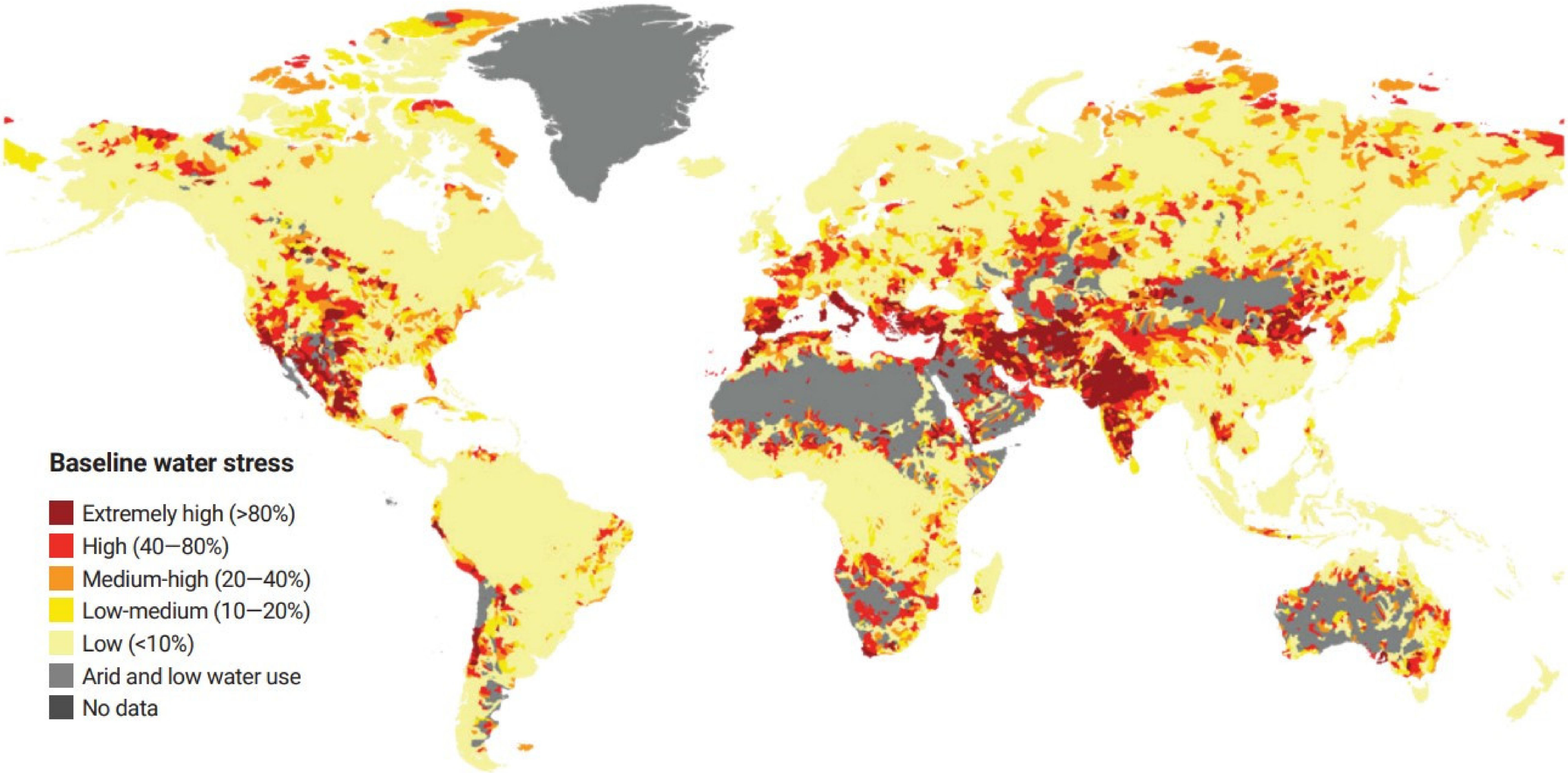

Figure 2. Annual baseline water stress. This is a ration between total water withdrawals (domestic, industrial, livestock and irrigation) and available renewable water supplies. Source: United Nations [42].

To enable the development of the proposed drought indices, we have used data from the meteorological stations represented in Figure 1a for four locations: Alcácer do Sal, Alvalade, Setúbal and Sines. These stations were chosen because they have long and homogenous observation datasets and also their distribution provides a good spatial coverage of Setúbal district.

The Setúbal district climate according to Köppen classification is classified both as Csa and Csb [43]. As Figure 1b–e shows, the distribution of precipitation and maximum, minimum and mean temperatures are almost identical between the four locations. However, there are some differences between them, for example: Sines has a smaller thermal amplitude and Setúbal has higher precipitation values.

2.2. Meteorological Data

To analyse the proposed drought indices (PDSI, scPDSI SPI, SPEI) and the potential evapotranspiration (PET), we have used hourly precipitation and temperature data from the Portuguese Institute for Sea and the Atmosphere (IPMA) meteorological stations and from the ERA5 reanalysis model [44] (available in the C3S data store) (Table 1). The ERA5 variables have been extracted for the same coordinates as the meteorological stations. The ERA5 data were used to fill in some missing values in the IPMA stations' series, but before that, both datasets had been compared and evaluated. After this, a homogenization process was conducted on the combined dataset using the software package RClimDex. Lastly, to enable the drought indices' calculation, the variables have been converted from hourly to monthly data.

Table 1. Metadata.

Data	Source	Period	Frequency	Spatial Resolution
Precipitation (mm) 2 m mean, maximum and minimum temperature (°C)	IPMA	Alcácer do Sal: 1953–2019; Alvalade: 1950–2019; Setúbal: 1950–2019; Sines: 1989–2019	Hourly	Meteorological station
	Era5 Climate Data Store—Copernicus	1979–2019	Hourly	lat-lon grid 0.25° × 0.25°

3. Methods

3.1. Potential Evapotranspiration

In this study, the PET has been calculated using the Hargreaves method, even though initial tests with the FAO Penman–Monteith method had shown better results. The FAO Penman–Monteith is considered the best method to calculate the potential evapotranspiration [45]; however, it was deemed inefficient for this study for several reasons. Firstly, FAO Penman–Monteith requires several meteorological variables, some of which are not available for the studied period and area. Due to this limitation, the missing variables were not replaced by the Era5 data because they could not be validated with the observed values;

Secondly, the Hargraves method has shown very satisfactory results for the study area, requiring fewer variables than the previous method and less effort. According to FAO [45], in case of data unavailability, namely, relative humidity, solar radiation and wind speed, the Hargreaves method presents itself as a valid alternative to estimate PET with reasonable and globally validated results. Lastly, according to Vicente-Serrano et al. [7], the method used to obtain PET is not critical since it will be included in a drought index calculation. Furthermore, Mavromatis [46] has demonstrated that simple or complex PET methods present similar results when drought indices are calculated. This way, to calculate PET with the Hargreaves method, the following equations were applied:

$$\text{PET} = 0.0023 * (0.408) * (\text{Tavg} + 17.78) * (\text{Tmax} - \text{Tmin})0.5 * \text{Ra} \tag{1}$$

Equation (1): PET Hargreaves method. Source: Equation (52) from FAO [45]. The Ra is the global solar radiation which is calculated with (Equation (2)). The 0.408 value is the conversion rate from MJ m^{-2} to mm.

$$\mathrm{Ra} = \frac{24(60)}{\pi} G_{sc}\ d_{r\ [\omega_s\ \sin(\varphi)\ \sin(\delta)+\cos(\varphi)\ \cos(\delta)\sin(\omega_s)]} \quad (2)$$

Equation (2): Ra calculation formula. Source: Equation (21) from FAO [45]. The Gsc is a solar constant (0.082); the dr is the inverse relative distance Earth–Sun (Equation (23) from FAO [45]); the ω_s is the radiation angle at sunset (Equations (25) and (26) from FAO [45]); the φ is the latitude in radians (Equation (22) from FAO [45]); the δ is the solar declination in radians (Equation (24) from FAO [45]).

3.2. Drought Indices

The drought indices have been implemented using the software Rstudio. This way, the scPDSI has been built using the PDSI package (More information about the package can be found here: https://www.rdocumentation.org/packages/scPDSI/versions/0.1.3/topics/pdsi, (accessed on 1 March 2022)). The SPI and the SPEI have been produced using the SPEI package (More information about the package can be found here: https://cran.r-project.org/web/packages/SPEI/SPEI.pdf, (accessed on 1 March 2022)). The PDSI has been computed directly by IPMA, with its calculation being fully calibrated for the Portuguese climatic conditions and made available for this study. The Available Water Capacity (AWC) needed to develop scPDSI was defined as the standard value for the four locations. The SPI and SPEI have only been modelled for the 9-month accumulation period, because this timescale has the best statistical behaviour with the PDSI and the scPDSI (see Section 3.1).

3.2.1. PDSI and scPDSI

The PDSI is assessed monthly and it is based on a two-stage soil model [16] represented in Figure 3 by (1) and (2). The amount of moisture in the soil is calculated with 8 variables: evapotranspiration (ET), recharge (R), potential recharge (PR), potential loss (PL), runoff (RO), loss (L), potential runoff (PRO) and potential evapotranspiration (PET), estimated with the Hargreaves method (Figure 3). In Figure 3, stage (1a) refers to the water-balance coefficients (α, β, γ and δ). These weighted coefficients will give the Climatically Appropriate For Existing Conditions (CAFEC) potential values [16]. In stage (1b), the CAFEC values are combined to obtain P(cafec), which is the precipitation needed to maintain a normal soil moisture level for a month [16]. Stage (1c) is the difference between the precipitation that fell during a specific month and P(cafec) [16]. To enable d to be compared between different locations or be compared at different periods, it needs to be weight using k, represented in stage (2), which is the refined climatic characteristics [16]. In stage 2, k is obtained through two equations Figure 3(2a,2b), where: D is the multi-year average of water-deficient value (d) [18]; and the value 17.67 is an empirical constant produced by Palmer [15]. Then, in stage (2c), d is multiplied by k, resulting in the moisture anomaly index or Z index, that shows the dryness or wetness during a month without taking into account recent precipitation trends [17]. The Z index is used to obtain the PDSI value for a certain month through the following equation:

$$\mathrm{PDSI_i} = 0.897\mathrm{PDSI_{i-1}} + \frac{1}{3}\mathrm{Z_i} \quad (3)$$

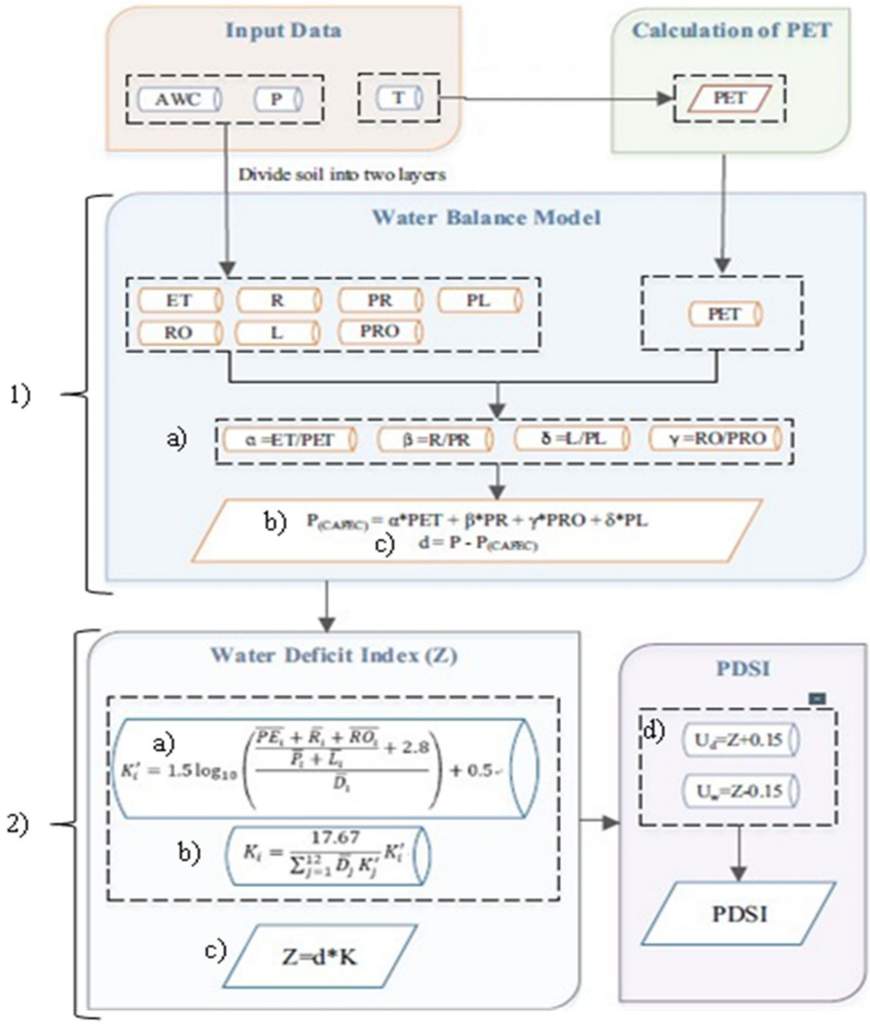

Figure 3. Procedure to calculate the PDSI. (**1**) Represents the water balance model, and (**2**) the water deficit index. The letters (**a**–**d**) represent the different stages to build models (**1**) and (**2**). Source: Adapted from Yu et al. [18].

Equation (3): PDSI calculation. Source: Equation (20) from Yu et al. [18]. The 0.897 and 1/3 are empirical coefficients.

To calculate the current value of PDSI, the 0.897 coefficient is multiplied by the previous PDSI value added to a third of the Z index value for the current month [16]. Three PDSI values are calculated each month [16]. The PDSI was developed originally for the USA, so to be applied correctly to mainland Portugal, some modifications have been made [47]. Despite maintaining the logical structure that forms the basis of its definition, some important changes have been introduced, with its calculation being fully calibrated in order to be adapted to the climatic conditions of Portugal [47]. The calculation of ETP, the calculation of potential runoff, the calculation methodology of the parameters necessary for the water balance, the calculation of the climatic coefficient K (Equation (4)) and the determination of the beginning or end of a dry or rainy period have been modified. For example, we have obtained a different equation for the calculation of K that guarantees valid results of the drought index in Portugal. An extensive analysis has been made in order to evaluate the necessary changes that would best fit the PDSI to the Portuguese climate.

$$\mathrm{K_{final}} = \frac{514.28}{\sum_{1}^{12} \mathrm{DK'_{final}}} \mathrm{K'_{final}} \tag{4}$$

Equation (4): K factor recalibration for mainland Portugal. Source: Pires [47].

However, the K ratio was yet to be revised into a ratio between the expected value of the PDSI and the observed value of the PDSI [16] (Equation (5)). Since K would be expected to be 0 and Palmer defined that the distribution of PDSI would use the central tendency, Wells et al. [16] changed it to be defined through fe, which corresponds to a percentile, (Equations (5) and (6)). This percentile is different according to the extreme values in each side of the value range defined by Palmer.

$$\tilde{K} = \begin{cases} \frac{\text{expected } f_e\text{th percentile of the PDSI}}{\text{observed } f_e \text{ percentile of the PDSI}} \\ \frac{\text{expected } (100-f_e)\text{th percentile of the PDSI}}{\text{observed } (100-f_e)\text{th percentile of the PDSI}} \end{cases} \tag{5}$$

Equation (5): PDSI ratio between expected and observed values. Source: Equation (8) from Wells et al. [16].

$$K = \begin{cases} K'(-4.00/2\text{nd percentile}), & \text{if } d < 0 \\ K'(4.00/98\text{th percentile}), & \text{if } d \geq 0. \end{cases} \tag{6}$$

Equation (6): PDSI percentile definition. Source: Equation (9) from Wells et al. [16].

This K redefinition allowed Wells et al. [16] to remove the climatic conditions assessed in nine locations across the USA by Palmer, which were used to define the given coefficients. This way, the climatic characteristics are only based on the studied location's climate, specifically how the d factor relates to the defined range of PDSI [16].

In regard to the duration coefficients, Wells et al. [16] defined that dry and wet spells should have different factors. To better identify the slope and y interception of the best fit lines, these coefficients have been determined through a linear least squares regression method for both extreme conditions, instead of a simple linear regression used by Palmer. Wells et al. [16] wanted to give emphasis to long-term droughts instead of short-term ones like Palmer did, so they changed through trial and error the minimum threshold for 0.85, instead of the previous 0.15. All these changes allowed to increase the range of expected values to below −4 and above 4, to develop the index based on local climate, to increase the index sensitivity to moisture or lack of it, and to update the index on different analyzed periods [16]. Both indices use the same value range classification, described in Table 2.

Table 2. PSDI and scPDSI value range classes.

Value Range	Classification
≥4.00	Extremely wet
3.00 to 3.99	Very wet
2.00 to 2.99	Moderately wet
1.00 to 1.99	Slightly wet
−0.99 to 0.99	Normal
−1.99 to −1.00	Mild drought
−2.99 to −2.00	Moderate drought
−3.99 to −3.00	Severe drought
≤−4.00	Extreme drought

3.2.2. SPEI and SPEI

To calculate the SPI, a monthly precipitation dataset with at least 30 years of data is required. The SPI can be computed for 1, 3, 6, 9, 12, 24 and 48 months, which represent timescales that may affect five different types of usable water sources [22]. The calculation of the SPI for a given month is determined by previous months' values and then its dataset is adjusted to a gamma function of precipitation probability according to historical records [22]. After obtaining the probability it is used an approximation of the inverse normal [22]. This will enable to assess the precipitation deviations for a normal distributed probability [22]. Thus, the SPI can be calculated through Equation (7), where X_i is the monthly precipitation data, X is the mean precipitation value calculated for the whole period, and σ it is the monthly standard deviation [33].

$$\mathrm{SPI} = \frac{X_i - \overline{X}}{\sigma} \tag{7}$$

Equation (7): SPI formula. Source: (Equation (1)) from Li et al. [33].

The SPEI is a water balance model, like the PDSI and scPDSI since it takes into account the role of temperature, although it is mathematically similar to the SPI [7]. The SPEI calculates the deficit or surplus of water on a multiscale level adjusted for a log-logistic probability distribution [7]. The SPEI can be calculated through Equation (8).

$$\mathrm{SPEI} = W - \frac{C_0 + C_1 W + C_2 W^2}{1 + d_1 W + d_2 W^2 + d_3 W^3} \tag{8}$$

Equation (8): SPEI formula. Source: Vicente-serrano et al. [7].

In Equation (8), C and d are constants (C_0 = 2.515517, C_1 = 0.802853, C_2 = 0.010328, d_1 = 1.432788, d_2 = 0.189269, and d_3 = 0.001308), while W is represented in Equation (9). In Equation (9), P is the probability of exceeding a determined D value [7], which is a water-balance value, meaning that it is the difference between precipitation and potential evapotranspiration. If P is > 0.5, then it is replaced by 1—P [7]. Both the SPI and SPEI use the same value range classification, described in Table 3.

$$W = \sqrt{-2\mathrm{In}(P) \text{ for } P \leq 0.5} \tag{9}$$

Table 3. SPI and SPEI value range classes.

Value Range	Classification
≥2.00	Extremely wet
1.50 a 1.99	Very wet
1.00 a 1.49	Moderately wet
0.50 a 0.99	Slightly wet
−0.49 a 0.49	Normal
−0.99 a −0.50	Mild drought
−1.49 a −1.00	Moderate drought
−1.99 a −1.59	Severe drought
≤−2.00	Extreme drought

Equation (9): W formula. Source: Vicente-Serrano et al. [7].

3.3. Statistical Tests

To assess the statistical behaviour of the drought indices, a Pearson correlation and an Euclidian distance test were run using the IBM SPSS software. These tests were conducted to understand which timescales from the SPEI and SPI had the most similarities in terms of lagged response to the PDSI and scPDSI. The timescale with the best result from each model was chosen for the identification of drought events and further comparison with the PDSI and scPDSI.

4. Results

4.1. Drought Indices Comparison

As mentioned before, the Pearson correlation and the Euclidian Distance tests were executed to understand which time set from the SPI and SPEI indices were closer to PDSI and scPDSI. From the different time sets from the SPI and SPEI indices, it is observed through Table 4 that the SPI-9 months and SPEI-9 months have the highest correlations with the PDSI and the scPDSI indices. According to the Euclidian Distances (Table 5), it is also seen that, from the three different SPI and SPEI indices, the ninth-month time set has the smaller values, which means that it is closer to the scPDSI and PDSI. With these results, we then decided to use the SPI and SPEI for 9 months to assess their behaviour and help to identify drought periods.

Table 4. Pearson correlations.

Correlations		scPDSI	PDSI	SPI 6	SPEI 6	SPI 9	SPEI 9	SPI 12	SPEI 12
scPDSI	Pearson Correlation	1	0.816	0.721	0.709	0.783	0.779	0.761	0.767
PDSI	Pearson Correlation	0.816	1	0.800	0.803	0.814	0.820	0.749	0.761
SPI6	Pearson Correlation	0.721	0.800	1	0.938	0.798	0.772	0.712	0.682
SPEI6	Pearson Correlation	0.709	0.803	0.938	1	0.754	0.816	0.666	0.720
SPI9	Pearson Correlation	0.783	0.814	0.798	0.754	1	0.952	0.868	0.829
SPEI9	Pearson Correlation	0.779	0.820	0.772	0.816	0.952	1	0.828	0.877
SPI12	Pearson Correlation	0.761	0.749	0.712	0.666	0.868	0.828	1	0.947
SPEI12	Pearson Correlation	0.767	0.761	0.682	0.720	0.829	0.877	0.947	1

Table 5. Euclidian distances.

	scPDSI	PDSI	SPI 6	SPEI 6	SPI 9	SPEI 9	SPI 12	SPEI 12
scPDSI	-	0.72	1.00	0.98	0.91	0.89	0.93	0.90
PDSI	0.72	-	0.92	0.88	0.88	0.85	0.95	0.92
SPI 6	1.00	0.92	-	0.00	0.27	0.31	0.38	0.41
SPEI 6	0.98	0.88	0.00	-	0.33	0.23	0.44	0.36
SPI 9	0.91	0.88	0.27	0.33	-	0.00	0.17	0.24
SPEI 9	0.89	0.85	0.31	0.23	0.00	-	0.24	0.14
SPI 12	0.93	0.95	0.38	0.44	0.17	0.24	-	0.00
SPEI 12	0.90	0.92	0.41	0.36	0.24	0.14	0.00	-

Comparing the four indices, it can be observed, in Figures 4–7 and Table 6, that the drought or wet periods have different duration, intensity and temporal scales. However, some of these indices show some similarities between each other's regarding these 3 factors. Having regard to this idea, it can be seen that the PDSI results are mostly identical to the scPDSI, having nonetheless a few significant differences. The most significant difference between these indices is that the scPDSI tends to reduce the importance of short period recovering, resulting in the indication of longer periods either in drought or in wet spells.

The SPEI compared to PDSI has similar durations for the events but tends to enhance the recovering, thus indicating globally less intense events. The SPEI and SPI are comparable with each other since they identify the same events with similar time durations and intensity. When observed in detail, the SPEI results, however, show that drought events are slightly longer than in SPI. The SPI has much less significant similarities with the other two indices, apart from identifying the same most significant drought events, and in fact, introduces a stronger and faster recuperation when conditions are prone to such changes, and the result is shorter drought periods than the other indices.

Table 6. Percentage of months per wet or drought class for the PDSI, scPDSI, SPI and SPEI at the four studied locations. Since Sines data only start in 1989, the first 8 months (2.1%) were not calculated.

% of Months		Extremely Wet	Very Wet	Moderately Wet	Slightly Wet	Normal	Mild Drought	Moderate Drought	Severe Drought	Extreme Drought	NA
PDSI	Alcácer do Sal	1.0	3.0	7.3	13.3	25.2	25.8	12.1	9.3	3.0	-
	Alvalade	1.6	4.2	8.7	14.7	18.1	19.2	19.0	10.5	4.0	-
	Setúbal	0.2	3.8	7.5	15.1	18.8	29.4	15.7	6.3	3.2	-
	Sines	2.9	5.5	10.7	18.0	19.5	21.1	10.2	8.4	3.9	-
scPDSI	Alcácer do Sal	0.4	5.0	7.3	9.9	30.2	17.3	20.0	5.2	4.8	-
	Alvalade	2.0	9.3	17.1	12.5	13.5	15.5	15.1	9.7	5.4	-
	Setúbal	0.2	3.6	7.7	7.7	25.5	23.6	18.2	11.1	2.4	-
	Sines	2.3	12.5	16.1	9.1	25.3	14.8	8.3	9.4	2.1	-
SPI 9-month	Alcácer do Sal	2.6	5.8	7.7	14.5	33.9	15.7	10.3	6.5	3.0	-
	Alvalade	2.2	4.0	9.7	18.7	30.2	13.1	10.3	9.5	2.4	-
	Setúbal	2.4	4.0	9.9	13.5	32.1	16.1	11.7	7.3	3.0	-
	Sines	2.6	4.2	11.7	11.5	36.2	16.4	8.6	4.4	2.3	2.1
SPEI 9-month	Alcácer do Sal	1.0	6.0	7.3	11.7	33.3	17.3	14.5	6.2	2.8	-
	Alvalade	2.0	4.0	10.9	13.9	29.6	13.9	14.9	9.3	1.6	-
	Setúbal	2.0	2.8	10.5	9.9	29.8	21.0	13.7	8.9	1.4	-
	Sines	0.8	6.0	12.0	11.7	34.9	16.4	9.4	6.3	0.5	2.1

Comparing the individual behaviour of the PDSI, scPDSI and SPEI in the four studied areas, it can be seen that these indices are globally identical among the four locations even though they have some localised significant differences. Despite the close geographical proximity, the SPI shows some differences for the four different studied locations, namely, some events' length and intensity.

4.2. Identification of Drought Events

4.2.1. Alcácer do Sal

Figure 4a–d shows that the most noticeable drought events were detected between 2002 and 2006 and between 2015 and 2020. The are some differences in the temporal scale among the four indices. For example, for SPEI and SPI, the drought event between 2002 and 2006 is shorter, starting only in 2004. There are some other relevant events, for example, between 1979 and 1983 and between 2007 and 2009.

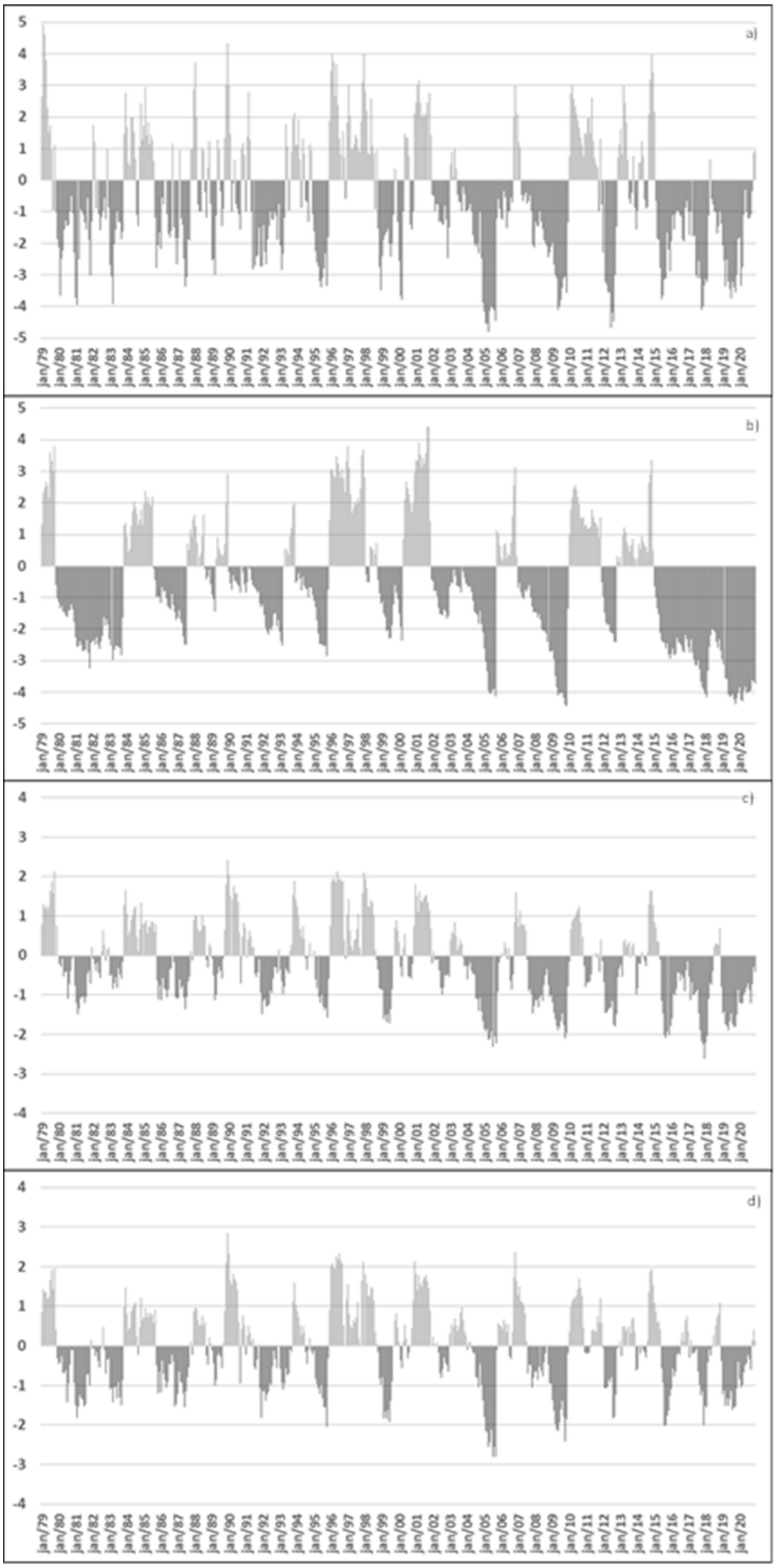

Figure 4. Drought evolution in Alcácer do Sal from 1979 to 2020. (**a**)—PDSI; (**b**)—scPDSI; (**c**)—SPEI 9 months; (**d**)—SPI 9 months.

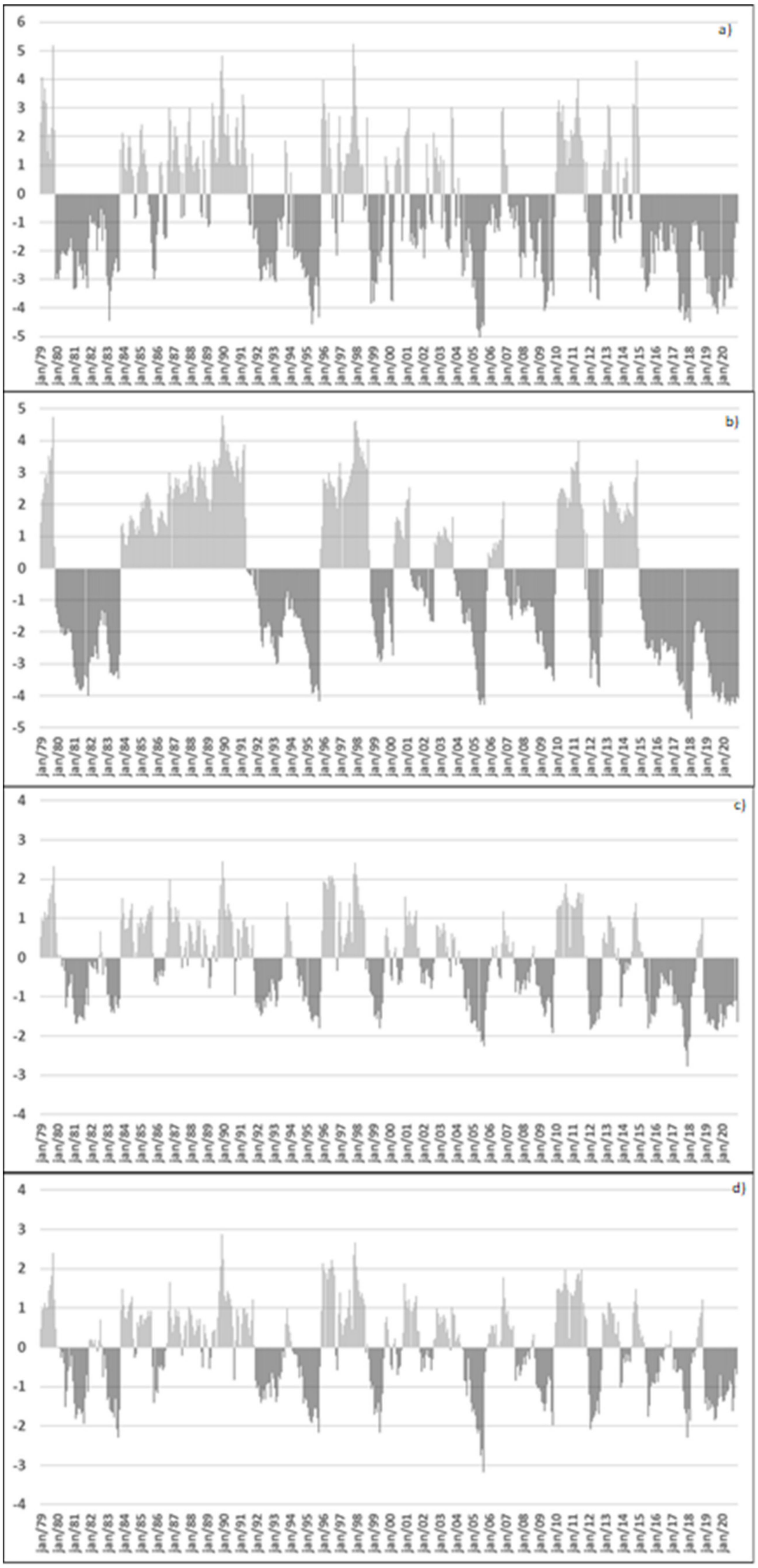

Figure 5. Drought evolution in Alvalade from 1979 to 2020. (**a**)—PDSI; (**b**)—scPDSI; (**c**)—SPEI 9 months; (**d**)—SPI 9 months.

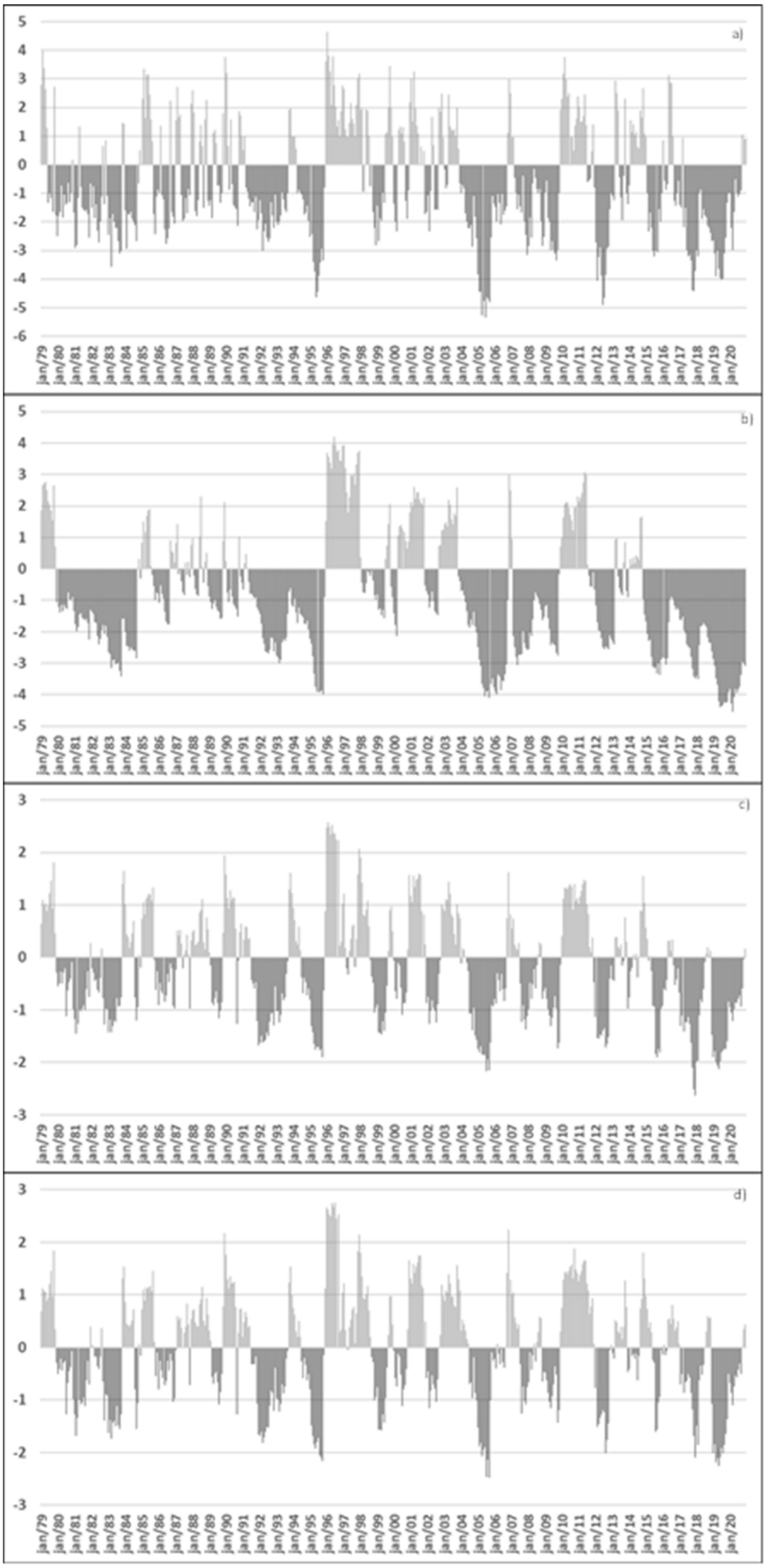

Figure 6. Drought evolution in Setúbal from 1979 to 2020. (**a**)—PDSI; (**b**)—scPDSI; (**c**)—SPEI 9 months; (**d**)—SPI 9 months.

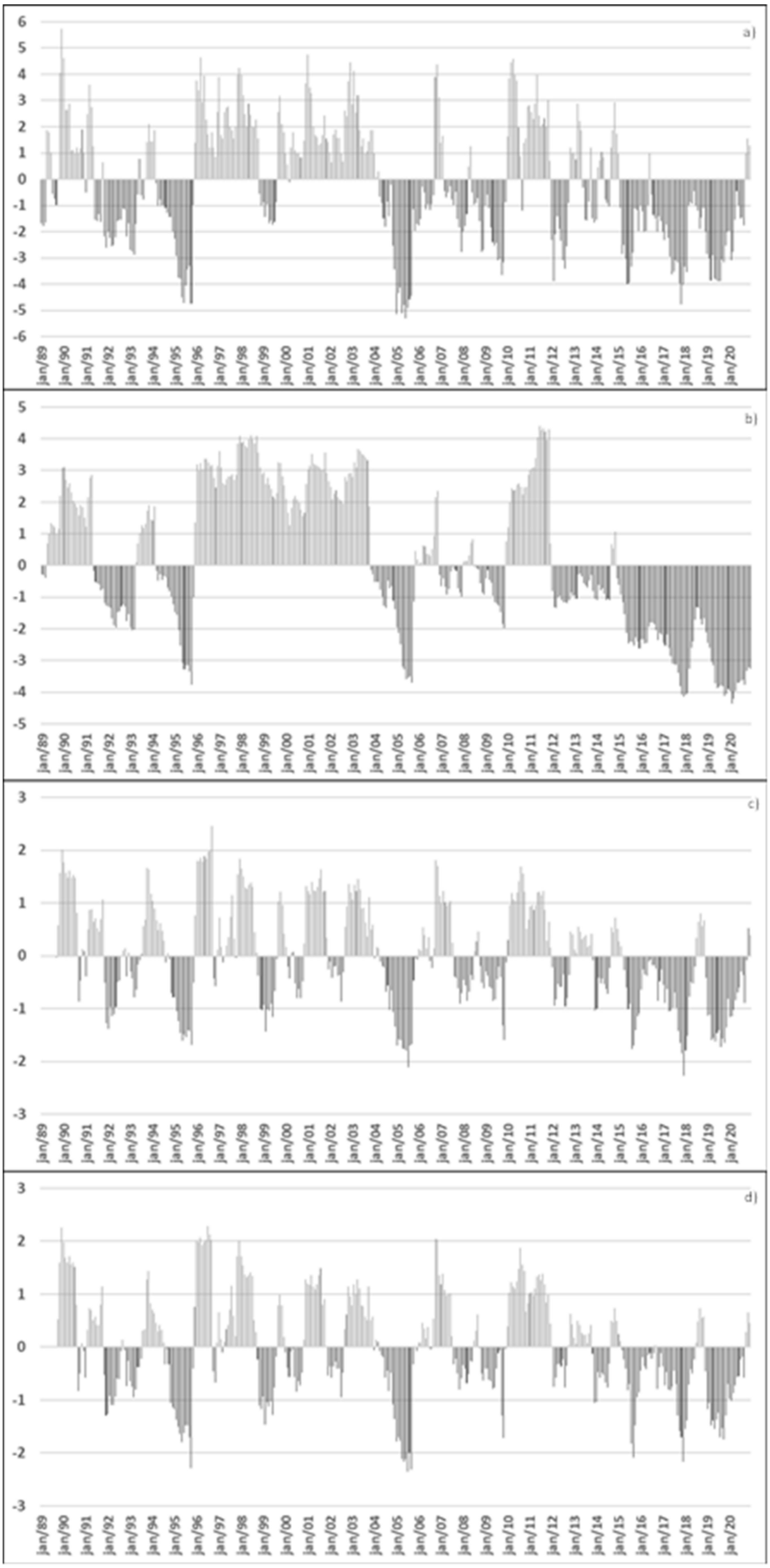

Figure 7. Drought evolution in Sines from 1989 to 2020. (**a**)—PDSI; (**b**)—scPDSI; (**c**)—SPEI 9 months; (**d**)—SPI 9 months.

According to PDSI the 2004/05 drought was the most severe in mainland Portugal: highest magnitude, highest duration and highest severity; but since 2000, other periods of drought have stood out: 2009, 2012 and 2017/2018. In the scPDSI, the most significant drought events occurred in the years 2004/2005, 2009 and in the period 2017–2019. The SPEI shows that some of the most significant months were recorded in 2004/2005, 2009, 2015 and 2018. Lastly, the most intense drought conditions according to SPI were observed in 2004/2005, 2009, 2015 and in 2017.

For these four indices, each drought class has a higher percentage than the wet classes' counterparts (Table 6). The months in drought represent 50.2% of the total period for PDSI, 47.3% for scPDSI, 40.7% for SPEI and 35.5% for SPI (Table 6).

4.2.2. Alvalade

In Alvalade, Figure 5a–d, shows that the most significant drought events were recorded in the following periods: 1979–1984 and 2015–2020. However, some temporal scales' differences have been found between indices. One such example can be seen in SPEI during 1979–1984, in which the drought event is only found between 1980 and 1982. The same thing is seen in SPI, only that it ends a year before. Besides these two most intense periods, there are some other relevant ones, according to the different indices. In this regard, 1991–1995 and 2004–2005 can also be considered important drought events.

During these periods, some months in 1995, 2005, 2017, 2018 and 2019 were recorded as the highest drought class of the index (extreme drought) for this location according to PDSI and scPDSI. For the SPEI and the SPI, some of the months in 2005 and 2017 were the driest ever recorded.

For these four indices, the summed-up drought classes have a higher percentage than the wet classes' counterparts (Table 6). The months in drought represent 52.8% of the total period for PDSI, 45.7% for scPDSI, 39.7% for SPEI and 35.3% for SPI (Table 6).

4.2.3. Setúbal

In Setúbal (Figure 6a–d), similar periods of droughts have been identified (1991–1995, 2003–2007 and 2015–2020), as seen in previous locations. During these periods, some indices have shorter temporal scales, but they are all within these timeframes. Furthermore, other relevant periods which have not been identified throughout all the indices were recorded, as, for example, 1979–1984 for scPDSI and 1980–1982 for SPI. According to these four indices, some months in 1995, 2005, 2017 and 2019 were the highest drought class of the index (extreme drought). Some indices have also detected other periods such as 2012 for PDSI and 2020 for scPDSI. The PDSI, scPDSI and SPI show that each drought class has higher percentages than their wet counterparts (Table 6). For SPEI, the scenario is similar except for the extreme class (Table 6). Consequently, for the four indices, the majority of the months have been recorded in drought situation (PDSI—54.6%; scPDSI—55.3%; SPEI—38.1%; SPI—45%).

4.2.4. Sines

In Sines (Figure 7a–d), the most important drought periods were recorded between 1994 and 1995, 2004 and 2005 and 2015 and 2020. Once again, some indices have within these timeframes shorter or even longer periods. The months with the highest drought classes of the indices (severe and extreme drought) were recorded in 2005 and 2017 (according to the four indices). Highlights are also evident for 1995 in the PDSI; 1995, 2018, 2019 and 2020 in the scPDSI; 2004 and 2015 in the SPI.

For the PDSI, with the exception of the moderate class, each of the drought classes has higher percentages than their equivalent wet classes (Table 6). Regarding the scPDSI, the wet classes are more significative than the respective drought classes, excepting the slightly wet class (Table 6). For SPEI and SPI, the mild and severe classes have higher percentages for drought periods, while the moderate and extreme classes are higher for the wet periods (Table 6). Consequently, for the PDSI, SPI and SPEI, the majority of the months were classified in drought classes (43.5%, 32.6% and 31.8%, respectively), while for the scPDSI, the majority was classified as wet months (40.1%) (Table 6).

5. Discussion and Conclusions

As it was expected, the most similar model to the PDSI, according to the Pearson Correlation and the Euclidian Distance, is the scPDSI. In fact, according to the drought indices' behaviour and according to the identification of drought events, both these indices present many similarities. However, they also have some differences regarding the temporal continuity and in the value range. This way, it can be seen that some drought events identified by the scPDSI are longer than the ones identified by PDSI, as shown by Yang et al. [21], while the later index shows extreme drought values more frequently for two of the four locations (Setúbal and Sines). According to Wells et al. [16], Sousa et al. [17] and Yang et al. [21], the scPDSI reduces the frequency in which severe and extreme values occur, thus being more accurate and reliable than the PDSI. However, for the other two stations, Alvalade and Alcácer do Sal, which have higher temperatures and less precipitation, the scPDSI presents a higher percentage of extreme drought values. This way, there is a possibility that scPDSI is more sensitive to dryer conditions than PDSI.

Our results in this study also show that the different timescales from the SPI and SPEI also have relatively good correlations with the PDSI and with the scPDSI. The best correlation between the PDSI/scPDSI and the SPI and the SPEI is for the 9-month timescale. Wang et al. [13] confirmed this by mentioning that the SPI, SPEI and scPDSI have good correlations between them. Moreover, both the SPI and the SPEI have shown in this study and in Paulo et al. [12] that they correlate well with one another, having equivalent results regarding occurrence and severity of drought events. According to Vicente-Serrano et al. [8], the SPI and SPEI are better indices in assessing drought impacts than the Palmer indices. Vicente-Serrano et al. [8] also point out that these indices have significant differences, some of which might be seen in our results, such as the value range and the temporal continuity of some events. Vicente-Serrano et al. [8] said that one of the differences is that SPEI is better at responding to drought situations during summer. This assumption may be seen through our results, even though the SPI appears to be more sensitive to both wet and dry extreme spells. Other results show that the scPDSI and PDSI have more noticeable events than the other two indices, with longer periods and higher percentages of extreme drought values, in general. The results presented by WMO [3] indicate that SPI is smoother than PDSI, due to the mathematical model itself. This may explain, in part, why the SPI normal class is more representative than the others.

Some authors have compared further these indices and concluded that some of them are more adequate for some purposes than the others. For further details, we present in the introduction chapter a comparison of some of the results found in the literature.

In Setúbal district, the sum of the different drought and wet classes shows that drought is prevalent in the study area, except in Sines according to the scPDSI. In most scenarios (indices' results for each meteorological station location), it is shown that each drought class is usually more representative than their wet counterparts, except in Sines for some of the indices. The normal class was the most representative for each location/index, although it differs for the PDSI, which shows the mild drought class as the most relevant one. Therefore, it can be concluded that the behaviour of these indices is similar, at least for the proposed study area, which is climatically classified by Köppen as Csa in Alvalade, Alcácer do Sal and Setúbal [42]. Although, there is a major difference in Sines, which is classified as Csb, and that may explain some of the contrasts seen [42].

As for the drought events, there are some well distinguishable and commonly identified in most indices for the different locations. For example, during the periods of 1979–1984, 1991–1995, 2002–2007, 2007–2010 and 2015–2020, several drought periods were identified.

The 2004–2005 drought event was the most severe one, with the highest duration in the worst classes of the indices (severe and extreme), and with the highest severity (combination of magnitude and persistence of a drought). These results are confirmed by

DGADR et al. [14], IPMA [48,49] and García-Herrera [50]. In the two reports published by IPMA [48,49], it is reported that the period between 2004 and 2005 was extremely dry, with the smallest precipitation values since 1931. As stated by García-Herrera [50], this event was the driest in 140 years. Besides this, it had the biggest territorial coverage ever recorded [14]. This extreme dry spell caused severe damages in various sectors. According to DGADR et al. [14], IPMA [48,49] and García-Herrera [50], this drought event affected crops and livestock reproduction, leading to an increase in prices, also affected the production of energy which led the country to rely more on fossil fuels, caused limitations to the urban supply of water, and was one of the main reasons behind the quantity and severity of forest fires that year. Regarding a more recent drought event between 2017 and 2019, the reports from IPMA [51–53] mention that, at the end of 2017, 58% of the country was in severe drought with the condition worsening in the first two months of 2018. This drought was classified in the reports as a meteorological drought with severe consequences, namely, by creating the proper conditions for the occurrence of huge forest fires that resulted in the loss of many human lives and critical socioeconomic and environmental impacts. At the end of 2018, the situation was less serious, but in 2019, a new meteorological drought affected the country as a whole [52,53].

The driest years in the study area were 1995, 2005, 2009, 2017, 2018 and 2019 according to the results. This way, it can be understood that, apart from a few differences, the four indices are able to identify the same significant drought periods, which are ever more frequent in the study area. Regarding these mentioned drought events, Páscoa et al. [39] mentioned that, in the last 112 years, drought events in the Iberian Peninsula have been an increasing trend. As our study shows, the last years of the last decade have been the driest ever recorded in this region. It is then expected that, in the near future, more records might be broken.

Concluding, we assess that SPI is more sensitive to extreme situations, being able to detect them earlier. Since the PDSI, scPDSI and SPEI are not as volatile as the SPI, they can be more reliable for drought monitorization at medium and long spells. This can also be explained by the fact that SPI only takes into account precipitation. Thus, SPEI, PDSI and scPDSI are more complete and might represent the complex environmental interactions more closely to the reality. Furthermore, we have also assessed that the scPDSI tends to reduce the importance of short period recovering. All of them have their advantages and disadvantages for different types of use and analysis. Therefore, it would be advisable for impact studies and scientifical papers to use some of these indices together and in an integrated way when it comes to identifying and analysing drought events. They should not be analysed solely individually, because they can complement each other by adding important and useful information for users and decision makers. For example, we consider that SPEI and SPI may be more convenient to use for impact studies (if evapotranspiration data are not available), because they can access drought periods at different time scales regarding different water uses.

In Portugal, the study of droughts should be more developed since it is one of the most frequent and potentially hazardous natural events. Following studies could focus on the comparison of these indices for the other possible timescales (1, 3, 6, 12 and 24 m), on the severity and spatial extent of some of the most intense drought periods identified in this study or on the creation of a new index combining the indices used in this study. It is then suggested to the scientific community to increase their focus on this matter.

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References

1. Wilhite, D.; Glantz, M. Understanding: The Drought Phenomenon: The Role of Definitions. *Water Int.* **1985**, *10*, 111–120. [CrossRef]
2. Tate, E.; Gustard, A. Drought Definition: A Hydrological Perspective. In *Drought and Drought Mitigation in Europe*; Vogt, J., Somma, F., Eds.; Springer: Dordrecht, The Netherlands, 2000; pp. 23–48.
3. World Meteorological Organization (WMO). *Standardized Precipitation Index User Guide*; World Meteorological Organization: Geneva, Switzerland, 2012; Volume 1090.
4. Vivas, E.; Maia, R. Caracterização Das Principais Situações de Seca Históricas Em Portugal Continental—A Importância Da Utilização de Indicadores. In Proceedings of the 2as Jornadas de Hidráulica, Recursos Hídricos e Ambiente, Faculdade de Engenharia da Universidade do Porto, Porto, Portugal, 24 October 2007; pp. 51–61.
5. Mpelasoka, F.; Hennessy, K.; Jones, R.; Bates, B. Comparison of Suitable Drought Indices for Climate Change Impacts Assessment over Australia towards Resource Management. *Int. J. Climatol.* **2008**, *28*, 1283–1292. [CrossRef]
6. Lu, J.; Jia, L.; Zhou, J.; Zheng, C.; Hu, G. Adaptability of Six Global Drought Indices over China. In Proceedings of the IGARSS 2019—2019 IEEE International Geoscience and Remote Sensing Symposium, Yokohama, Japan, 28 July–2 August 2019; pp. 9922–9925. [CrossRef]
7. Vicente-Serrano, S.; Beguería, S.; López-Moreno, J. A Multiscalar Drought Index Sensitive to Global Warming: The Standardized Precipitation Evapotranspiration Index. *J. Clim.* **2010**, *23*, 1696–1718. [CrossRef]
8. Vicente-serrano, S.; Beguerín, S.; Camarero, J.; Lorenzo-lacruz, J.; Azorin-molina, C.; Lo, J. Performance of Drought Indices for Ecological, Agricultural, and Hydrological Applications. *Earth Interact.* **2012**, *16*, 1–26. [CrossRef]
9. Mishra, A.; Singh, V. Drought Modeling—A Review. *J. Hydrol.* **2011**, *403*, 157–175. [CrossRef]
10. Pires, V.; Silva, Á.; Mendes, L. Riscos de Secas Em Portugal Continental. *Territorium* **2010**, *17*, 27–34. [CrossRef]
11. Sheffield, J.; Wood, E.; Roderick, M. Little Change in Global Drought over the Past 60 Years. *Nature* **2012**, *491*, 435–438. [CrossRef]
12. Paulo, A.; Rosa, R.; Pereira, L. Climate Trends and Behaviour of Drought Indices Based on Precipitation and Evapotranspiration in Portugal. *Nat. Hazards Earth Syst. Sci.* **2012**, *12*, 1481–1491. [CrossRef]
13. Wang, H.; Pan, Y.; Chen, Y. Comparison of Three Drought Indices and Their Evolutionary Characteristics in the Arid Region of Northwestern China. *Atmos. Sci. Lett.* **2017**, *18*, 132–139. [CrossRef]
14. DGADR; APA; ANMP; ANPC; DGEG; ERSAR; GPP; ICNF; IPMA. Plano de Prevenção, Monitorização e Contigência Para Situações de Seca; República Portuguesa. 2017. Available online: https://apambiente.pt/sites/default/files/_Agua/DRH/OrgaosConsultivos/ComissaoPermanenteSeca/Reunioes/02_PlanoMonitorizacaoPrevencaoContingencia_Seca_19Jul2017.pdf (accessed on 1 March 2022).
15. Palmer, W. *Meteorological Drought*; US Department of Commerce, Weather Bureau: Washington, DC, USA, 1965; pp. 1–59.
16. Wells, N.; Goddard, S.; Hayes, M. A Self-Calibrating Palmer Drought Severity Index. *J. Clim.* **2004**, *17*, 2335–2351. [CrossRef]
17. Sousa, P.; Trigo, R.; Aizpurua, P.; Nieto, R.; Gimeno, L.; Garcia-Herrera, R. Trends and Extremes of Drought Indices throughout the 20th Century in the Mediterranean. *Nat. Hazards Earth Syst. Sci.* **2011**, *11*, 33–51. [CrossRef]
18. Yu, H.; Zhang, Q.; Xu, C.; Du, J.; Sun, P.; Hu, P. Modified Palmer Drought Severity Index: Model Improvement and Application. *Environ. Int.* **2019**, *130*, 104951. [CrossRef] [PubMed]
19. World Meteorological Organization; Global Water Partnership. *Handbook of Drought Indicators and Indices*; World Meteorological Organization: Geneva, Switzerland, 2016; ISBN 9789263111739.

20. Wang, Y.; Zhang, C.; Meng, F.; Bourque, C.; Zhang, C. Evaluation of the Suitability of Six Drought Indices in Naturally Growing, Transitional Vegetation Zones in Inner Mongolia (China). *PLoS ONE* **2020**, *15*, e0233525. [CrossRef] [PubMed]
21. Yang, Q.; Li, M.; Zheng, Z.; Ma, Z. Regional Applicability of Seven Meteorological Drought Indices in China. *Sci. China Earth Sci.* **2017**, *60*, 745–760. [CrossRef]
22. Mckee, T.; Doesken, 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, 17–21 January 1993; pp. 17–22.
23. Costa, A. Local Patterns and Trends of the Standard Precipitation Index in Southern Portugal (1940–1999). *Adv. Geosci.* **2011**, *30*, 11–16. [CrossRef]
24. European Comission. *Standardized Precipitation Index (SPI)*; Copernicus European Drought Observatory (EDO): Ispra, Italy, 2020; pp. 1–5.
25. Zargar, A.; Sadiq, R.; Naser, B.; Khan, F. A Review of Drought Indices. *Environ. Rev.* **2011**, *19*, 333–349. [CrossRef]
26. Naumann, G.; Dutra, E.; Barbosa, P.; Pappenberger, F.; Wetterhall, F.; Vogt, J.V. Comparison of Drought Indicators Derived from Multiple Data Sets over Africa. *Hydrol. Earth Syst. Sci.* **2014**, *18*, 1625–1640. [CrossRef]
27. Silva, Á.; Santo, F.; De Lima, I.; Pires, V. Spatial statistics of spi for drainage basins. In Proceedings of the 9° Simpósio de Meteorologia e Geofísica da APMG, Tavira, Portugal, 16 March 2015; p. 1.
28. Cota, T.; Pires, V.; Silva, Á.; De Lima, I.; Santo, F. Análise de Índices de Seca Meteorológica e Hidrológica Aplicação na Bacia Hidrográfica do Sado. In Proceedings of the VII Congresso Sobre uso e Manejo do Solo Conservação e Recuperação do Solo e da Água, Coimbra, Portugal, 13–15 July 2016; pp. 1–2.
29. Pathak, A.; Channaveerappa; Dodamani, B. Comparison of Two Hydrological Drought Indices. *Perspect. Sci.* **2016**, *8*, 626–628. [CrossRef]
30. Adnan, S.; Ullah, K.; Shuanglin, L.; Gao, S.; Khan, A.; Mahmood, R. Comparison of Various Drought Indices to Monitor Drought Status in Pakistan. *Clim. Dyn.* **2018**, *51*, 1885–1899. [CrossRef]
31. Bayissa, Y.; Maskey, S.; Tadesse, T.; van Andel, S.; Moges, S.; van Griensven, A.; Solomatine, D. Comparison of the Performance of Six Drought Indices in Characterizing Historical Drought for the Upper Blue Nile Basin, Ethiopia. *Geosciences* **2018**, *8*, 81. [CrossRef]
32. Fırat, E.; Yılmaz, K.; Aydın, H.; Kemeç, S.; Sürer, S.; Aras, M. Evaluation and Comparison of Drought Indices and Determination of Drought Events in Van Lake Basin, Turkey. In Proceedings of the 20th EGU General Assembly, EGU2018, Vienna, Austria, 8–13 April 2018; Volume 20, p. 13773.
33. Li, X.; Sha, J.; Wang, Z.L. Comparison of Drought Indices in the Analysis of Spatial and Temporal Changes of Climatic Drought Events in a Basin. *Environ. Sci. Pollut. Res.* **2019**, *26*, 10695–10707. [CrossRef] [PubMed]
34. Katipoglu, O.; Acar, R.; Şengül, S. Comparison of Meteorological Indices for Drought Monitoring and Evaluating: A Case Study from Euphrates Basin, Turkey. *J. Water Clim. Chang.* **2020**, *11*, 29–43. [CrossRef]
35. Silva, J.; Nogueira, H. Contributo dos Espaços Verdes para o Bem-Estar das Populações—Estudo de Caso em Vila Real. *Cad. Geogr.* **2014**, *33*, 117–121. [CrossRef]
36. Silva, Á. Analysis and Comparison of SPI and VHI for Drought Monitoring: Results for Mainland Portugal. In Proceedings of the Satellite Applications: Drought and Crop Monitoring, Lisbon, Portugal, 23 November 2015; pp. 1–19.
37. De Lima, I.; Silva, Á.; Coelho, M.; Pires, V. Análise de Eventos Extremos de Precipitação Nas Bacias Hidrográficas de Portugal Continental Através Do Índice SPI. In Proceedings of the 6.º Encontro de Engenharia Sanitária e Ambiental e XVI Simpósio Luso-Brasileiro de Engenharia Sanitária e Ambiental (APRH, APESB), Lisbon, Portugal, 5–8 March 2014.
38. Santo, F.; De Lima, I.; Silva, Á.; Pires, V. Precipitation variability and trend analysis using the standardized precipitation index. In Proceedings of the APMG 2015—9° Simpósio de Meteorologia e Geofísica da APMG, Tavira, Portugal, 16 March 2015; p. 1.
39. Páscoa, P.; Gouveia, C.; Russo, A.; Trigo, R. Drought Trends in the Iberian Peninsula over the Last 112 Years. *Adv. Meteorol.* **2017**, *2017*, 1–13. [CrossRef]
40. Russo, A.; Gouveia, C.; Páscoa, P.; Da Camara, C.; Sousa, P.; Trigo, R. Assessing the Role of Drought Events on Wildfires in the Iberian Peninsula. *Agric. For. Meteorol.* **2017**, *237–238*, 50–59. [CrossRef]
41. Ribeiro, A.; Russo, A.; Gouveia, C.; Pires, C. Drought-Related Hot Summers: A Joint Probability Analysis in the Iberian Peninsula. *Weather Clim. Extrem.* **2020**, *30*, 100279. [CrossRef]
42. United Nations. *The United Nations World Water Development Report 2021: Valuing Water*; United Nations Educational, Scientific and Cultural Organization: Paris, France, 2021; pp. 1–206.
43. Instituto Português do Mar e da Atmosfera (IPMA). Normais Climatológicas. Available online: https://www.ipma.pt/pt/oclima/normais.clima/?print=true (accessed on 1 August 2021).
44. Hersbach, H.; Bell, B.; Berrisford, P.; Biavati, G.; Horányi, A.; Sabater, J.; Nicolas, J.; Peubey, C.; Radu, R.; Rozum, I.; et al. ERA5 Hourly Data on Single Levels from 1979 to Present. Copernicus Climate Change Service (C3S) Climate Data Store (CDS). Available online: https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-pressure-levels?tab=overview (accessed on 1 April 2021).
45. FAO. *Evapotranspiración del Cultivo. Guías para la Determinación de los Requerimientos de Agua de los Cultivos*, 56th ed.; FAO: Rome, Italy, 2006; ISBN 92-5-304219-2.
46. Mavromatis, T. Drought Index Evaluation for Assessing Future Wheat Production in Greece. *Int. J. Climatol.* **2007**, *27*, 911–924. [CrossRef]

47. Pires, V. Intensity and Frequency of Extreme Meteorological Phenomena Associated to Precipitation. Developing of a Monitoring System for Drought in Mainland Portugal. Master's Thesis, University of Lisbon, Lisbon, Portugal, 2003. (In Portuguese)
48. IPMA. *Caracterização Climática 2004*; Instituto de Meteorologia: Lisbon, Portugal, 2004. Available online: https://www.ipma.pt/resources.www/docs/im.publicacoes/edicoes.online/20140903/NrWhlIgTddpLNJIybpiM/cli_20040101_20041231_pcl_aa_co_pt.pdf (accessed on 1 March 2022).
49. IPMA. *Caracterização Climática Ano 2005*; Instituto de Meteorologia: Lisbon, Portugal, 2005. Available online: https://www.ipma.pt/resources.www/docs/im.publicacoes/edicoes.online/20081014/KZcwnQrfVHeUZOaTzIth/cli_20050101_20051231_pcl_aa_co_pt.pdf (accessed on 1 March 2022).
50. García-Herrera, R.; Paredes, D.; Trigo, R.; Trigo, I.; Hernández, E.; Barriopedro, D.; Mendes, M. The Outstanding 2004/05 Drought in the Iberian Peninsula: Associated Atmospheric Circulation. *J. Hydrometeorol.* **2007**, *8*, 483–498. [CrossRef]
51. IPMA. *Boletim Climático Anual Portugal Continental 2017*; Instituto Português do Mar e da Atmosfera: Lisbon, Portugal, 2017. Available online: https://www.ipma.pt/resources.www/docs/im.publicacoes/edicoes.online/20180315/GLoWcBXPqGauRNYDpUAC/cli_20171201_20171231_pcl_aa_co_pt.pdf (accessed on 1 March 2022).
52. IPMA. *Boletim Climatológico Anual Portugal Continental 2018*; Instituto Português do Mar e da Atmosfera: Lisbon, Portugal, 2018. Available online: https://www.ipma.pt/resources.www/docs/im.publicacoes/edicoes.online/20190131/ddliTNijyEWyfrhUMDTy/cli_20180901_20181231_pcl_aa_co_pt.pdf (accessed on 1 March 2022).
53. IPMA. *Boletim Climatológico Anual Portugal Continental 2019*; Instituto Português do Mar e da Atmosfera: Lisbon, Portugal, 2019. Available online: https://www.ipma.pt/resources.www/docs/im.publicacoes/edicoes.online/20200318/piMisHmKRkiueuXQgHpM/cli_20191201_20191231_pcl_aa_co_pt.pdf (accessed on 1 March 2022).