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Spatio-Temporal Assessment of Meteorological Drought in Puerto Rico between 1950 and 2019 †

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Abstract: The phenomenon of drought is one of the most dangerous for small islands because of its impacts on freshwater availability. Thus, in this study, the spatio-temporal evolution of meteorological drought that affected the main island of Puerto Rico in the period 1950–2019 was investigated. In doing so, the Standardized Precipitation–Evapotranspiration Index (SPEI), using monthly values of minimum and maximum temperatures and precipitation derived from Daymet Version 4 daily data at a 1 km × 1 km spatial resolution, was used. At a 1 month temporal scale, the SPEI showed great temporal variability, but there was a clear tendency towards wetting in the last years of the study period. A total of 85 meteorological drought episodes were identified. The spatial analysis also revealed that major affectation by moderate drought conditions occurred across the half west and south of the island, by severe drought also in the west half of the island but also along the eastern coast, and finally the extreme drought conditions, which were less frequent, principally affected the northeast of the country. A trend analysis of the area affected by moderate, severe, and extreme drought conditions revealed a tendency to decrease, which is reflected by the prevalence of positive spatial trends of the SPEI1 across the country.

Keywords: drought; drought episodes; SPEI

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1. Introduction

Drought is one of the most frequent and dangerous natural disasters. According to previous studies, the complexity of this phenomenon allows for the separation of it into meteorological, agricultural, hydrological, and socioeconomic droughts [1,2], a classification widely utilized. Meteorological drought is characterized by a prolonged absence or marked deficiency of precipitation and, therefore, is considered a trigger for other types of droughts [3]. Because of this, many studies have focused on investigating the meteorological droughts to assess the propagation of dry conditions, the occurrence of long-term drought events, and their impacts. However, the combination of rainfall deficits and increased atmospheric water demand may lead to a prolonged and pronounced decline in soil moisture [4]. The atmospheric water demand is highly modulated by some factors, such as the temperature, which plays an important role in the modulation of local evapotranspiration, and consequently on the severity of drought. For this reason, drought indices that consider just precipitation may lack a correct assessment of drought conditions, particularly, in energy-limited regions. Despite this, drought indices based on precipitation, such as the Standardized Precipitation Index (SPI) [5], have been widely used and recommended by the World Meteorological Organization.

Small islands are especially vulnerable to the effects of severe drought due to the impact on the limited freshwater resources, which are crucial for social and economic activities such as agriculture. The small archipelago of Puerto Rico is located in the Caribbean Sea and is commonly affected by drought [6–8]. During the 20th century, Puerto Rico has experienced periods of major droughts that have caused great economic, social, and agricultural consequences [9]. The period 1966–1968 was one of the most severe because the mean annual rainfall was 32% below normal [7]. Between 2000 and 2016, 92.01% of territory of Puerto Rico experienced periods of drought; the most recent widespread event was between 2014 and 2016, resulting in water deficits in 86% of the island's territory and substantial losses in the agricultural sector [9,10]. Over 13 million dollars in agricultural losses were reported in 2015, affecting mainly the livestock [10]. This highlights the region's agricultural vulnerability and the growing need for adjustment mechanisms that support sustainable production. Thus, drought remains a persistent issue affecting regional agricultural production, yet its effects on the region's agricultural economy are still poorly understood. Therefore, in this study, we aimed to investigate the spatio-temporal evolution of meteorological drought in mainland Puerto Rico for the period 1950–2019. The statistical analysis will permit the identification of those regions more frequently affected by drought conditions and determine the trends in wet/dry conditions. Findings by Méndez-Tejeda [11] revealed that the average temperature in Puerto Rico has increased by 2.24 °C during the period 1950–2014. This is why the role of temperature in the identification of drought conditions will be taken into account.

Region of Study

Puerto Rico is a small archipelago located in the humid tropics at a latitude of 18.25° (Figure 1) [12]. It is surrounded by the Atlantic Ocean, but on the south and west extends into the Caribbean Sea. In this position, it lies directly in the path of the trade winds associated with the North Atlantic subtropical high-pressure system (NASH), which provides moisture to precipitation [7,8]. Moreover, owing to its geographical location, Puerto Rico is exposed to major tropical storms. Hurricanes, in particular, are one of the major environmental disruptions in Puerto Rico, being capable of delivering a great amount of rainfall to the island [12–14].

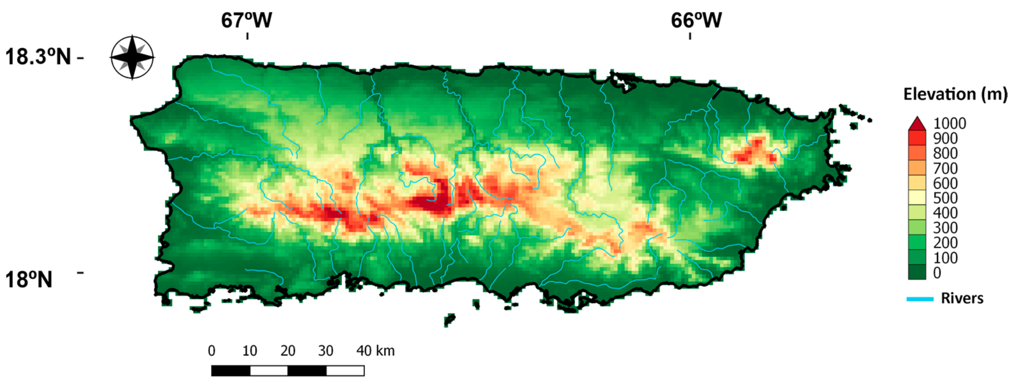

Figure 1. Geographical location and elevation map of the main island Puerto Rico from Lehner et al. [15].

The entire center of the island is a continuous series of mountains that extend from east to west, named "La Cordillera Central", which highlights the mountain Cerro de Punta with a major altitude of 1338 m. The average rainfall in the northern part of the island is approximately 1550 mm, while in the southern part it is approximately 910 mm. Some coastal regions receive rainfall around 3810 cm per year, while some areas in the mountains receive more than 5000 mm of rain annually [13].

2. Methodology and Data Sets

2.1. Identification of the Drought Episodes: The Standardized Precipitation–Evapotranspiration Index (SPEI)

The Standardized Precipitation–Evapotranspiration Index (SPEI) [16] was utilized to identify dry conditions in mainland Puerto Rico from 1950 to 2019. This index is based on the same methodology used to calculate the Standardized Precipitation Index (SPI) [5], but instead of using only precipitation data, the SPEI takes into account the effects of temperature through the atmospheric evaporative demand or the evapotranspiration ($Et0$) in the climatic water balance represented in Equation (1):

$$D = (P - Et0) \tag{1}$$

where D represents the water balance over a given period, P is the precipitation, and $Et0$ the evapotranspiration. Thus, the SPEI combines the water balance with the multiscalar nature of the SPI [17], which permits for the assessment of the response of different systems (e.g., hydrological and agricultural) to drought [18]. The $Et0$ was calculated using the Hargreaves method [19]. This method computes $Et0$ as a function of minimum and maximum temperatures and extraterrestrial radiation. For the calculation of $Et0$, Equation (2) was used:

$$Et0 = 0.0023 \times Ra \times \left(\sqrt{Tx - Tn}\right) \times (Tm + 17.8) \tag{2}$$

where 0.0023 is a constant value; Ra is the extraterrestrial radiation (derived from the latitude and the month of the year); Tx, Tn, and Tm are the maximum, minimum, and mean temperature, respectively.

The SPEI has been widely used for identifying dry and wet conditions and evaluating drought severity in many regions of the world. We chose the SPEI at a one-month time scale (SPEI1), which corresponds to the water balance for one month, the most appropriate time scale for identifying meteorological droughts. The classification of drought categories for SPI values proposed in [5] (Table 1) was used in this study.

Table 1. Drought classification according to that proposed by McKee et al. [5].

SPEI Values	Drought Category
0 to -0.99	Mild
-1 to -1.49	Moderate
-1.50 to -1.99	Severe
≤ -2	Extreme

2.2. Data Sets

Daymet Version 4 monthly climate summaries for Puerto Rico, derived from Daymet Version 4 daily data at a 1 km $\times$ 1 km spatial resolution for three Daymet variables, minimum and maximum temperatures and precipitation [20], were used. Data sets are available for a long period of study (1950–2019). This database is based on a combination of interpolation and extrapolation, using inputs from multiple instrumented sites and weights for each site that reflect the spatio-temporal relationship. The approximate number of instrumental observations to use for each estimation is defined as a parameter for each of the primary Daymet variables. More details about this data set and previous versions are provided by Thornton et al. [20], Menne et al. [21], and Menne et al. [22]. Previous studies have also used this data set to investigate the relationship between seasonal precipitation and the thermodynamic environment in Puerto Rico [23].

3. Results and Discussion

3.1. Temporal Evolution of the SPEI at a 1 Month Temporal Scale

Figure 2a shows the temporal evolution of the SPEI1 from 1950 to 2019. As appreciated, the variability of the series was high, although, it highlighted some periods, such as 1963–1969, 1980–1988, and 1990–1998, because of the affectation of severe and extreme drought conditions. This is in agreement with previous findings that quantified a rainfall decrease over Puerto Rico between 1990 and 1997, which caused a severe drought, reducing the streamflow and the water reservoir, which affected more than 1 million people in the capital, San Juan [7]. A trend analysis for the whole period revealed a positive trend although not statistically significant at $p < 0.05$. However, a more in-depth study is being conducted to determine possible points of change in the series and their respective trends.

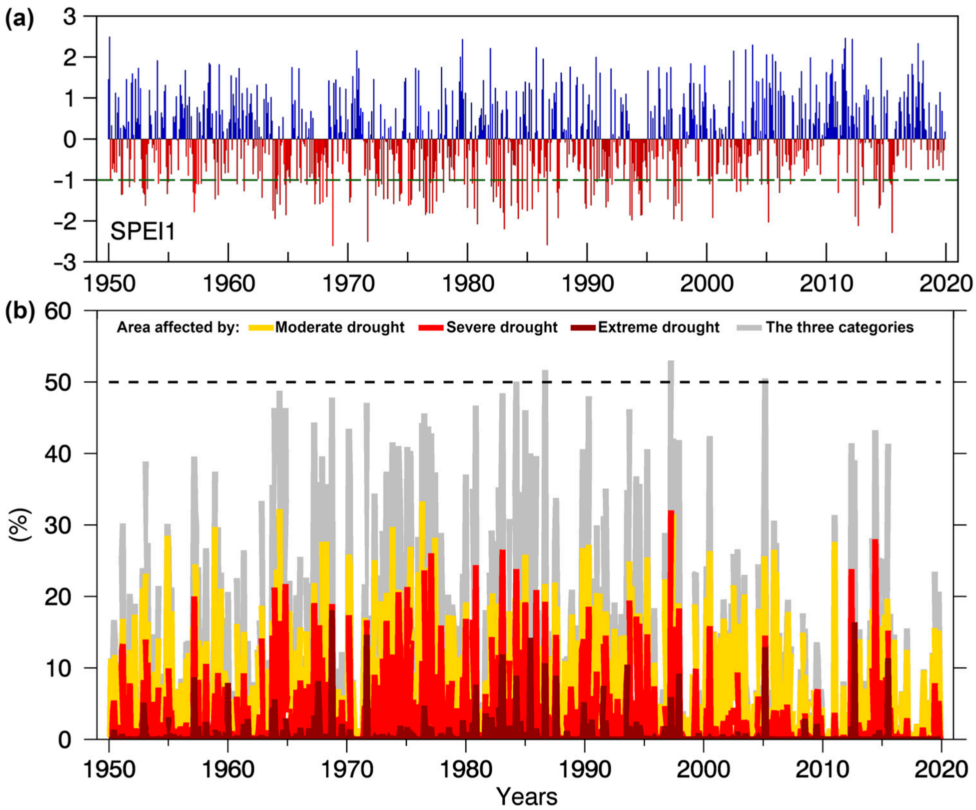

Figure 2. Temporal evolution of the SPEI1 (**a**) and the area affected by moderate, severe, and extreme drought conditions and their sum (**b**). Period: 1950–2019.

The temporal evolution of the area affected by each category of drought, according to the range of SPEI values (Table 1), and the sum of them is shown in Figure 2b. The mild drought category was not considered in this analysis as it reflects normal conditions. A visual analysis confirms that along the study period, the area affected by moderate, severe, and extreme drought conditions rarely exceeded 50% of the area of mainland Puerto Rico. In addition, the percentage of the area affected was higher for moderate drought conditions, followed by severe and lesser percentages for extreme drought. A trend analysis revealed a statistically significant ($p < 0.05$) decrease in the area (in %) of mainland Puerto Rico affected by moderate, severe, and extreme drought.

For the entire period of study, there were 85 identified meteorological drought episodes, which are listed in Table 2 as well as their duration, severity, and peak. The most severe (17.55) and longest (18 months) episode occurred from August 1993 to January 1995. This episode affected the entire year of 1994, for which a significant rainfall deficit over Puerto Rico was reported [24,25]. The second most severe drought episode (12.8) affected mainland Puerto Rico from March 1967 to May 1968 (15 months), while the third most severe (7.9) was identified from March 1991 to December 1991 (10 months). The durations of the remaining drought episodes were less than 10 months. The occurrence of other episodes, such as March–September 2015 and others during 1982, are in agreement with already reported severe dry conditions in Puerto Rico. Work is underway on seasonal drought analysis and the use of other SPEI time scales to investigate the occurrence of extreme drought conditions, such as those reported for the summer of 2015 [26].

Table 2. Number of drought episodes that affected Puerto Rico between 1950 and 2019 ordered by date of occurrence. The information of the Onset, End, Duration (D) expressed in months, Severity (S), and Peak (P) is also provided. The names of the months are abbreviated as: January (Jan), February (Feb), March (Mar), April (Apr), May (May), June (Jun), July (Jul), August (Aug), September (Sep), October (Oct), November (Nov) and December (Dec).

No.	Onset	End	D	S	P	No	Onset	End	D	S	P	No	Onset	End	D	S	P
1	Mar-50	Mar-50	1	1.0	−1.0	30	Sep-73	Dec-73	4	2.7	−1.6	59	Apr-90	May-90	2	2.4	−1.6
2	Feb-51	Mar-51	2	2.7	−1.4	31	Feb-74	Jul-74	6	5.5	−1.5	60	Jul-90	Aug-90	2	1.5	−1.4
3	Oct-51	Nov-51	2	1.7	−1.2	32	Dec-74	Feb-75	3	1.7	−1.6	61	Nov-90	Nov-90	1	1.0	1.0
4	Mar-52	Mar-52	1	1.1	−1.1	33	Apr-75	Aug-75	5	5.1	−1.6	62	Mar-91	Dec-91	10	7.9	−1.7
5	Oct-52	May-53	8	7.7	−1.6	34	Jan-76	Jan-76	1	1.3	−1.3	63	Feb-92	Feb-92	1	1.1	−1.1
6	Mar-54	Mar-54	1	1.1	−1.1	35	May-76	Sep-76	5	6.0	−1.9	64	Aug-93	Jan-95	18	17.6	−2.0
7	Nov-54	Apr-55	6	4.5	−1.3	36	Nov-76	Dec-76	2	2.9	−1.8	65	Mar-95	Apr-95	2	1.9	−1.5
8	Jan-57	May-57	5	5.9	−1.8	37	Feb-77	Jun-77	5	5.6	−1.8	66	Oct-96	Oct-96	1	1.5	1.5
9	Jul-57	Jul-57	1	1.1	−1.1	38	Dec-77	Jan-78	2	2.0	−1.3	67	Mar-97	Sep-97	7	7.5	−2.0
10	Oct-57	Oct-57	1	1.1	−1.1	39	May-78	Sep-78	5	2.8	−1.0	68	Nov-97	Dec-97	2	2.7	1.3
11	Oct-58	Dec-58	3	2	−1.5	40	Nov-78	Jan-79	3	2.2	−1.0	69	Feb-00	Apr-00	3	2.1	−1.1
12	Dec-59	Mar-59	2	1.9	−1.4	41	Oct-79	Oct-79	1	1.1	−1.1	70	Jun-00	Jul-00	2	2.8	−1.9
13	Jun-59	Jun-59	1	1	−1	42	Dec-79	Mar-80	4	2.5	−1.7	71	Jan-02	Feb-02	2	1.2	−1.0
14	Oct-60	Oct-60	1	1.1	−1.1	43	Jun-80	Aug-80	3	3.5	−1.7	72	May-02	Dec-02	8	5.5	−1.3
15	May-61	Jun-61	2	1.4	−1.3	44	Oct-80	Nov-80	2	2.4	−2.1	73	May-03	Sep-03	5	3.0	−1.1
16	Nov-62	Dec-62	2	1.6	−1.4	45	Jan-82	Jan-82	1	1.2	−1.2	74	Aug-04	Aug-04	1	1.1	−1.1
17	Oct-63	Mar-64	6	7.2	−1.9	46	Mar-82	Apr-82	2	2.6	−1.5	75	Feb-05	Mar-05	2	3.1	−2.0
18	May-64	Jul-64	3	1.8	−1.6	47	Jun-82	Jun-82	1	1.4	−1.4	76	Feb-06	Feb-06	1	1.3	−1.3
19	Sep-64	Apr-65	8	7.5	−1.9	48	Aug-82	Oct-82	3	3.0	−1.7	77	Aug-06	Feb-07	7	3.8	−1.1
20	Jan-66	Feb-66	2	1.8	−1.1	49	Jan-83	Feb-83	2	4.0	−2.2	78	Jan-11	Feb-11	2	1.7	−1.3
21	Aug-66	Aug-66	1	1.1	−1.1	50	Aug-83	Jan-84	6	3.9	−1.6	79	Jun-12	Jun-12	1	1.9	−1.9
22	Mar-67	May-68	15	12.8	−1.6	51	Mar-84	May-84	3	3.6	−1.9	80	Sep-12	Sep-12	1	2.1	−2.1
23	Sep-68	Oct-68	2	3.5	−2.6	52	Jul-84	Aug-84	2	1.9	−1.7	81	Nov-12	Feb-13	4	2.0	0.5
24	Feb-70	Apr-70	3	3.8	−1.5	53	Jan-85	Jan-85	1	1.8	−1.8	82	Jan-14	Jan-14	1	1.0	−1.0
25	May-71	Sep-71	5	4.3	−2.5	54	Jun-85	Aug-85	3	3.0	−1.7	83	Mar-14	Jul-14	5	5.1	−1.7
26	Apr-72	Sep-72	6	5.1	−1.4	55	Dec-85	Mar-86	4	3.2	0.8	84	Sep-14	Oct-14	2	1.4	−1.3
27	Nov-72	Nov-72	1	1.1	−1.1	56	Jun-86	Oct-86	5	4.8	−2.6	85	Mar-15	Sep-15	7	6.9	−2.3
28	Jan-73	Jan-73	1	1.5	−1.5	57	Jul-87	Oct-87	4	4.5	−1.9						
29	Mar-73	May-73	3	1.6	−1.5	58	Oct-89	Dec-89	3	3.9	1.3						

3.2. Spatial Analysis of the SPEI1

Figure 3a–c show the frequency of moderate, severe, and extreme drought conditions according to the classification of the SPEI1 provided in Table 1, except for mild drought. It is noted that a major frequency of moderate drought prevailed in the western half of the island, but also along the southern coast. For severe drought, the major frequency occurred in the west half of the island, but also along the east and south-east coast. However, the map of extreme drought frequency shows a different pattern, with the highest occurrence of months affected by extreme drought conditions being in the northeast of the island. As expected, the frequency of SPEI1 ≤ -1 (Figure 3d) also showed that the occurrence of drought conditions was more frequent in western mainland Puerto Rico. Indeed, the trade winds from the east and the orographic effects from the Cordillera Central and the Sierra de Cayey mountains in Puerto Rico result in the greater amount of rainfall in the Sierra de Luquillo rainforest, in the eastern part of Puerto Rico [27]. Moreover, during the cyclonic season, the tropical cyclones' rainfall contribution is also greater in the east-half of the country [14].

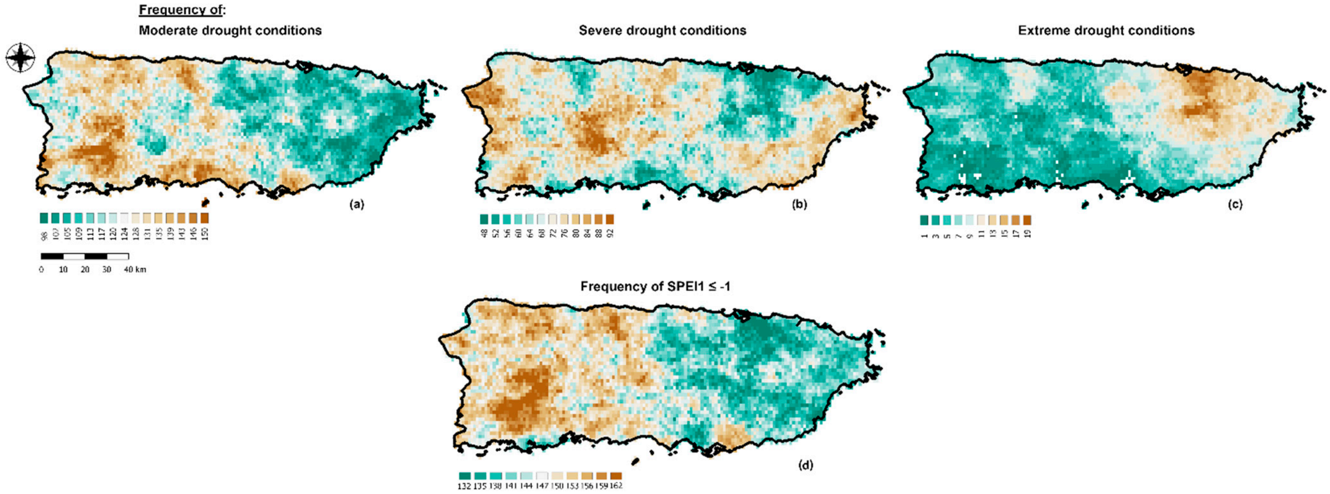

Figure 3. Monthly frequency of moderate (**a**), severe (**b**), and extreme (**c**) drought conditions in mainland Puerto Rico and the frequency of drought conditions considering the three categories (**d**). Period 1950–2019.

A spatial trend analysis of the SPEI1 revealed positive values in a major part of mainland Puerto Rico, which indicated an evolution towards wetting conditions during the period 1950–2019 (Figure 4). This increase was higher and statistically significant in the northeastern region, along the southern coast, and from the south to north in the central-west region. Areas with negative trends were smaller and not as intense as the positive. This result is in agreement with previous studies. For a shorter period of study (1981–2019), there has been documented a positive precipitation and soil moisture trend in mainland Puerto Rico [24]. For a region with a negative trend of the SPEI1 in the northeast (Figure 4), there has been documented, in contrast, an increasing trend in the precipitation during a shorter study period (2001–2013) [28]. A study carried out using other precipitation and temperature data sets to compute in the Self-Calibrating Palmer Drought Severity Index also showed that over a long period of time (1950–2016), the trend was towards an increase in humid conditions in Puerto Rico [26].

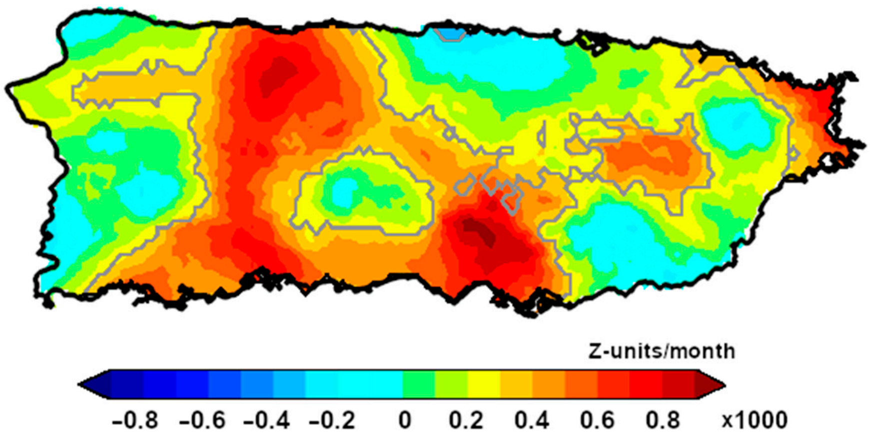

Figure 4. Linear trend in the SPEI1 between 1950 and 2019. The gray line encloses statistically significant trends at $p < 0.05$.

4. Conclusions

In this study, the spatio-temporal evolution of meteorological drought in Puerto Rico through the Standardized Precipitation–Evapotranspiration index (SPEI) at a 1 month temporal scale for the period 1950–2019 was investigated. The high-resolution data sets utilized to compute this index together with the long period of study permitted an accurate spatial assessment. A total of 85 drought episodes were identified, for which were calculated their main characteristics. The most severe occurred from August 1993 to January 1995 (18 months). The results also showed that moderate and severe drought conditions were more frequent in the west half of mainland Puerto Rico, while extreme drought conditions were less frequent but, on the contrary, have mostly affected the northeast of the island. A trend towards wetting conditions was observed for a major part of mainland Puerto Rico and, consequently, a decrease in the area affected by moderate, severe, and extreme drought. However, a change-point analysis could be useful for identifying different trends signs across the territory. To deepen the results, the processes of temporal and spatial propagation of drought are under research as well as their relationship with synoptic conditions and different modes of climate variability.

Author Contributions: R.S., R.M.-T., R.N. and L.G. conceived the idea of the study. R.S., R.M.-T. and M.S. wrote the manuscript. M.S., R.S., J.C.F.-A. and A.P.-A. made the figures. All the authors discussed the results and revised the final document. All authors have read and agreed to the published version of the manuscript.

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