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Drought Assessment in Zacatecas, Mexico

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Abstract: Water has always been an essential development factor for civilizations, but its erratic distribution in space and time has caused severe socio-economic problems throughout human history due to both scarcity and excess. In Mexico, insufficient rainwater to satisfy crop water requirements is a recurrent phenomenon. From a meteorological perspective, drought refers to a decay of the rainfall–runoff process below normal values, resulting in lower availability of water resources to satisfy the needs of human activities, particularly those related to agriculture and livestock. This research reports on drought assessment for Zacatecas, Mexico using monthly data from 111 weather stations with temperature and precipitation information from a 33-year period. Drought was characterized by applying the Standardized Precipitation Index and the Reconnaissance Drought Index using 3, 6, and 12 month timescales; both indexes were plotted and mapped for the period 2005 to 2014. The trend indicates rainfall anomalies (from incipient drought to severe drought) in 6 or 7 years, depending of the selected timescale. April was selected to start the drought analysis because it is the month when farmers usually establish rainfed crops in the region. In ten years, Zacatecas has lost 478 million US dollars due to drought. 2005, 2009, and 2011 were the most critical years, with 47%, 39%, and 63% losses in agricultural income. Such values are in agreement with drought severity estimates: 2005 and 2011 were both dry years (drought indexes were less than −1.25 in the whole territory).

Keywords: drought mapping; SPI and RDI estimations; agricultural losses

1. Introduction

The progress of humanity has taken place around water. This natural resource has been an essential development factor for civilizations, but its erratic distribution in space and time has caused severe socio-economic problems along human history due to both scarcity and excess. In the last decades, countries around the world have faced unprecedented extreme weather events causing major human suffering and economic damages to infrastructure and productive sectors [1–3]. In the particular case of dryland agriculture, changes in precipitation directly impact crop production. Consequently, farmers need to adapt their practices to the changing rainfall patterns. The geographical location of rainfed agricultural areas determines that potential evapotranspiration is often higher than precipitation. In these conditions, crop yield is almost always lower than potential, and the yield gap increases as drought intensifies [4,5]. In Mexico, insufficient rainwater to satisfy crop water requirements is a recurrent phenomenon. Padilla et al. [6] reported 39 droughts from 1821 to 1910, and classified them as severe, moderate or incipient, taking into account their effects on agricultural production. Additionally, several studies have illustrated the recurrence of water scarcity in the Mexican Northeast. As an example, regional political representatives requested the construction of dams and wells to mitigate losses of livestock and crops occurring in various years during the 1935–1958 period [7]. The frequency and economic cost of droughts have increased from 1988 to the present time. The yield of extensive and intensive crops in 4.2 Mha of irrigated and non-irrigated land located in the center and north of Mexico has been reduced. Additionally, 292,438 cattle died in seven years (1988–1994). Moreover, during a period of thirteen years (1993–2005) the Rio Bravo watershed (a basin shared between the USA and Mexico) suffered the most prolonged registered drought, with strong social and economic consequences for the region. Finally, the second most devastating drought in 60 years was observed in 2009, and in 2011 40% of Mexican territory experienced the worst drought in 70 years, losing 2.7 Mha of cultivated land [8,9].

The study of drought involves multiple perspectives. From a purely meteorological perspective, drought refers to a decay of the rainfall–runoff process below normal values, resulting in insufficient water resources to satisfy the needs of human activities, particularly those related to agriculture and livestock [10–13]. A number of drought indexes have been developed to quantitatively characterize the intensity, duration and frequency of a drought. The Index of Palmer Drought Severity (IPDS), Standardized Precipitation Index (SPI), and Reconnaissance Drought Index (RDI), are some of the methodologies proposed to assess the effects of this natural phenomenon [14–16]. Among these indexes, SPI has been widely used because (1) it is easy to compute, as it only requires precipitation data; (2) it is unaffected by geographical or topographical differences; (3) it is spatially invariant in drought interpretation; (4) it has a probabilistic approach; and (5) it is an excellent predictor of soil moisture that allows crop production to be predicted from the prevailing precipitation conditions [17–19]. More refined estimations of drought require analysis of the relationship between water demand and supply through the analysis of potential evapotranspiration (ETP) and precipitation. In fact, these are the two climatic factors directly related to vulnerability in crop production. In this respect, the RDI index was developed to characterize drought events as the ratio of precipitation and ETP [19]. A study by Elagib [20], focused on drought duration, showed that SPI estimated for three-month periods can effectively characterize the agricultural effects of drought. When the purpose is to characterize hydrological drought events, a period of SPI calculation of 12 months is required. Vicente-Serrano et al. [18] selected timescales of 1, 3, 6, and 12 months to predict cereal production in the central Ebro valley of Spain, taking into account February as the sowing date and combining information of remote sensing and SPI; their findings show the highest correlations for 1 month and 3 month SPI timescales. Furthermore, Tsakiris et al. [21] used RDI to estimate drought impacts on crop yield in rainfed agriculture for the region of Thessaly, Greece. The authors identified five relevant drought events in the 1955–2002 period. The hydrological year of 1965–1966 presented the maximum yield loss, reaching 100%, 50%, and 35% for maize, wheat, and sorghum, respectively. Spinoni et al. [22] conducted a study in Europe to identify critical drought events in 1950–2012 using SPI and RDI. These authors showed that Northern Europe and Russia suffered the highest drought frequency, duration, and severity in the 1950s and 1960s. In Central Europe and the British Islands, the critical period was the 1970s, while in the Mediterranean area and the Baltic Republics the worst drought was observed in the 1990s and 2000s. On the other hand, Naumann et al. [23] assessed the damage of drought in cereal crop production and hydropower generation for 21 European countries. They presented maps on drought severity and damages; in the case of cereal crop production and drought severity, the best correlation occurred for indexes computed in a three-month timescale. Jayasree and Venkatesh [24] analyzed drought using daily rainfall data available for 178 rain gauge stations in Karnataka, India. Methodology included the evaluation of aridity as well as the variability of precipitation in the region. They reported that 51% of the area was under extreme drought, 41% under severe drought, and 8% under moderate drought.

The present research reports on drought characterization by applying SPI and RDI and using timescales of 3, 6, and 12 months to associate drought severity and crop yield losses. From a practical perspective, the mapping of drought indexes permits to reveal spatial and temporal patterns for a specific region. Drought maps were created using monthly data from 111 weather stations for the period of 1981–2014 in the state of Zacatecas, Mexico [25]. Ten drought events were selected to compare both indexes in humid and dry scenarios.

2. Materials and Methods

2.1. Location of Study

Zacatecas is located in the Northern region of Mexico, between extreme geographical coordinates 21°01′45.0″ N latitude and 100°43′34.3″ W longitude, and 25°07′21.5″ N latitude and 104°22′56.4″ W longitude (Figure 1). The West and Southwest of the territory is part of the *Sierra Madre Occidental* mountain range conformed by plateaus reaching 2850 m above sea level. The Central portion is set in the *Meseta Central* Highland, with valleys around 1000 m above sea level. The North is part of the *Sierra Madre Oriental* mountain range, with the highest elevations of the State, reaching an altitude of 3200 m above sea level [26]. Zacatecas climate is semiarid, with minimum and maximum mean monthly temperatures of 6.5 °C (January), and 29.6 °C (May), respectively. Average annual precipitation is approximately 350 mm, of which 80% occurs from June through September. A total of 1.7 Mha are devoted to agriculture, and 89% of this area is under rainfed conditions. A network composed of 111 weather stations located within the area of study was used to measure daily rainfall, and daily minimum, maximum, and average air temperature. The weather stations are monitored by the National Water Commission of the Mexican Government.

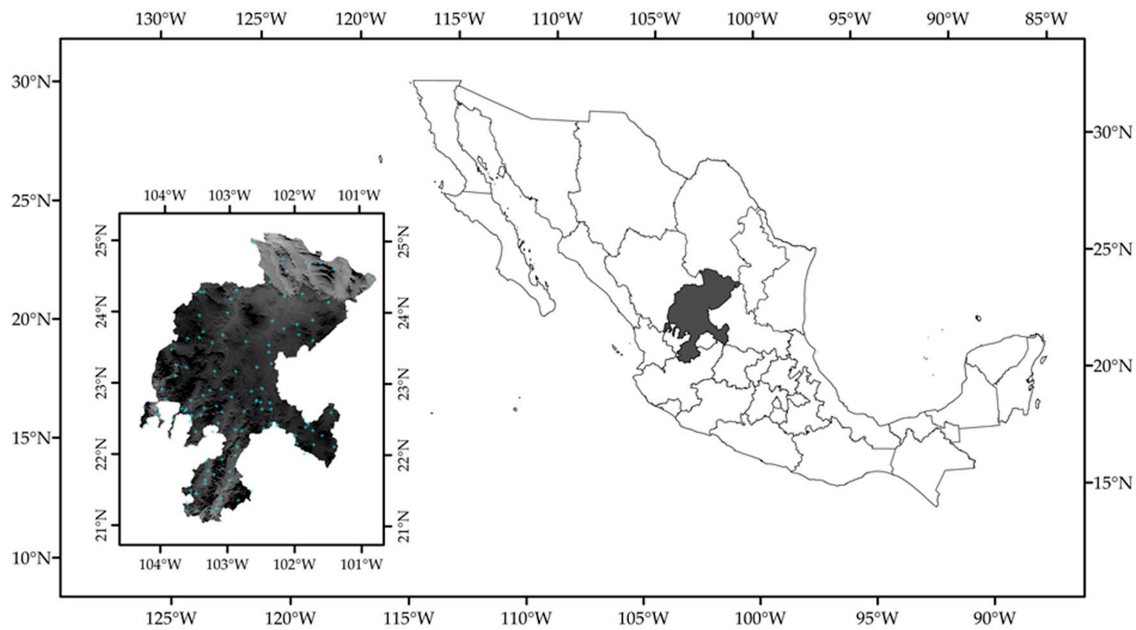

Figure 1. Geographical location of Zacatecas, Mexico. Blue dots represent weather stations.

2.2. SPI and RDI Approaches

Soil moisture conditions respond to rainfall anomalies in a short time, while groundwater, runoff and reservoir storage reflect water scarcity in the mid to long term. The SPI and RDI approaches can assess water deficit using different timescales [27], and using historical records of precipitation or precipitation/potential evapotranspiration, respectively. The dataset was adjusted to the Probability Density Function (PDF) to transform raw information to standardized normal distributions. Both indexes represent the number of standard deviations separating an observation from the historical average [7], with values between −3.0 and 3.0. A negative index expresses water deficit. Drought intensity increases as the value reaches −3.0 [28]. To take into account variations in precipitation occurring among months, the incomplete Gamma distribution (Equation (1)) is the commonly used PDF to characterize the drought phenomenon [29,30].

$$G(x) = \frac{1}{\Gamma(\alpha)} \int_0^x t^{\alpha-1} e^{-t} dt \tag{1}$$

Parameters $\Gamma(\alpha)$, α, and β are obtained as

$$\Gamma(\alpha) = \int x^{\alpha-1} e^{-x} \tag{2}$$

$$\alpha = \frac{1}{4A}\left(1 + \sqrt{1 + \frac{4}{3}A}\right) \quad \beta = \frac{\bar{x}}{\alpha} \quad A = \ln(\bar{x}) - \frac{\sum \ln(x)}{n'} \tag{3}$$

where α is a shape parameter (adim); β is a scale parameter (adim); n' is the precipitation data (no zeroes); x is precipitation (mm) or precipitation/potential evapotranspiration (adim) in month *i*; and $\bar{x}$ is the average precipitation (mm) or the average ratio of precipitation to potential evapotranspiration (adim) in the analyzed period. For α values lower than 5.6, the shape parameter was corrected by subtracting $\Delta\alpha$ (Equation (4)) to consider the maximum likelihood estimation of the Gamma distribution parameters [10,31].

$$\Delta\alpha = a_0 + a_1\alpha + a_2\alpha^2 + a_3\alpha^3 + a_4\alpha^4 + a_5\alpha^5 \tag{4}$$

Equation (4) includes the a_i coefficients, as determined by Thom [32]. Since Equation (1) is not defined for x = 0, and the dataset contains months without precipitation, Equation (5) must be used to account for zero value probability [29].

$$H(x) = q + (1-q)\,G(x); \quad \text{If } x = 0, \quad H(0) = q \tag{5}$$

where H(x) is a cumulative probability function (adim), q is the probability of zeroes, which is determined using the relationship between the number of zeroes and the total number of data (adim), and $1 - q$ (adim) is the probability of values different from zero. Finally, Equation (5) is transformed into a normal distribution with a random variable Z (Equation (6)) with mean of zero and standard deviation of one [30,33].

$$Z = \begin{cases} -\left(t - \frac{c_0 + c_1 t + c_2 t^2}{1 + d_1 t + d_2 t^2 + d_3 t^3}\right) & \text{for } 0 < H(x) \leq 0.5 \\ \left(t - \frac{c_0 + c_1 t + c_2 t^2}{1 + d_1 t + d_2 t^2 + d_3 t^3}\right) & \text{for } 0.5 < H(x) < 1 \end{cases} \tag{6}$$

$$t = \begin{cases} \sqrt{\ln\left(\frac{1}{(H(x))^2}\right)} & \text{for } 0 < H(x) \leq 0.5 \\ \sqrt{\ln\left(\frac{1}{(1-H(x))^2}\right)} & \text{for } 0.5 < H(x) < 1 \end{cases} \tag{7}$$

In the estimation of SPI and RDI, x values represent cumulative precipitation or the relationship between cumulative precipitation and cumulative potential evapotranspiration in the period, respectively.

2.3. Drought Severity Assessment

Drought severity was assessed through SPI and RDI. Both indexes were computed to evaluate agricultural and hydrological drought. For each case, Z values were interpolated to obtain the quantitative magnitude of drought and the qualitative duration and frequency of drought. In this study, SPI and RDI were estimated in the initial (x) and standardized forms. The x values were calculated for the i-th year in a timescale basis of k months. Equation 8 was used to estimate the initial values of SPI.

$$x_k^{(i)} = \sum_{j=1}^{k} P_{ij} \quad i = 1, 2, 3, \ldots, N \quad j = 1, 2, 3, \ldots, k \tag{8}$$

The initial RDI was estimated with Equation (9). This is applicable to the estimation of RDI in both normalized (RDI_n) as standardized (RDI_{st}) forms [29,34,35]. RDI_n and RDI_{st} were obtained using Equations (10) and (11), respectively. However, Equation (11) is not defined for initial values equal to zero. For this reason, RDI_{st} is usually calculated by fitting the Gamma PDF [15,36–38].

$$x_k^{(i)} = \frac{\sum_{j=1}^{k} P_{ij}}{\sum_{j=1}^{k} PET_{ij}} \quad i = 1, 2, 3, \ldots, N \quad j = 1, 2, 3, \ldots, k \tag{9}$$

$$RDI_n^{(i)} = \frac{x_k^{(i)}}{\overline{x_k^{(i)}}} - 1 \tag{10}$$

$$RDI_{st}^{(i)} = \frac{y_k^{(i)} - \overline{y_k^{(i)}}}{\hat{\sigma}_{yk}} \qquad y_k^{(i)} = \ln x_k^{(i)} \tag{11}$$

in which P_{ij} and PET_{ij} are the precipitation and the potential evapotranspiration of the j-th month of the i-th year, and N is the total number of years in the available data set. According to Kousari et al. [15] and Zarch et al. [29] both SPI and RDI perform similar for Gamma distribution (Equations (1)–(7)), this approach solves the problem of lognormal distribution (Equation (11)) which includes zero values of precipitation. In this sense, Equation (12) express the condition of SPI_{st} and RDI_{st}.

$$Z = \begin{cases} SPI_{st} & \text{If Z is estimated from Equation (8)} \\ RDI_{st} & \text{If Z is estimated from Equation (9)} \end{cases} \tag{12}$$

Potential evapotranspiration was estimated using the Thornthwaite method (Equation (13)) because is only based on temperature. Additionally, RDI estimation has been found to be similar when the index is computed using more sophisticated PET methodologies, such as the FAO Penman-Monteith [35,37].

$$PET = 16\, K_a \left(10 \frac{\overline{T}}{I}\right)^a \tag{13}$$

$$I = \sum_{m=1}^{12} \left(\frac{\overline{T}_m}{5}\right)^{1.514} \qquad a = 675 \times 10^{-9}\, I^3 - 771 \times 10^{-7}\, I^2 + 179 \times 10^{-4}\, I + 0.492 \tag{14}$$

where PET is potential evapotranspiration (mm), $\overline{T}$ is the mean temperature for the month (Celsius); K_a is a constant depending on the latitude and the month for the year (adim); and I is the temperature efficiency index (adim).

Z values for both SPI and RDI can be related to drought severity. Table 1 shows the relationship between Standardized Precipitation Index or Reconnaissance Drought Index and drought condition [39].

Table 1. Z values vs. drought condition (applicable to both Standardized Precipitation Index and Reconnaissance Drought Index).

Index Value	Condition
$Z < -1.91$	Exceptional drought
$-1.90 < Z \leq -1.51$	Extreme drought
$-1.50 < Z \leq -1.21$	Severe drought
$-1.20 < Z \leq -0.71$	Moderate drought
$-0.70 < Z \leq -0.51$	Incipient drought
$-0.50 < Z \leq 0.51$	Normal conditions

Table 1. *Cont.*

Index Value	Condition
0.51 < Z ≤ 0.70	Incipient wet
0.71 < Z ≤ 1.20	Moderate wet
1.21 < Z ≤ 1.50	Very wet
1.51 < Z ≤ 1.90	Extreme wet
1.91 < Z	Exceptional wet

2.4. Software for Data Analysis and Drought Mapping

The database was assembled in a Microsoft® Excel 2016 spreadsheet. For every weather station data were filtered and chronologically sorted. Daily precipitation and reference evapotranspiration data went through a quality check to identify spurious values. Subsequently, these daily values were transformed into monthly average series. The methodology described in Equations (1)–(14) for SPI and RDI calculations was performed with a MATLAB software script. Z values were interpolated using the ordinary Kriging method due to its benefits in comparison with alternative, traditional methods. Thiessen polygons and arithmetic procedures have been reported to overestimate average rainfall [40]. Kriging interpolation is based in a mathematical multistep process, and an exploratory statistical analysis minimizes its predictive errors [41–44]. Kriging is a standard method of optimal interpolation included in ArcMap for ArcGIS® with a 0.005 output cell size.

3. Results and Discussion

A number of drought studies recognized SPI and RDI as meteorological and agricultural indexes, respectively [45]. Other authors have found that SPI for a 3 month timescale can be used to estimate agricultural droughts, while a 12-month timescale is useful to evaluate hydrological droughts [18,20,46]. Based on the monthly homogeneous precipitation and temperature dataset, SPI and RDI were mapped using 3, 6, and 12 months timescales. Producers choose a specific sowing date according to regional customs; farmers who irrigate tend to sow as early as possible to take advantage of the market (high prices for early producers). Farmers who do not irrigate wait for the best opportunity that precipitation can provide, choosing the sowing date empirically after the first significant rainfall. For rainfed crops, the sowing period usually oscillates between April and July, depending on the type of crop established and once precipitation starts [47,48]. April was selected to start the drought analysis because this is the month when farmers commonly start to establish crops in the region. Ten years of data (2005–2014) were plotted for each index. The results indicate that Zacatecas region suffers from incipient drought to severe drought in 6 or 7 years, depending of the selected timescale.

The analysis of drought parameters (magnitude, duration and frequency) did not reflect clear differences between SPI and RDI. Both indexes characterize drought condition (Table 1) with differences between them not reaching 10%. Nevertheless, our findings evidence exceptional variations among timescales with differences between SPI and RDI higher than 5 times in some cases. Figure 2 shows SPI and RDI values for 3 (April–June) and 6 (April–September) months timescales for drought years (2005 and 2011) and wet years (2007 and 2014). The eight plots present the weather in the Zacatecas territory (x-axis) through Z values (y-axis); weather stations with indexes below normal conditions (Z lower than -0.5) reflect climate anomalies to satisfy crop water requirements; the opposite happens for weather stations with indexes above normal conditions (Z higher than 0.5).

Eighty maps were produced to assess the space-time drought performance in Zacatecas from 2005 to 2014, using 3, 6, 9, and 12 months timescales. For a 3 month timescale, SPI and RDI show incipient drought in the April–June period in 2006, 2008 and 2013 (Figures 3 and 4). Such indexes change to wet conditions for July–September in same years (Figures A1 and A2). A quantitative analysis of drought magnitude for 3 and 6 months showed differences in the type of drought severity in less than 10% of the territory when SPI and RDI were compared; nevertheless, the difference increased for the 12 months period. In 2011, RDI (3- and 6-month timescales) was higher than SPI in 5% of the region; for 12 months the difference was about 8%. In 2014 (12 months scale) SPI analysis found 74% of territory in normal conditions, while RDI analysis only found 21% in the same drought condition, and 59% of the State was in moderate wet condition. A qualitative analysis of the information indicated similar durations and frequencies between indexes (Figures 3 and 4 and Figures A1–A6). For the period studied, the duration of drought events ranged between 3 months and 3 years. In 2005 a severe drought occurred from April to June; however, normal conditions were found from July to September. However, the 12-month map indicated a dry year, extending this category to the first trimester of 2006. A drought with a duration of 3 months (July–September) was found in 2009. From April to June the conditions were categorized as wet. A 6-month drought analysis in the same year and semester (April–September) found the territory under normal conditions. The 12-month timescale revealed that parts of the region were under extreme humidity. In the period of 2005 to 2014, the longest drought event occurred from 2010 to 2012, with 2011 being the year with the most severe conditions. Exceptional drought was found at all scales (3, 6 and 12 months).

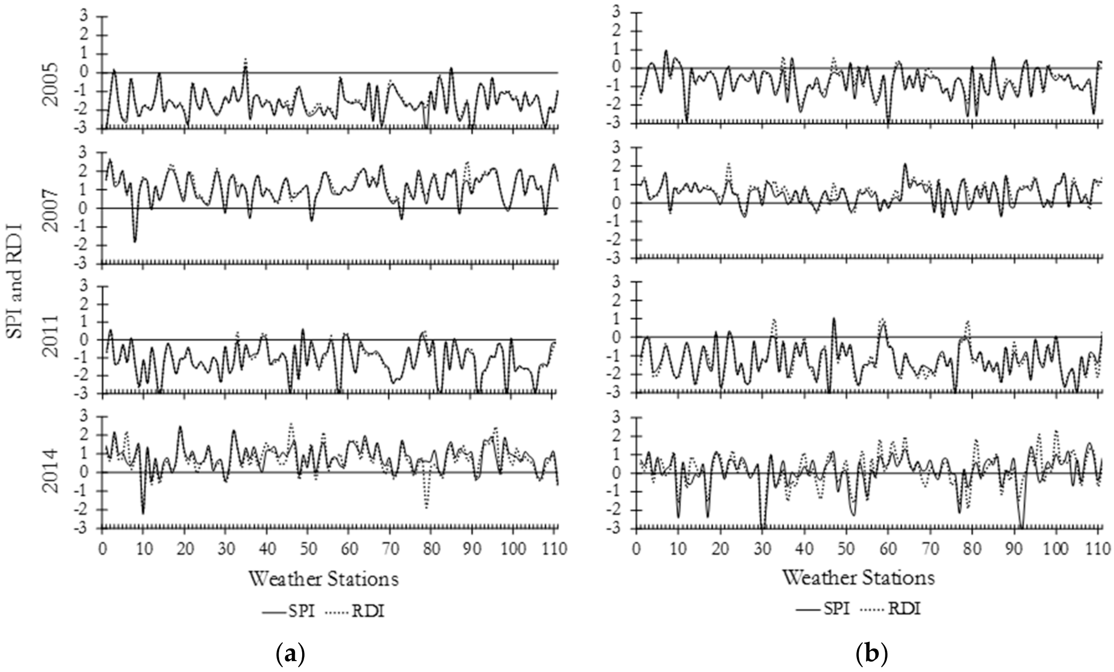

Figure 2. SPI and RDI values for all weather stations in 2005, 2007, 2011 and 2014: (**a**) 3 months (April–June) timescale; (**b**) 6 months (April–September) timescale.

Drought estimation using a six-month timescale (April–September) and twelve-month timescale (April–March) for the abovementioned three years (2006, 2008 and 2013) show wet conditions. The corresponding drought maps are included in Appendix A: SPI and RDI for six-month and twelve-month timescale are expressed in Figures A3–A6. Due to the variations that can occur between periods, it is advisable to select the period of analysis properly. In an agricultural context, the three-month timescale is required to analyze drought severity in order to avoid underestimation of seasonal drought. The severity of drought is commonly used to express the resulting damage (Table 2). Taking into account 2005 and 2011 as drought years, Table 2 shows that, for the 3-month (April–June) timescale, around 70% of the Zacatecas territory suffered from severe to exceptional drought. Nevertheless, for the 6-month (April–September) timescale, drought conditions were apparently less severe: the Zacatecas territory changed to moderate or incipient drought, and even reached normal conditions.

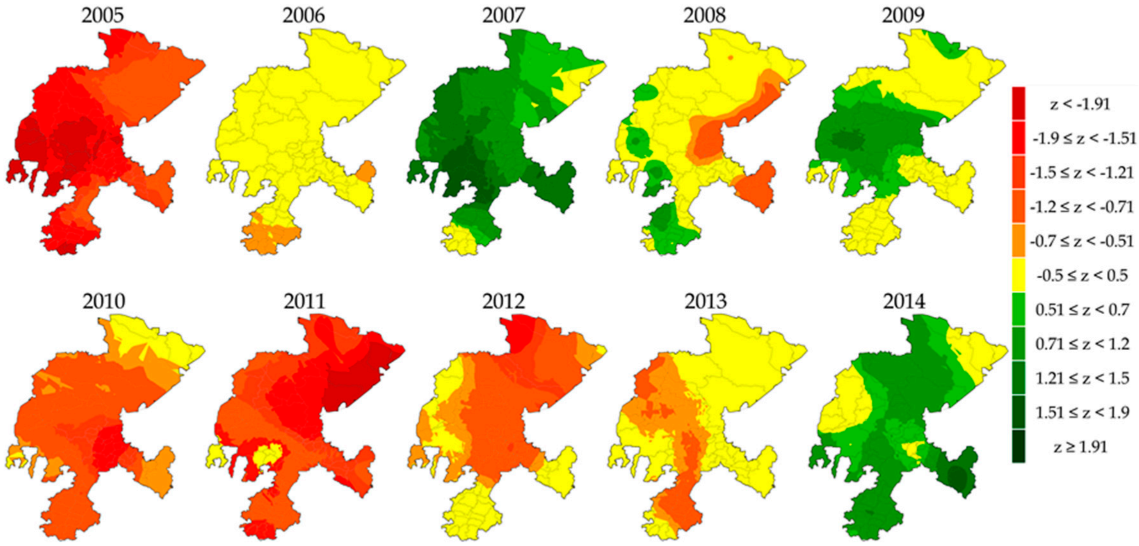

Figure 3. Three-month timescale Standard Precipitation Index (April–June).

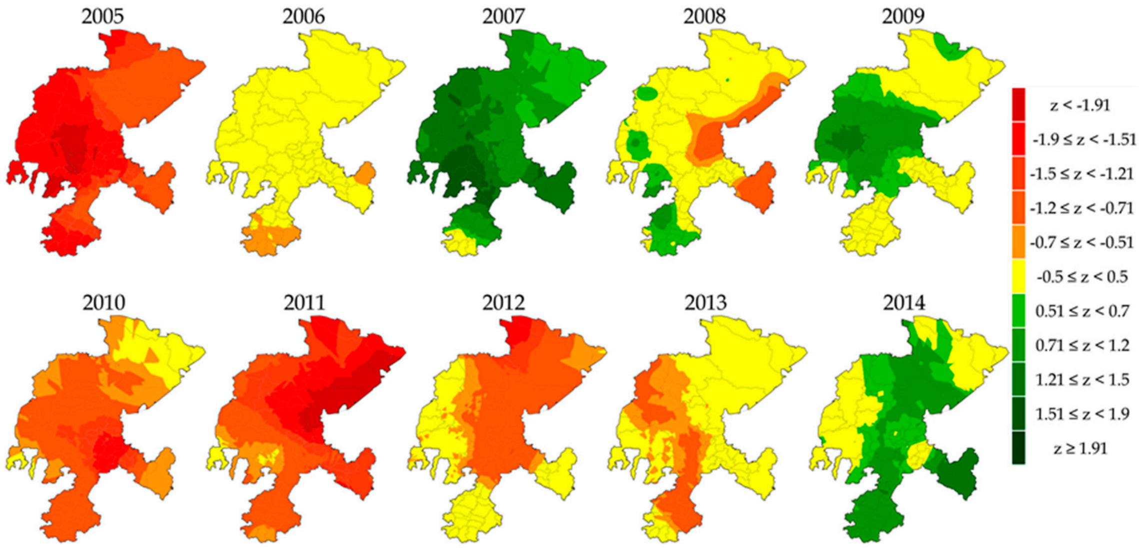

Figure 4. Three-month timescale Reconnaissance Drought Index (April–June).

The impact of drought is usually measured by assessing its effect on specific sectors (hydrological, productive, social). Table 3 presents the economic losses of the main rainfed crops (bean, corn, oats, barley, wheat, and sorghum) in the region of study. In ten years, Zacatecas has lost 478 million US dollars because of droughts. 2005, 2009, and 2011 were the most critical years, with 47%, 39%, and 63% agricultural economical losses. Conversely, 2006 and 2013 barely reached 2% and 1% losses, respectively. Such values are in agreement with drought severity estimates (Table 2): 2005 and 2011 were both dry years (drought indexes were less than −1.25 in whole territory), while 2006 and 2013 were wet years with periods of normal precipitations (drought indexes were higher than −0.05 in the whole territory).

Table 2. Percent of Zacatecas territory exposed to different drought conditions in 2005, 2007, 2011, and 2014.

Year	Index	Timescale (Months)	Period	Exceptional Drought	Extreme Drought	Severe Drought	Moderate Drought	Incipient Drought	Normal Conditions	Incipient Wet	Moderate Wet	Very Wet	Extreme Wet	Exceptional Wet
2005	SPI	3	April–June	21	34	19	27							
			July–September					11	87					
	RDI		April–June	8	40	19	32							
			July–September					8	91					
	SPI	6	April–September				51	35	12					
	RDI						44	35	20					
	SPI	12	April–March				60	19	18					
	RDI						61	20	15					
2007	SPI	3	April–June						9	18	35	28	10	
			July–September					5	88	6				
	RDI		April–June							18	35	34	10	
			July–September						92	7				
	SPI	6	April–September						44	47	9			
	RDI								24	49	26			
	SPI	12	April–March						97					
	RDI								100					
2011	SPI	3	April–June	12	23	25	27	9						
			July–September			8	43	11	39					
	RDI		April–June	14	21	26	28	8						
			July–September			10	41	8	41					
	SPI	6	April–September		11	36	52							
	RDI				16	36	46							
	SPI	12	April–March		8	25	60		6					
	RDI				8	32	51		6					
2014	SPI	3	April–June						20	24	49	5		
			July–September				5	10	77					
	RDI		April–June						35	24	35	6		
			July–September				9	8	71					
	SPI	6	April–September						77	10	8			
	RDI								66	16	14			
	SPI	12	April–March						74	16	7			
	RDI								21	15	59			

Table 3. Comparison between drought severity and agricultural economic losses.

Year	Sown		Harvested		Sinistered		Economic Losses (%)
	Mha	**M$**	**Mha**	**M$**	**Mha**	**M$**	
2005	1.05	98	0.55	52	0.50	46	47
2006	1.10	200	1.08	197	0.02	3	2
2007	1.11	145	0.90	117	0.21	28	19
2008	1.10	263	0.99	243	0.11	20	8
2009	1.10	359	0.65	219	0.42	140	39
2010	1.10	175	0.87	138	0.23	37	21
2011	0.93	197	0.35	74	0.58	123	63
2012	1.01	302	0.83	250	0.17	52	21
2013	1.10	289	1.08	286	0.02	3	1
2014	1.02	246	0.92	220	0.10	26	11

4. Conclusions

Mexico has frequently suffered from adverse climatic conditions. While the southeastern part of the country has undergone huge floods, the Central and North portions have experienced critical droughts. Understanding drought and its patterns (frequency, duration, and severity) is particularly important in semiarid regions. Such knowledge allows us to combat the adverse effects of drought in a proactive manner, and to address the risks that drought implies. 73% of Zacatecas territory (75,284 km^2) is characterized by dry climate (rainfall is lower than potential evapotranspiration). This implies significant limitations on agriculture [26], as confirmed by the drought maps presented in this article. For the period 2005–2014, regardless of the timescale or index used, large parts of the Zacatecas area ranged from normal conditions to exceptional drought during five out of ten analyzed years. Results confirmed that the 12-month time scale was the most benevolent analyzed timescale. Nevertheless, the three-month timescale [24,48] is crucial for the analysis of drought in agricultural contexts. In this sense, the reported maps identify major threats to rainfed crop production: seven out of ten analyzed years ranged from minimum wet to vast scarcity, causing economic losses in agriculture exceeding 10% in of these years. Losses reached values as high as 39%, 47%, and 63% in 2009, 2005, and 2011, respectively. As Mishra and Singh [17] stated, the importance of analyzing historical droughts lies in the generation of information related to water deficits with respect to water demands during drought periods. This allows the design of policies to meet the challenges likely to occur in case of future droughts, either for new or existing water resource projects. The mapping of drought offers a broad spatial and temporal spectrum of droughts in Zacatecas, Mexico; the eighty maps generated show how drought severity and drought duration evolve across both space and time. For a given timescale it was very common to observe that almost the entire study area suffered the same drought conditions. Nevertheless, some peculiarities arose: (1) the most frequent and severe droughts occurred in the Northern region, reaching extreme and exceptional drought conditions in some years; and (2) wet conditions occurred only in very few locations located in the Southern part of the State. The recurrence of drought in the country has prompted the Mexican Government to define stricter policies to deal with this phenomenon. In 2013, it launched a series of actions aimed at preventing and mitigating its effects; among them is the research into drought indexes and methodologies that contribute to early warning for drought [49]. Because of this, our contribution could support the management of regional drought, providing fresh information about incidence and severity of drought in Zacatecas using maps plotted trough SPI and RDI as two well-accepted indexes to evaluate agricultural drought.

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

Appendix A

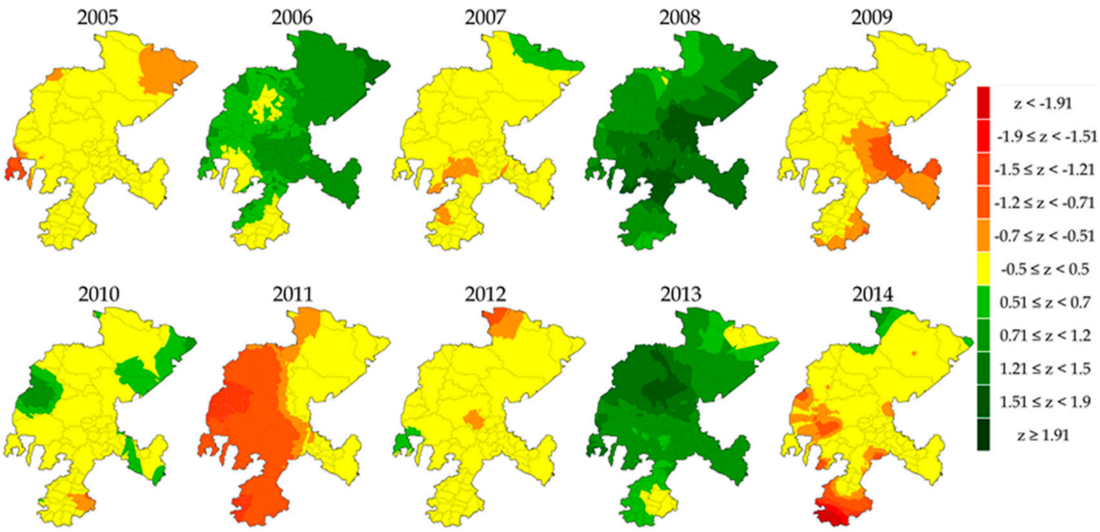

Figure A1. Three-month timescale Standard Precipitation Index (July–September).

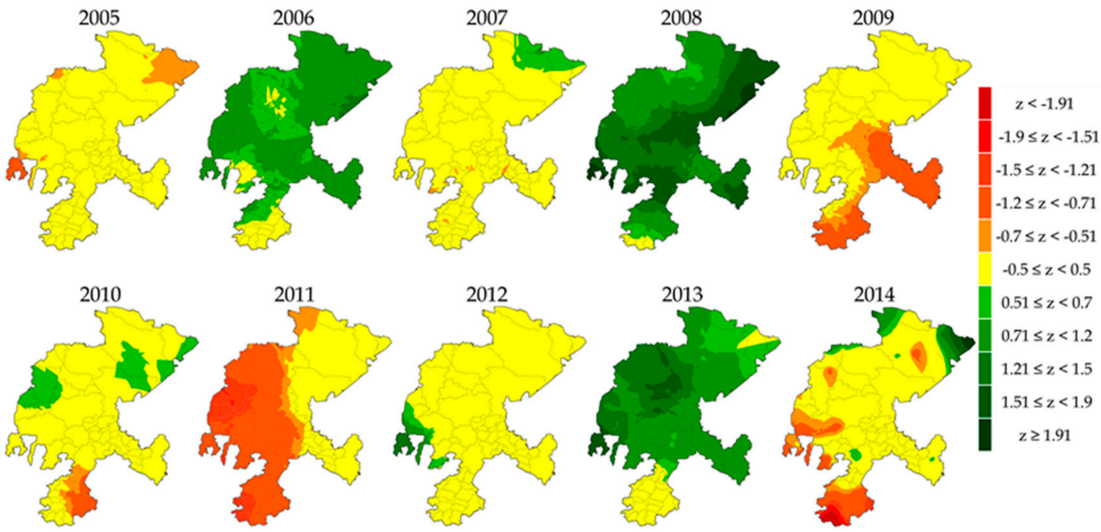

Figure A2. Three-month timescale Reconnaissance Drought Index (July–September).

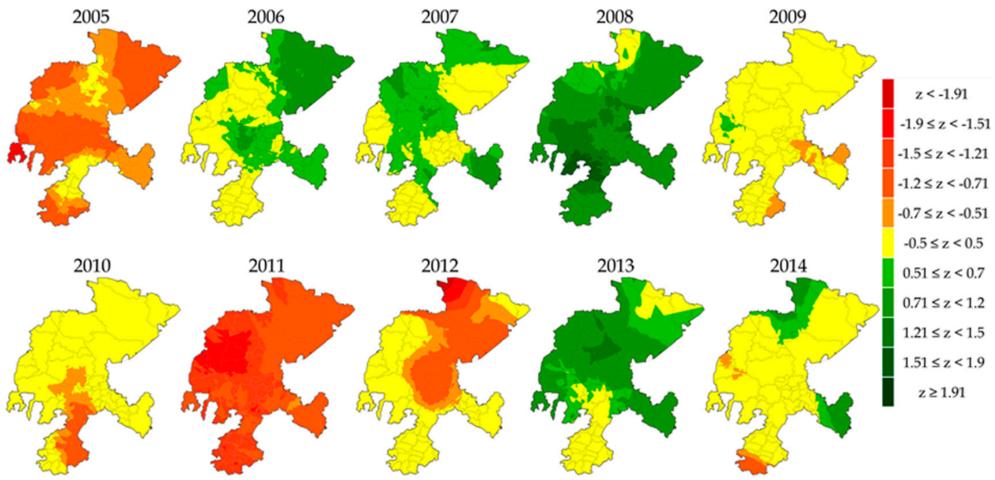

Figure A3. Six-month timescale Standard Precipitation Index (April–September).

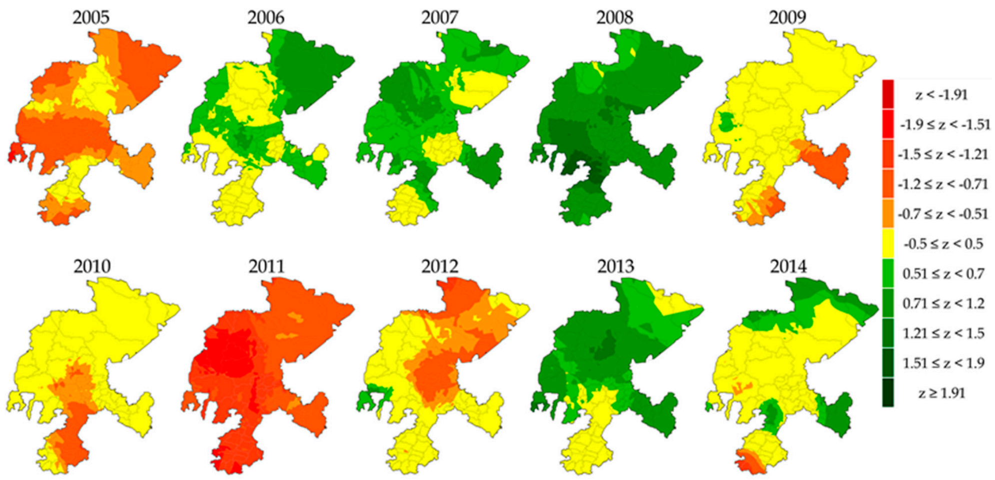

Figure A4. Six-month timescale Reconnaissance Drought Index (April–September).

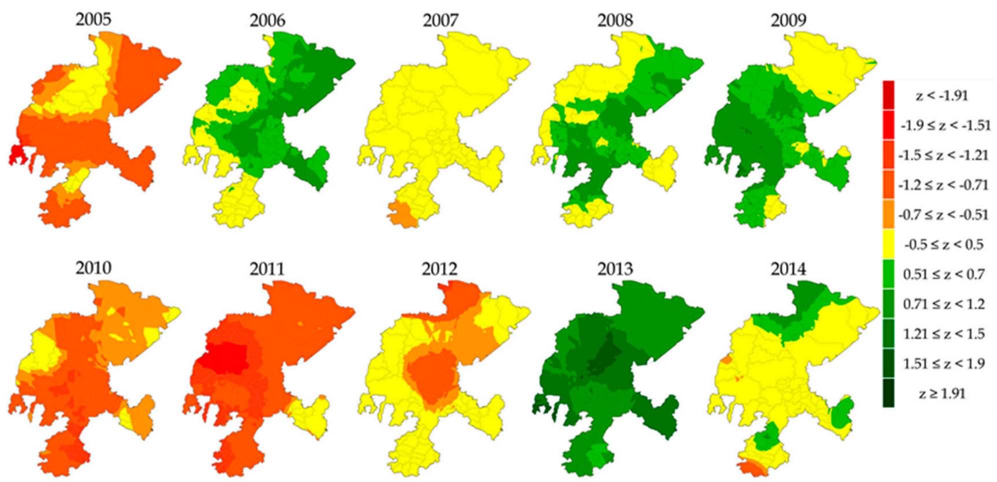

Figure A5. Twelve-month timescale Standard Precipitation Index (April–March).

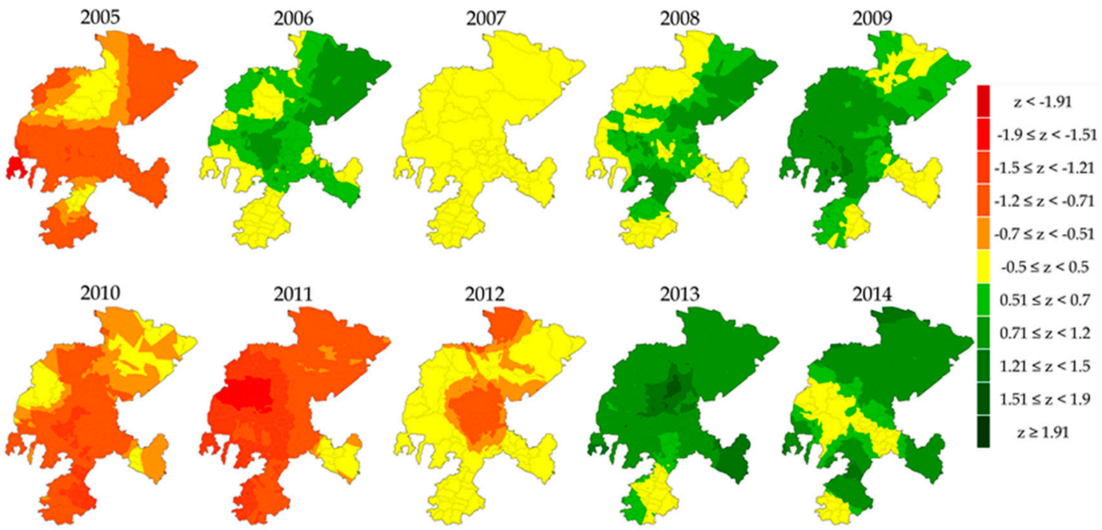

Figure A6. Twelve-month timescale Reconnaissance Drought Index (April–March).

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