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IDENTIFICATION OF CHANGES IN THE RAINFALL REGIME IN CHIHUAHUA'S STATE (MÉXICO)

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ABSTRACT. The impacts of Climate Change are not homogeneous globally or for a country or region as a whole. Consequently, it is essential to carry out studies to identify its effects in particular areas. Due to its geographical and topographic characteristics, Chihuahua's state is vulnerable to the adverse effects of Climate Change. The scarce availability of water resources leads to problems of social pressure and economic impact. This paper analyzes the alteration of the rainfall regime in Chihuahua's state and its association with Climate Change. For this, historical characterization is used; trend analysis using the Mann Kendall test; and calculation of 10 indices of climatic extremes proposed by the Group of Experts for Detection and Climate Change Indices for the precipitation variable. The results showed that the precipitation patterns in the south and southeast of Chihuahua's state have been gradually modifying, with a downward trend in annual accumulated and reduction of wet days. Still, in counterpart, there is a slight intensification of extreme rainfall. This fact added to the growing demand for water resources in the entity, requests for public policies for sustainable management and responsible use by users. Otherwise, there is a risk of experiencing negative effects associated with the over-exploitation of water, not only for the resource users but also for the environment.

Identificación de cambios en el régimen pluvial en el estado de Chihuahua, México

RESUMEN. Los impactos del Cambio Climático no son homogéneos de manera global ni para un país o región en su totalidad. En consecuencia, es imprescindible realizar estudios para identificar sus efectos en zonas particulares. Por sus características geográficas y topográficas, el estado de Chihuahua es vulnerable a los efectos adversos del Cambio Climático. La escasa disponibilidad del recurso hídrico conlleva problemas de presión social y de impacto económico. En este trabajo se analiza la alteración del régimen pluvial en el estado de Chihuahua y su asociación a Cambio Climático. Para ello se recurre a la caracterización histórica; análisis de la tendencia mediante la prueba de Mann Kendall; y, cálculo de 10 índices de extremos climáticos propuestos por el Grupo de Expertos de Detección e Índices de Cambio Climático para la variable de precipitación. Los resultados demostraron que los patrones de precipitación en el sur y sureste del estado de Chihuahua se han ido modificando paulatinamente, con una tendencia a disminución en los acumulados anuales y reducción de los días húmedos. Pero en contraparte, existe una ligera intensificación de las precipitaciones extremas. Este hecho, sumado a la creciente demanda del recurso hídrico en la entidad demanda de políticas públicas de gestión de forma sustentable y uso responsable por parte de los usuarios, de lo contrario se corre el riesgo de experimentar efectos negativos asociados a la sobreexplotación del agua, no solo para los usuarios del recurso, sino también para el medio ambiente.

Key words: Standard Normal Homogeneity test, Mann Kendall test, Pettitt test, trend analysis, interannual variability.

Palabras clave: prueba de Homogeneidad Normal Estándar, prueba Mann Kendall, prueba Pettitt, análisis de tendencia, variabilidad interanual.

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1. Introduction

Climate Change, in a simplified way, can be understood as an alteration of the environmental characteristics and their variability in the average climate that occurs in a given region so that it can involve both heating and cooling conditions (Flores-Campaña *et al.*, 2012). These climate changes occur both naturally and through human actions that contribute to the increase in greenhouse gas emissions, main agents responsible for Climate Change (Benavides-Ballesteros *et al.*, 2007; Miller, 2007; Useros-Fernández, 2013). There is an accepted consensus among the scientific community, and in a multidisciplinary way, on the evidence of Climate Change and its effects at a global level (Watkiss *et al.*, 2005; Caballero *et al.*, 2010; Loyola-Martínez *et al.*, 2011; Sánchez-Cohen *et al.*, 2011; Serrano-Vincenti *et al.*, 2017; Pérez-Palmar, 2017; Pacheco *et al.*, 2019). Nevertheless, the impacts of Climate Change are not homogeneous globally or for a country or region as a whole. Likewise, some areas are more sensitive to change than others (IPCC, 2014; Greenpeace, 2018). For this reason, it is essential to carry out studies to identify the effects of Climate Change in particular areas.

The scarce availability of water resources in Chihuahua leads to social pressure and economic impact since agriculture and livestock depend on this vital element, primary activities of great importance in the entity (Government of the State of Chihuahua, 2005). This fact, from a scientific point of view, denotes the importance of studying changes in precipitation patterns in the state, that quantitatively demonstrate the existing variability and the prevailing trend. Which may allow authorities to design policies aimed at planning the use of water resources in a sustainable way, which is more important in regions where this vital resource is scarce (Ferrelli *et al.*, 2020), as is the state of Chihuahua.

Of the 67 municipalities that make up the Chihuahua´s state, 79.10% have a vulnerability to climate change from very low to low, while 19.40% have a medium vulnerability and only 1.49% a high vulnerability (UACJ, 2019). Vulnerable points in the state are found in underserved groups such as female-headed households, indigenous communities and the high population in food poverty. This situation is closely related to the use of the entity's natural resources, because the ecosystems of the area do not allow adapting them to generate a good natural capital, with which the population would be better prepared to respond to the adversities of climate change (Monterroso, 2012).

This work aims to answer the questions: Is there evidence of changes in the rainfall regime that may alter the availability of water in the state of Chihuahua? Are the droughts of recent years in Chihuahua the consequence of natural climate variability or Climate Change? Can we attribute the increase in more extreme and frequent rainfall in Chihuahua to Climate Change? For this, historical characterization, trend analysis, and calculation of climatic extreme indices for the precipitation variable are used.

2. Study Area

The state of Chihuahua is located in the northwest region of Mexico between 25°29' - 31°54' north latitude and between 103°16' - 109°17' west longitude. To the north, it borders the United States of America; to the west with Sonora and Sinaloa's states; to the south with Durango and to the east with Coahuila de Zaragoza. Chihuahua has an area of 247,456 km^2 and includes altitudes ranging from 1,000 to 3,300 m elevation. 18.1% of the territory belongs to the Great Plateau and Canyons of Chihuahuenses and 17.4% to the plains and dunes of the north (Fig. 1). The rest corresponds to other physiographic areas (INEGI, 2013).

In the state, arid, semi-arid and temperate sub-humid climates predominate with 40%, 33%, and 24% of the total territory. In accordance with Cervera-Gómez *et al.* (2018), has both surface water supply sources (Rio Conchos and Rio Bravo) like underground (aquifers: Sauz Encinillas, Valle de Juárez, Parral Valle Verano and Bolsón del Hueco). The rains are scarce, with an average annual rainfall of 462 mm (Esparza, 2014). However, although water scarcity is a limitation for agricultural activity, this is practiced as temporary and irrigated. Corn, beans, oats, alfalfa, cotton, sorghum, wheat, apple, among others, are grown. The arid and semi-arid climate favors the growth of grasslands in the plains, which has selected the development of livestock (Stock Informático, 2012).

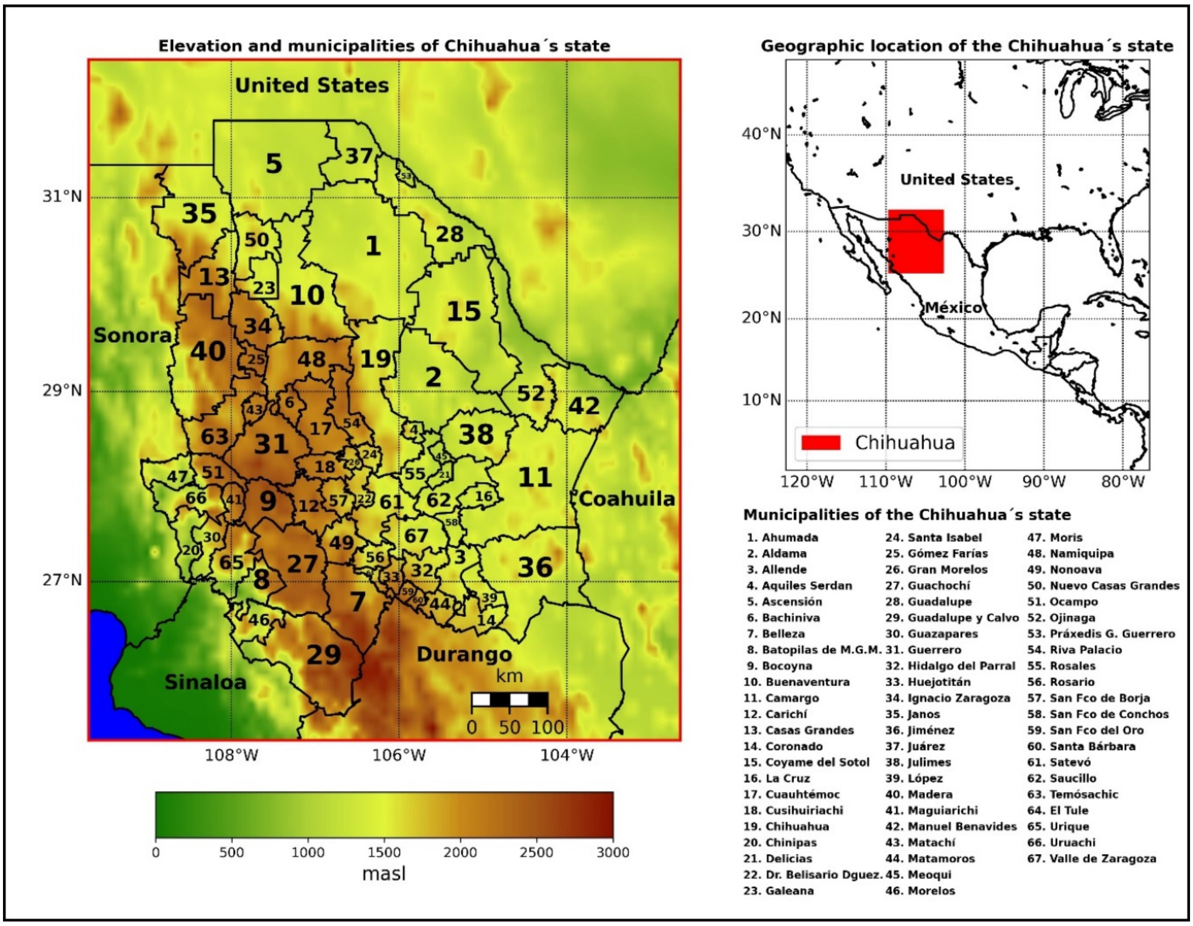

Figure 1. Geographic location of the Chihuahua's state.

3. Methodology

The study was carried out in 4 steps. First, the data set and quality control metrics were defined to select representative weather stations of Chihuahua's state. Second, the annual and monthly climatology was obtained at the state and weather stations for different periods. Third, the precipitation trend was analyzed using the Mann Kendall test. Fourth and last, 10 indices of climatic extremes of precipitation were calculated.

3.1. Dataset

Historical data was consulted from the CLICOM climate data management system (WMO, 1986) for Mexico, currently operated by the National Meteorological Service. The study period was defined as between 1961 and 2012. This last year corresponds to the most recent data stored in the database for the state of Chihuahua. The inventory amounts to 279 conventional weather stations installed in the entity. In this type of station, the data is collected by an observer at 8 in the morning and recorded in a notebook to later capture and process data. To identify possible errors in the data, either due to data collection, failures in measuring instruments, data capture and/or relocation of climate observation stations, three quality control criteria were applied to identify the stations that contained reliable data series. The tests are minimum availability of 80% of the data for the study period and operation; logical congruence of daily data; and homogeneity test (Guajardo-Panes *et al.*, 2017).

3.1.1. Minimum availability of 80% of data and in operation

The first requirement of a practical climatic series is to meet the minimum data number conditions and the climatological station's current state, operating or suspended. This last indicator indicates that the observation site is in operation and that the data series has a high possibility of being updated and maintaining continuity for future studies. For this study, as the first filter, the weather stations with at least 80% of data for the study period 1960-2012 and with operating status were selected.

3.1.2. Logical congruence of daily precipitation data

This test validates the integrity of the data, that is to say, the data correspond to values within a valid range. For this test, the daily precipitation records were compared against a limit established by the UNE 500540: 2004 standard (AENOR, 2004). Since the rains are scarce in the study area, the valid range of rainfall was set between 0 and 100 mm per day (Equation 1). The values of -99999 present in the database correspond to null values, that is, without observation.

$$validity(X_{ij}) = \begin{cases} Valid\ record\ if\ 0 \leq X_{ij} \leq 100 \\ Invalid\ record\ if\ X_{ij} < 0\ \ or\ if\ X_{ij} > 100 \\ Null\ record\ if\ X_{ij} = -99999 \end{cases} \qquad (1)$$

where X_{ij} corresponds to the precipitation data in the year *i* and day *j*.

3.1.3. Homogeneity test

For an adequate climate study, it is necessary that the data series be of the exact nature and have been obtained through similar procedures. They represent the normal variability of the observation sites. The station environment's characteristics may change over time, how can be the increase urbanization, but these changes must occur gradually. Abrupt discontinuities, which are the most common type of inhomogeneities, can be caused by changes in the weather station's site and/or modification of the measuring instrument (WMO, 2018). Instrument-related maintenance or calibration problems may also occur. Consequently, before starting any analysis, modeling or forecasting, these inhomogeneities should be detected and removed from the series, if possible (Yozgatligil *et al.*, 2015).

To validate the homogeneity of the data series, the Pettitt and Standard Normal Homogeneity (SNHT) tests have been widely accepted and applied by the scientific community (Zarenistanak *et al.*, 2014; Mallakpour *et al.*, 2016; Guajardo-Panes *et al.*, 2017; Khosravi *et al.*, 2017; Palaniswami *et al.*, 2018).

The Pettitt test (Pettitt, 1979), is a rank-based nonparametric statistical test. The null hypothesis of the test is that, by arbitrarily dividing the sample into two segments, there is no change in each segment's mean value. At the same time, the alternative hypothesis is accepted when, by arbitrarily dividing the sample into two pieces, there is a significant change in each segment's mean value. This test does not require normalized data series. The test is based on the ranking order of the ranks $r_1, r_2, \ldots, r_n$ of the series (Equation 2).

$$U_d = 2\sum_{i=1}^{d} r_i - d(n+1) \quad for\ d = 1,2,\ldots,n \tag{2}$$

The test statistic U_0, critical value, is the maximum vector's total value (Equation 3). The probable turning point is where U_d has its maximum.

$$U_0 = \max|U_d| \quad where\ 1 \leq d \leq n \tag{3}$$

For his part, test SNHT, initially developed by Alexanderson (1986) and later modified by Alexanderson *et al.* (1997), is a widely used likelihood ratio test to detect inhomogeneities in a time series. The test identifies the breaks at the beginning and end of the time series. It is based on the ordered values of the observations under the assumption of independence and normality. Uses normalized values using standard deviation. The statistician T_d of the test is used to compare the mean of the first d observations with the mean of the remaining (n - d) observations (Equation 4).

$$T_d = d\bar{z}_1^{\,2} + (n-d)\bar{z}_1^{\,2} \quad for\ d = 1, 2, 3, \ldots, n \tag{4}$$

$$\bar{z}_1 = \frac{1}{d}\sum_{i=1}^{d}\frac{(Y_i - \bar{Y})}{s} \tag{5}$$

$$\bar{z}_2 = \frac{1}{n-d}\sum_{i=d+1}^{n}\frac{(Y_i - \bar{Y})}{s} \tag{6}$$

where Y_i is the value observed at position i, $\bar{Y}$ is the mean and S the standard deviation of the series.

The turning point, break, is where T_d gets its maximum value. The test statistic T_0, critical value, is defined in Equation 7.

$$T_0 = \max T_d \quad where\ 1 \leq d \geq 0 \tag{7}$$

3.2. Rainfall climatology

Climatological normals are a reference against which the non-linear fluctuations of the climate in a given region can be defined and compared (WMO, 2007). As a first analysis, the climatological normals of annual and monthly accumulated precipitation were calculated for periods 1961-1990, 1981-2010, and 1961-2012. The climatology was obtained by observation site and at the state level.

3.3. Rainfall trend

As a second analysis, the precipitation trend was calculated using the Mann-Kendall test (Mann, 1945; Kendall, 1975) for each data series and the state average. This test has been widely used in the evaluation of trends in climate data series (Berger, 1986; Kundzewicz *et al.*, 2000; Peña-Quiñones *et al.*, 2010; Alencar de Silva-Alves *et al.*, 2017). It corresponds to a non-parametric test that consists of the sequential comparison between the values that make up the same time series. The null hypothesis considers that the values of the time series are independent and identically distributed. In contrast, the alternative hypothesis assumes that the data follow a monotonic trend (Peña-Quiñones *et al.*, 2010). Equation 8 represents the *S* statistic of the Mann Kendall test.

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^{n} sgn(x_j - x_k) \tag{8}$$

$$sgn(x) = \begin{cases} +1, & X > 0 \\ 0, & X = 0 \\ -1, & X < 0 \end{cases} \tag{9}$$

where *j* y *k* corresponds to two consecutive positions, precedent and antecedent respectively, within data series X_n.

The result of *S* indicates the possible existence of a trend and its direction. A positive value of *S* indicates an increasing trend. In opposition, a negative value of *S* indicates a decreasing trend. Therefore, since *S* is different from zero, the null hypothesis is rejected, and the alternative hypothesis is accepted (Mann, 1945).

On the other hand, the existence of a statistically significant trend is evaluated by the *Z* statistic (Equation 10). Table 1 presents the interpretation of the *Z* statistic for a level of significance α=0.05.

$$Z = \begin{cases} \dfrac{S-1}{(Var(S))^{1/2}} & if\ S > 0 \\ 0 & if\ S = 0 \\ \dfrac{S+1}{(Var(S))^{1/2}} & if\ S < 0 \end{cases} \tag{10}$$

Table 1. Interpretation of the Z statistic of the Mann Kendall test.

Meaning	Symbology	Z
Significantly increasing trend	SIT	Z > +1.96
Not significantly increasing trend	NSIC	0 > Z < +1.96
No trend	NT	Z = 0
Not significantly decreasing trend	NSDT	-1.96 > Z < 0
Significantly decreasing trend	SDT	Z < -1.96

Source: Alves *et al.* (2015)

3.4. Extreme climatic indices of precipitation

The Expert Team on Climate Change Detection and Indices (ETCCDI) formulated a set of 27 Climate Change indices for the detection and monitoring of changes in the extremes of the climate associated with the variables of precipitation, maximum temperature and minimum temperature (Karl *et al.*, 1999; Peterson *et al.*, 2008). These indices provide a common theoretical basis so that they can be consistently calculated in different regions of the planet. For this study, the 10 indices of climatic extremes corresponding to the precipitation variable were calculated (Table 2). The calculation of the indices was performed using the RClimdex software (Zhang *et al.*, 2018).

Table 2. Extreme climatic indices for the precipitation variable proposed by the ETCCDI.

Index	**Description**	**Unit**
CDD	Consecutive dry days	Days
CWD	Consecutive wet days	Days
PRCPTOT	Annual precipitation on wet days	mm
R10MM	Days with precipitation greater than 10 mm	Days
R20MM	Days with precipitation greater than 20 mm	Days
R95P	Annual precipitation on very humid days	mm
R99P	Annual precipitation on extremely humid days	mm
RX1DAY	Maximum rainfall in one day	mm
RX5DAY	Maximum rainfall in five days	mm
SDII	Simple daily intensity index	mm

Source: Zhang *et al.* (2018).

3.4.1. Consecutive dry days (CDD)

Let RR_{ij} the daily amount of precipitation on day i in period j. Count the largest number of consecutive days where

$$RR_{ij} < 1\,mm \tag{11}$$

3.4.2. Consecutive wet days (CWD)

Let RR_{ij} the daily amount of precipitation on day i in period j. Count the largest number of consecutive days where

$$RR_{ij} \geq 1\,mm \tag{12}$$

3.4.3. Annual precipitation on wet days (PRCPTOT)

Let RR_{ij} the daily amount of precipitation on day i in period j. If I represents the number of days in period j, then

$$PRCPTOT = \sum_{i=1}^{I} RR_{ij}, \qquad where\ RR_{ij} \geq 1\,mm \tag{13}$$

3.4.4. Days with precipitation greater than 10 mm (R10MM)

Let RR_{ij} the daily amount of precipitation on day i in period j. Count the number of days where

$$RR_{ij} \geq 10\,mm \tag{14}$$

3.4.5. Days with precipitation greater than 20 mm (R20MM)

Let RR_{ij} the daily amount of precipitation on day i in period j. Count the number of days where

$$RR_{ij} \geq 20\,mm \tag{15}$$

3.4.6. Annual precipitation on very humid days (R95P)

Let RR_{wj} the daily amount of precipitation on a wet day w (where RR ≥ 1 mm) in period j, and let $RR_{wn}95$ be the 95th percentile of precipitation on wet days in the study period. If W represents the number of wet days in the period, where $RR_{wj} > 1\ mm$, then

$$R95P_j = \sum_{w=1}^{W} RR_{wj}\,, \qquad where\ RR_{wj} > RR_{wn}95 \tag{16}$$

3.4.7. Annual precipitation on extremely humid days (R99P)

Let RR_{wj} the daily amount of precipitation on a wet day w (where RR ≥ 1 mm) in period j, and let $RR_{wn}99$ be the 99th percentile of precipitation on wet days in the study period. If W represents the number of wet days in the period, where $RR_{wj} > 1\ mm$, then

$$R95P_j = \sum_{w=1}^{W} RR_{wj}\,, \qquad where\ RR_{wj} > RR_{wn}99 \tag{17}$$

3.4.8. Maximum rainfall in one day (RX1DAY)

Let RR_{ij} the daily amount of precipitation on day i in period j. Then the maximum 1-day values for period j are

$$RX1DAY_j = \max(RR_{ij}) \tag{18}$$

3.4.9. Maximum rainfall in five days (RX5DAY)

Let RR_{kj} the amount of precipitation for the five-day interval ending in k, of period j. Then, the maximum 5-day values for period j are

$$RX5DAY_j = \max(RR_{kj}) \tag{19}$$

3.4.10. Simple daily intensity index (SDII)

Let RR_{wj} the daily amount of precipitation on wet days. If W represents the number of wet days in period j, where $RR_{wj} >= 1$, then

$$SDII_j = \frac{\sum_{w=1}^{W} RR_{wj}}{W} \tag{20}$$

4. Results

4.1. Selected datasets

Of the 279 weather stations installed in Chihuahua, only 21 stations had 80% minimum data and as a status in operation (Table 3). The data were organized in time series to facilitate their processing. With the daily data logical congruence test, 12 records were identified that exceeded 100 mm. Anomalous data were verified by comparing them with values from neighboring stations and with contiguous values (previous and next) from the same series. Also, the occurrence of tropical cyclones on the data's date that could explain the extreme value was investigated. After finding no evidence of these values' validity, in all cases, the displacement of the decimal point was attributed as a capture error, so the data was corrected manually (Table 4). Pettitt and SNHT homogeneity tests were applied using Python's pyhomogeneity library, defining a significance level of α=0.05. Tables 5 and 6 list the parameters obtained in the tests.

Table 3. Weather stations with at least 80% data for 1961-2012 and with status in operation.

Station ID	**Name**	**Municipality**	**Latitude**	**Longitude**	**Altitude**	**%**
8004	Bachiniva	Bachiniva	28.7717	-107.2556	2017	98.11
8038	Creel	Bocoyna	27.7500	-107.6375	2348	87.40
8044	Delicias	Delicias	28.1942	-105.4636	1173	98.86
8049	Luis L. León	Aldama	28.9786	-105.3117	1080	90.64
8052	El Mulato	Ojinaga	29.3942	-104.1689	774	92.08
8059	El Tintero	Namiquipa	29.2636	-107.4572	2450	96.25
8081	Jiménez	Jiménez	27.1333	-104.9167	1370	94.71
8084	Ascensión	Ascensión	31.0964	-108.0128	1290	84.09
8085	La Boquilla	San Fco. de Conchos	27.5439	-105.4119	1323	94.79
8097	Madera	Madera	29.1900	-108.1414	2100	85.78
8099	Majalca	Chihuahua	28.8028	-106.4847	2119	93.81
8156	Villa Coronado	Coronado	26.7386	-10.1600	1516	90.77
8167	Chinipas	Chinipas	27.3931	-108.5361	440	86.59
8172	Guadalupe y Calvo	Guadalupe y Calvo	26.1083	-106.9750	2279	95.26
8182	Moris	Moris	28.1472	-108.5200	754	95.11
8194	Villa López	López	27.0031	-105.0361	1424	92.07
8202	Dam Fco. I. Madero	Rosales	28.1672	-105.6275	1242	98.71
8215	Las Chepas	Bachiniva	28.7153	-107.2458	2076	92.15
8219	Peñitas	Madera	29.2519	-108.0928	2135	95.92
8246	Basuchil	Guerrero	28.5181	-107.4019	2020	87.92
8270	La Mesa	Aldama	28.7733	-105.9636	1250	96.05

Table 4. Anomalous precipitation values detected with the logical congruence test, values from neighboring stations and corrected value.

Date	**Station ID**	**Abnormal value**	**Values of neighboring stations**						**Corrected value**
			Station 1	**Value 1**	**Station 2**	**Value 2**	**Station 3**	**Value 3**	
2006/08/28	8044	113.0	8049	1.0	8202	25.0	8270	42.0	11.3
1973/07/26	8049	107.9	8044	10.0	8052	0.0	8270	0.0	10.8
1987/10/22	8059	105.0	8004	0.0	8097	1.0	8219	5.0	10.5
2008/09/01	8085	101.0	8044	0.5	8194	0.1	8202	1.0	10.1
1973/08/29	8099	110.0	8004	28.0	8215	7.0	8270	0.0	11.0
1980/09/25	8099	120.0	8004	2.0	8215	0.0	8270	19.0	12.0
2000/10/21	8167	105.3	8038	0.0	8182	56.0	8246	8.0	10.5
1979/01/24	8172	131.4	8156	2.5	8167	61.7	8194	3.0	13.1
1983/03/03	8172	118.5	8156	5.0	8167	49.2	8194	0.0	11.9
1987/12/24	8172	111.0	8156	0.0	8167	0.0	8194	0.0	11.1
1989/12/17	8172	106.0	8156	0.0	8167	36.0	8194	0.0	10.6
1976/06/06	8246	114.0	8004	1.0	8059	1.0	8215	2.0	11.4

Table 5. Statistical values of the Pettitt homogeneity test by climatological station.

Station ID	**Breaking point (Year/Month)**	**Value P**	**U_0**	**Middle value**		**Homogeneous series**
				Before PC	**After PC**	
8004	92 (1968/09)	0.88	2.91	43.71	32.84	Yes
8038	536 (2005/09)	0.13	8.20	58.44	37.35	Yes
8044	597 (2010/10)	0.45	5.37	25.36	9.11	Yes
8049	597 (2010/10)	0.68	4.06	25.10	10.65	Yes
8052	556 (2007/05)	0.00	28.43	6.44	21.51	No
8059	618 (2012/07)	1.00	1.57	28.08	51.60	Yes
8081	597 (2010/10)	0.67	4.11	28.00	7.55	Yes
8084	396 (1994/01)	0.00	18.28	21.68	11.09	No
8085	250 (1981/11)	0.31	6.24	29.25	21.41	Yes
8097	453 (1998/10)	0.01	14.94	60.85	38.9	No
8099	498 (2002/07)	0.00	18.36	13.46	35.59	No
8156	316 (1987/05)	0.00	59.29	39.54	9.66	No
8167	65 (1966/06)	0.01	13.39	22.58	62.69	No
8172	453 (1998/10)	0.00	16.80	95.68	56.69	No
8182	137 (1972/06)	0.00	40.22	0.10	41.41	No
8194	102 (1969/07)	0.00	24.75	0.03	20.63	No
8202	597 (2010/10)	0.95	2.34	26.37	14.29	Yes
8215	450 (1998/07)	0.00	63.98	6.59	33.30	No
8219	144 (1973/01)	0.00	81.06	0.10	44.56	No
8246	162 (1974/07)	0.00	53.47	0.51	29.89	No
8270	176 (1975/09)	0.00	62.67	0.46	25.62	No

Table 6. Statistical values of the SNHT homogeneity test by climatological station.

Station ID	**Breaking point (year/month)**	**Value P**	**T_0**	**Middle value**		**Homogeneous series**
				Before PC	**After PC**	
8004	92 (1968/09)	0.89	2.91	43.71	32.84	Yes
8038	536 (2005/09)	0.14	8.20	58.44	37.35	Yes
8044	597 (2010/10)	0.45	5.37	25.36	9.11	Yes
8049	597 (2010/10)	0.68	4.06	25.10	10.65	Yes
8052	556 (2007/05)	0.00	28.43	6.44	21.51	No
8059	618 (2012/07)	1.00	1.57	28.08	51.60	Yes
8081	597 (2010/10)	0.67	4.11	28.00	7.55	Yes
8084	396 (1994/01)	0.00	18.28	21.68	11.09	No
8085	250 (1981/11)	0.32	6.24	29.25	21.41	Yes
8097	453 (1998/10)	0.00	14.94	60.85	38.90	No
8099	498 (2002/07)	0.00	18.36	13.46	35.59	No
8156	316 (1987/05)	0.00	59.29	39.54	9.66	No
8167	65 (1966/06)	0.01	13.39	22.58	62.69	No
8172	453 (1998/10)	0.00	16.80	95.68	56.69	No
8182	137 (1972/06)	0.00	40.22	0.10	41.41	No
8194	102 (1969/07)	0.00	24.75	0.03	20.63	No
8202	597 (2010/10)	0.96	2.34	26.37	14.29	Yes
8215	450 (1998/07)	0.00	63.98	6.59	33.30	No
8219	144 (1973/01)	0.00	81.06	0.10	44.56	No
8246	162 (1974/07)	0.00	53.47	0.51	29.89	No
8270	176 (1975/09)	0.00	62.67	0.46	25.62	No

Based on the results obtained in the three quality control tests, only stations 8004, 8038, 8044, 8049, 8059, 8081, 8085 and 8202 demonstrated consistency and reliability in their corresponding data series. Therefore, statistical analysis was only applied in these eight stations. Figure 2 shows the geographic location of the 21 stations with at least 80% data and in operation, differentiating the stations with homogeneous data series from those with no.

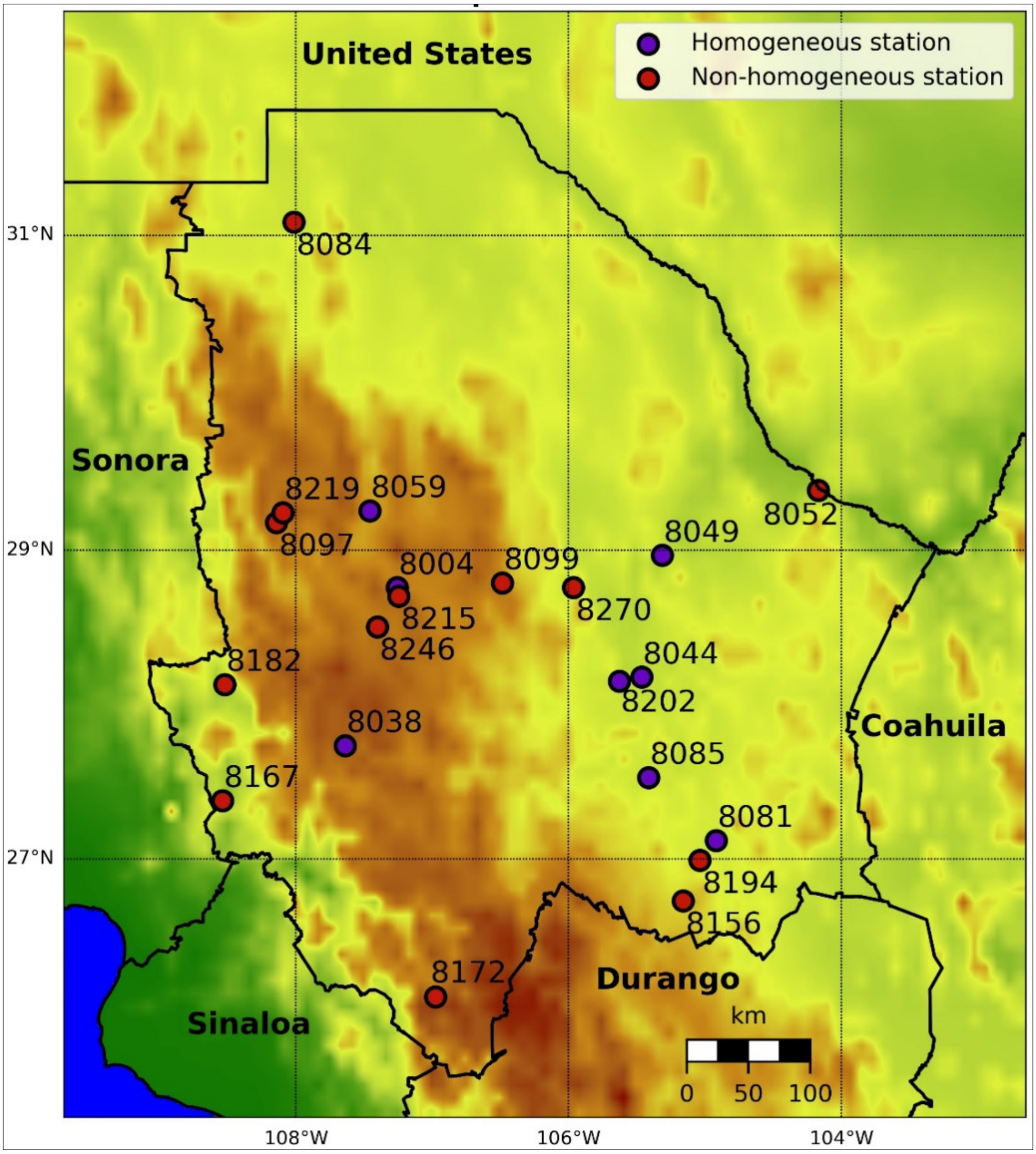

Figure 2. Geographical location of the climatological stations of the state of Chihuahua with at least 80% data and in operation.

4.2. Rainfall Climatology

Tables 7, 8, and 9 summarize the climatological normals of annual and monthly precipitation for the periods 1961-1990, 1981-2010, and 1961-2012. The difference in the state average of rainfall between the periods 1961-1990 and 1981-2010 shows a considerable decrease in the annual precipitation regime, with values of 389.06 and 371.96 mm, respectively, a loss of 17.01 mm corresponding to 4.40%. This decrease is accentuated in September, with an average variation of 17.25 mm between both periods. Figure 3 illustrates the distribution and evolution of monthly mean precipitation using the histogram and mass curve graph.

Table 7. Climatological precipitation normals for the period 1961-1990.

Month/Station	**8004**	**8038**	**8044**	**8049**	**8059**	**8081**	**8085**	**8202**	**State average**
January	12.87	39.34	8.05	7.36	11.51	7.64	6.92	6.51	12.53
February	6.07	29.24	5.01	3.79	6.15	6.09	6.09	4.07	8.31
March	6.82	17.53	3.58	3.41	4.37	2.67	3.41	3.18	5.62
April	5.47	12.92	11.17	6.84	7.66	5.72	6.97	8.79	8.19
May	9.11	15.18	12.61	12.16	8.64	13.16	11.92	10.90	11.71
June	40.09	70.75	33.75	35.44	21.38	43.66	35.91	32.79	39.22
July	118.99	164.64	66.33	60.48	83.30	76.98	74.44	70.12	89.41
August	123.96	128.60	67.76	77.61	88.16	75.12	75.35	78.81	89.42
September	82.96	103.51	65.92	56.98	65.95	64.91	75.59	73.63	73.68
October	24.62	41.88	21.48	24.92	23.17	24.35	20.37	25.99	25.85
November	8.16	26.25	5.85	8.09	8.22	6.88	6.35	6.44	9.53
December	16.10	52.25	8.46	10.95	11.06	7.12	9.78	8.95	15.58
Annual	**455.22**	**702.09**	**309.94**	**308.03**	**339.57**	**334.31**	**333.10**	**330.18**	**389.06**

Table 8. Climatological precipitation normals for the period 1981-2010.

Month/Station	**8004**	**8038**	**8044**	**8049**	**8059**	**8081**	**8085**	**8202**	**State average**
January	14.96	36.41	10.90	10.67	11.01	7.23	6.34	10.25	13.47
February	7.23	35.02	6.26	6.45	9.44	4.09	3.36	4.85	9.59
March	7.04	26.14	3.93	5.47	5.61	4.51	2.81	3.90	7.43
April	7.23	23.08	7.92	7.42	9.10	5.89	6.86	6.50	9.25
May	7.05	19.33	13.72	14.24	8.99	16.20	12.92	12.32	13.10
June	30.47	60.48	34.74	34.91	22.97	42.31	33.57	27.69	35.89
July	109.99	133.36	69.46	68.96	86.45	72.45	78.04	70.64	86.17
August	121.93	129.64	72.26	69.69	89.67	77.02	67.13	70.84	87.27
September	62.33	89.06	48.77	37.89	50.81	61.58	49.94	51.03	56.43
October	21.73	46.63	20.75	35.68	18.92	23.54	17.86	26.26	26.42
November	5.66	28.23	8.84	10.62	8.97	7.28	7.83	8.24	10.71
December	11.86	54.09	10.33	10.04	15.15	9.87	9.50	9.15	16.25
Annual	**407.47**	**681.46**	**307.86**	**312.03**	**337.08**	**331.97**	**296.16**	**301.68**	**371.96**

Table 9. Climatological precipitation normals for the period 1961-2012.

Month/Station	**8004**	**8038**	**8044**	**8049**	**8059**	**8081**	**8085**	**8202**	**State average**
January	13.45	36.78	8.25	8.80	10.90	5.87	6.53	8.16	12.34
February	6.53	31.19	6.02	4.98	7.64	5.35	4.74	4.40	8.86
March	6.73	21.13	3.59	4.31	4.92	3.66	3.08	3.53	6.37
April	6.34	17.42	7.95	7.27	8.11	5.06	7.03	7.63	8.35
May	7.81	16.70	13.22	13.14	8.66	14.11	12.18	11.27	12.14
June	34.53	64.04	32.82	34.17	21.49	40.67	34.37	29.29	36.42
July	114.23	149.54	67.44	63.68	84.94	73.33	76.23	70.40	87.47
August	121.43	128.31	67.63	72.23	88.83	72.99	71.59	73.12	87.02
September	72.21	95.25	56.52	46.90	58.30	65.57	62.83	61.93	64.94
October	25.57	43.49	20.98	29.58	20.46	23.69	19.40	25.61	26.10
November	7.11	27.34	7.33	9.18	8.45	7.37	6.93	7.55	10.16
December	13.51	51.62	9.11	10.14	12.68	8.26	9.48	8.81	15.45
Annual	**429.46**	**682.81**	**300.87**	**304.38**	**335.38**	**325.93**	**314.38**	**311.65**	**375.61**

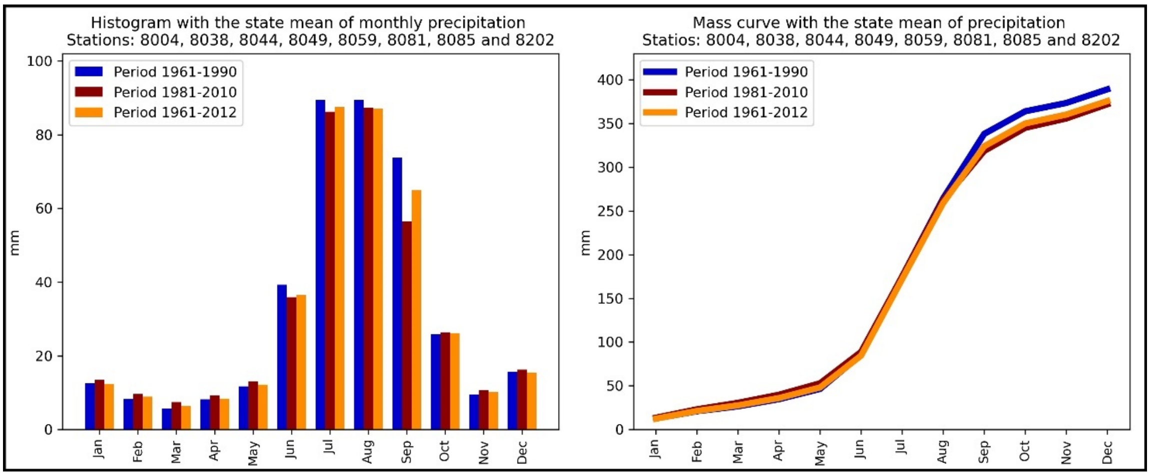

Figure 3. Histogram with the monthly mean of precipitation (left) and mass curve with the mean of precipitation (right) for the periods 1961-1990, 1981-2010 and 1961-2012. The values correspond to tables 7, 8 and 9.

Regarding the maximum precipitation values for the period 1961-2012, these were observed at station 8038, installed in the municipality of Bocoyna, in the southeast of the state, with an annual average of 682.81 mm; while the minimum annual accumulated were obtained in station 8044, installed in the municipality of Delicias, in the east of the state, with an annual average of 300.87 mm. It should be noted that the highest rainfall was obtained in the climatological stations closest to the western coastline of Mexico, specifically in the mountainous area of the Great Plateau and Chihuahuan Canyons, and as it moves further into the continental zone, towards the plains and dunes of the north, there is a considerable decrease in precipitation patterns. This is because the rainfall in Chihuahua is mainly induced by orographic forcing and is strongly influenced by cyclonic activity from the Pacific Ocean. Although the trajectories of tropical cyclones are interrupted by friction with the continental topography, strong winds and extreme rains can have effects in some states in the interior of the country, such as the state of Chihuahua (Rosengaus-Moshinsky *et al.*, 2014).

4.3. Precipitation trend

The precipitation trend was calculated using the *pymannkendall* library (Hussain *et al.*, 2019), precisely, the *seasonal_test* function, which corresponds to the Mann Kendall Seasonal test (Hirsch *et al.*, 1982), this variant eliminates the effect of seasonality. It was used as a level of significance α = 0.05 and a seasonal period of 12 months. The test returns the statistical trend values (*trend*), p-value of significance test (*Valor P*), the normalized test statistic (*Z*), Kendall Tau (*Tau*), Mann Kendall score (*S*), Theil-Sen slope (*slope*), and Kendall-Theil Robust Line interception (*interception*).

The results determined that, for the study period, in seven of the eight data series analyzed, a negative trend persists in the accumulated annual precipitation, but only at stations 8038 and 8085, located in the southern and southeastern part of the state, the existing trend is considered significantly decreasing with a slope of -66.56 and -35.25 mm respectively. On the opposite side, only station 8049, located in the northwest, presents a positive trend in increasing precipitation, with a slope of 4.56 mm. In the remaining five stations, a negative but not significant trend is maintained (Table 10).

Table 10. Statistical values of the Mann Kendall test for the six weather stations.

Station ID	Trend	p-value	Z	Tau	S	Slope	Interception
8004	NSDT	0.27	-1.12	-0.16	-14	-18.81	452.09
8038	SDT	0.05	-1.97	-0.27	-24	-66.56	803.65
8044	NSDT	0.93	-0.09	-0.02	-2	-1.72	278.72
8049	SIT	0.80	0.26	0.05	4	4.56	253.22
8059	NSDT	0.67	-0.43	-0.07	-6	-9.41	349.20
8081	NSDT	0.78	-0.27	-0.05	-4	-1.52	310.82
8085	SDT	0.02	-2.32	-0.32	-28	-35.25	370.83
8202	NSDT	0.44	-0.77	-0.11	-10	-10.66	315.35

Note. The abbreviation of the trend corresponds to the meaning of Table 1.

In Figure 4 the map of Chihuahua is presented with the geographical distribution of the precipitation trend by the climatological station. On the other hand, Figure 5 shows the interannual variability of rainfall and the Mann Kendall test's slope line for the period 1961-2012 by the weather station.

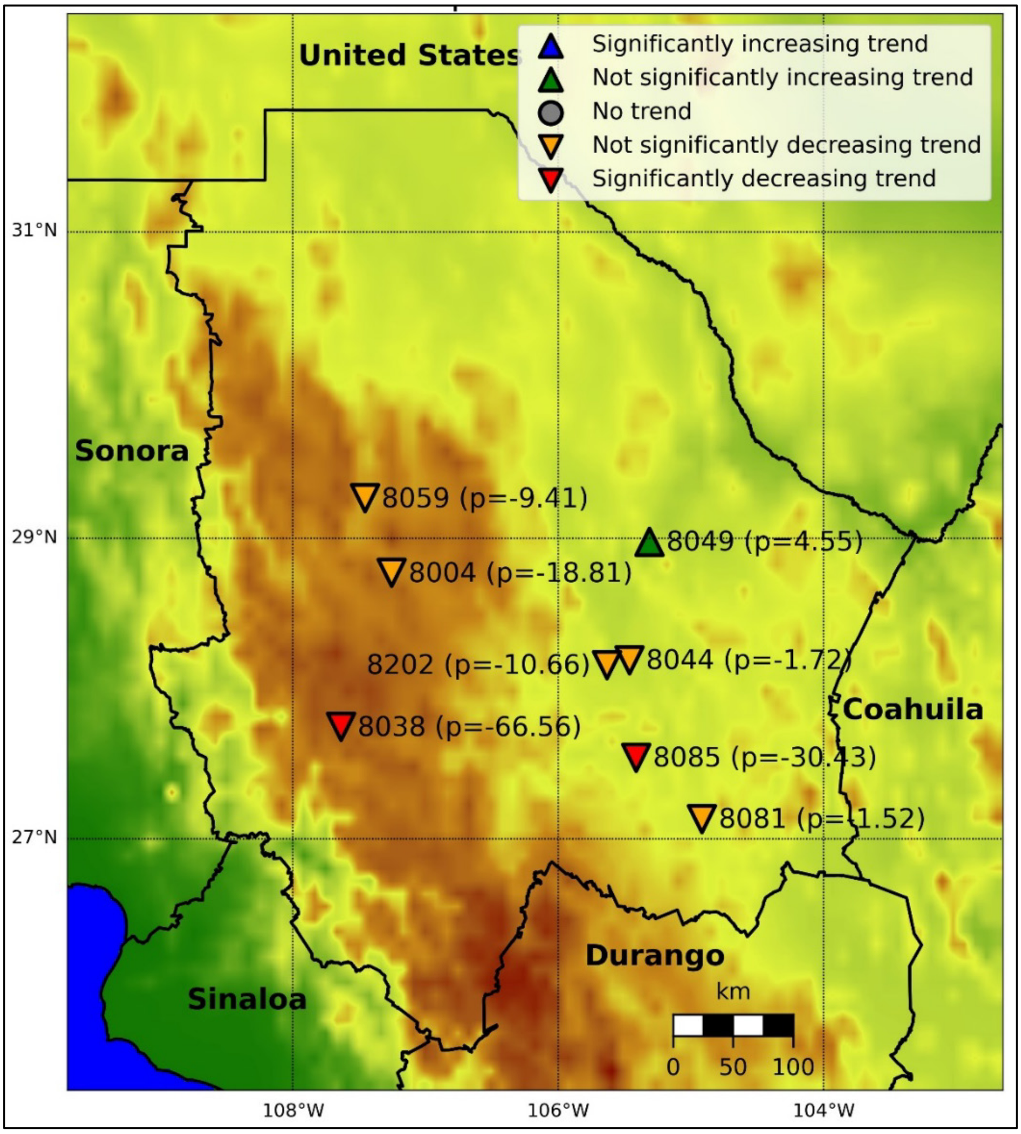

Figure 4. Geographical distribution of the precipitation trend according to the Mann Kendall test for the period 1961-2012.

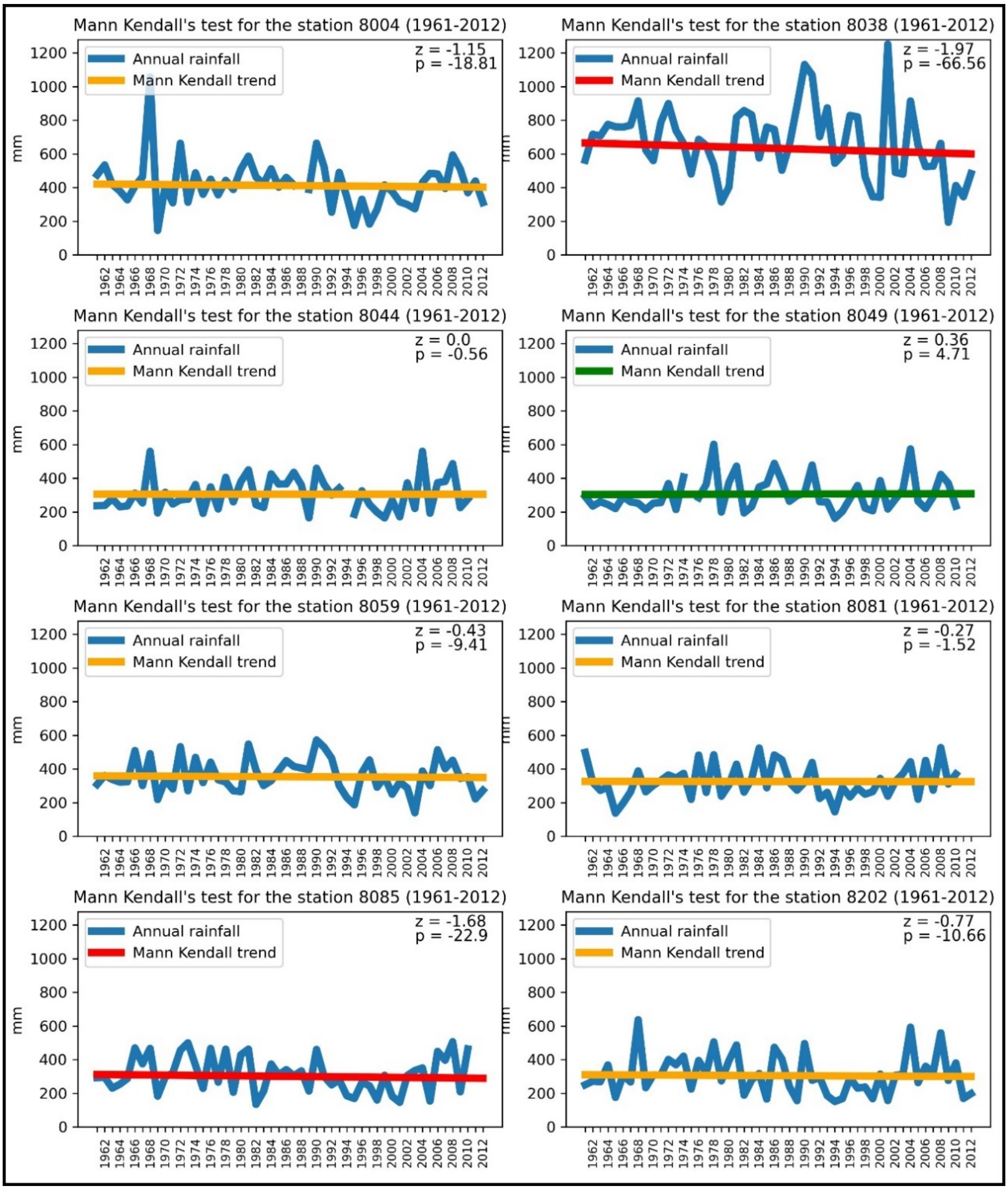

Figure 5. Rainfall trend with the Mann Kendall´s test by climatological station for the period 1961-2012. Not significantly increasing trend (green line), not significantly decreasing trend (orange line) and significantly decreasing trend (red line).

4.4. Climatic extremes indices of precipitation

The results obtained with the ten climatic extremes indices of rainfall events, showed a slight alteration in the precipitation regimes in Chihuahua. With respect to consecutive dry days (CDD), an increase of close to one day was observed in stations 8004 and 8038, with a slope of 0.71 and 0.96 respectively; a decrease of 1.73 and 3.47 mm in the annual precipitation of wet days (PRCTOT) in stations 8004 and 8038, respectively; increase in annual precipitation of very humid days (R95P) in stations 8044 and 8049, with values of 0.85 and 1.06 respectively; and an increase in the annual precipitation of extremely humid days (R99P) in stations 8004, 8038, and 8044, with values of 0.9, 0.4 and 0.80 respectively. In summary, the climate change indices proposed by the ETCCDI indicate a decrease in the days and in the annual amount of precipitation, but in contrast, a slight increase in the intensity of extreme storms in the state of Chihuahua (Table 11). The geographic distribution of trends by indices is illustrated in Figures 6 through 8.

Table 11. Trend values in the 10 indices of climatic extremes of precipitation.

Station ID	CDD (Days)	CWD (Days)	PRCTOT (mm)	R10MM (Days)	R20MM (Days)	R95P (Days)	R99P (Days)	RX1DAY (mm)	RX5DAY (mm)	SDII (mm)
8004	0.71	-0.07	-1.73	-0.08	-0.06	-0.13	0.90	0.27	-0.05	-0.01
8038	0.96	0.04	-3.47	-0.10	-0.01	0.24	0.40	0.13	0.16	0.03
8044	0.06	-0.02	-0.25	-0.03	0.01	0.85	0.80	0.23	0.17	0.01
8049	-0.13	-0.09	0.82	0.09	0.06	1.06	-0.22	0.17	0.20	0.05
8059	-0.25	-0.05	-0.45	-0.01	0.02	0.26	0.13	0.11	0.05	0.02
8081	-1.16	-0.01	-0.09	-0.02	0.01	-0.42	-0.18	-0.21	-0.28	-0.06
8085	-0.16	0.01	-0.92	-0.04	-0.03	0.02	0.29	-0.13	-0.08	-0.01
8202	0.46	-0.01	-0.62	-0.02	-0.02	-0.20	-0.20	-0.10	-0.30	0.00

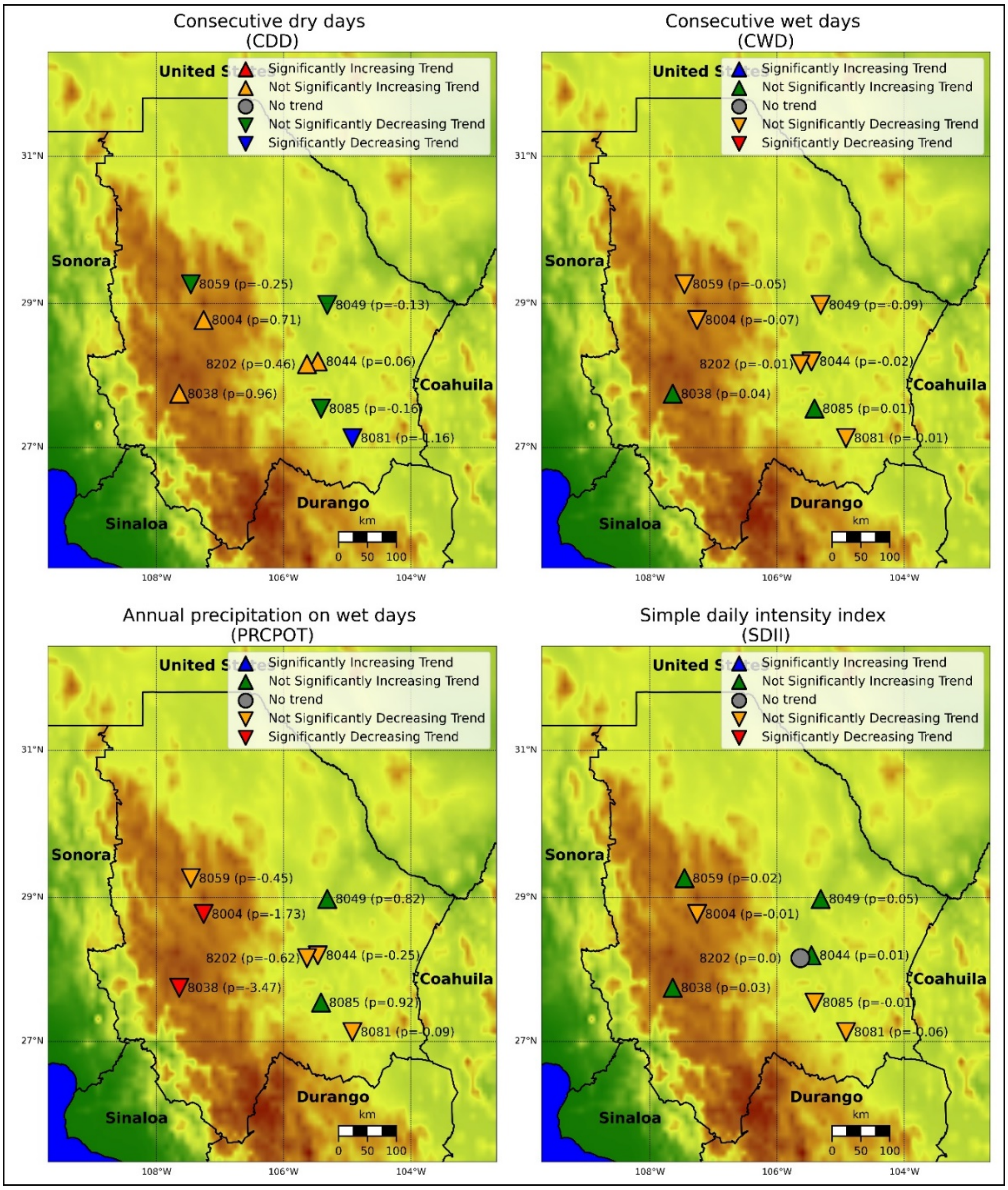

Figure 6. Geographical distribution of the trend for the CDD, CWD, PRCTOT and SDII indices.

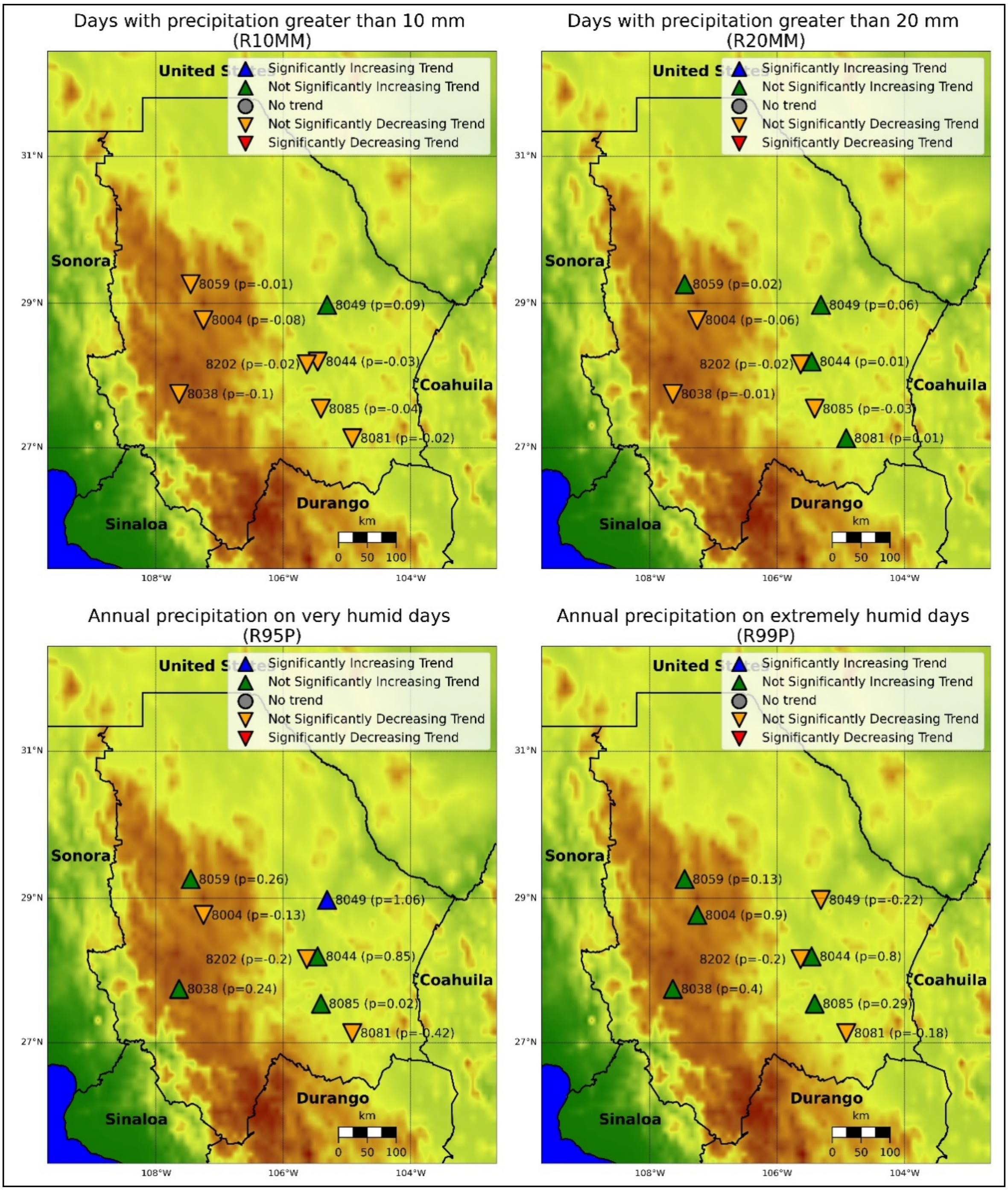

Figure 7. Geographical distribution of the trend for the R10MM, R20MM, R95P and R99P indices.

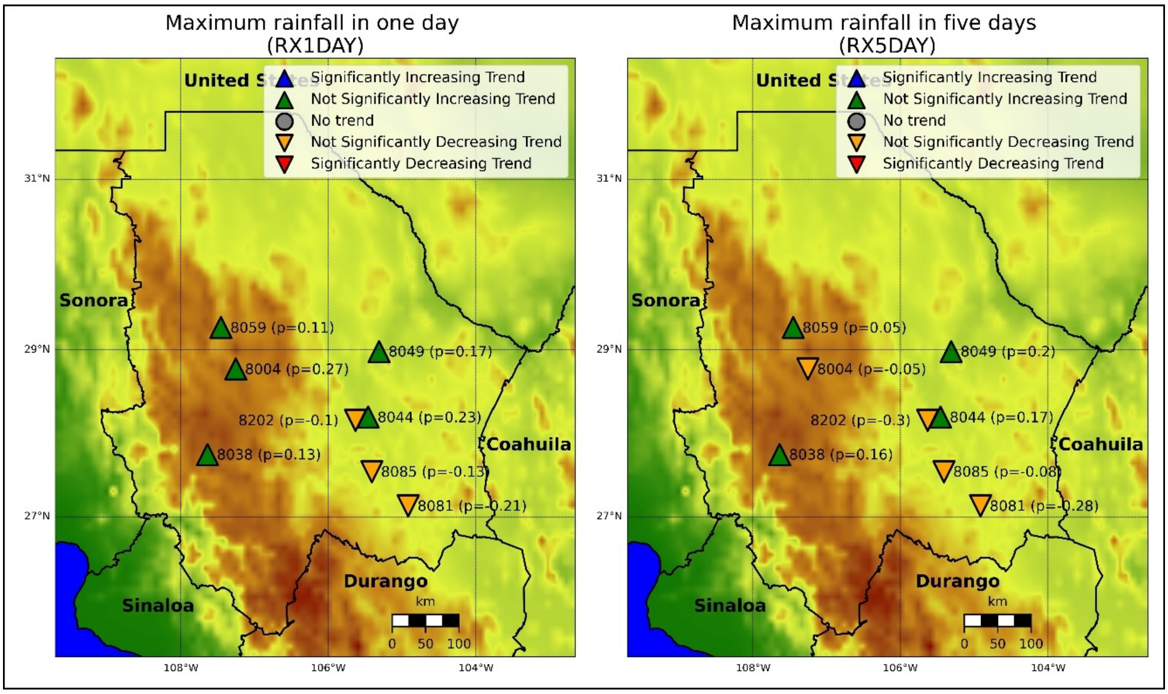

Figure 8. Geographical distribution of the trend for the RX1DAY and RX5DAY indices.

5. Discussion

In this work, the fluctuations in precipitation that occurred in the state of Chihuahua over 52 years, from 1961 to 2012, were analyzed. Of the 279 weather stations located in the state of Chihuahua, only eight exceeded the quality control and homogeneity criteria applied in this study. It should be noted that 226 stations, corresponding to 81%, present as out of service status, and the remaining ones, which are operating, have considerable information gaps. In addition, the similarity between the Pettitt and SNHT homogeneity tests was notorious. Both approved and rejected the same data series. This is in agreement with what was stated by Buishand (1982), who determined that there are minor differences between the different homogeneity tests to reject or accept the data series. No adjustments were applied to the data series identified as non-homogeneous, since this type of correction requires a clear identification of the reasons causing the breakdown before any action can be taken (Ahmed *et al.*, 2013). Otherwise erroneous results may be obtained.

The behavior of precipitation patterns is a highly complicated task since it is a chaotic phenomenon that fluctuates in time and space (Rousseau-Figueroa *et al.*, 2016; Haro *et al.*, 2016), and the high levels of dispersion presented by micro and mesoscale factors that generate it (Peña, 2004; Montoya *et al.*, 2005). However, through the selection of reliable data series and the application of validated statistical tests, it was possible to identify the existence of changes in the precipitation regimes in the study area in this work.

The surface of Chihuahua's state is located in a region that presents a natural scarcity of water, with average annual rainfall in the climatological stations analyzed of 389.06 mm for the period 1961-1990 and 371.96 mm for the period 1981-2010. The discrepancy between the annual and monthly average of state precipitation obtained in this work, with only eight stations, concerning the climatological normals for the state of Chihuahua from other sources of information (Breña-Puyol, 2004; Esparza, 2014), is associated with the calculation period, the number of weather stations considered and their spatial coverage.

The alteration in precipitation regimes, added to the growing demand for water resources, mainly for the agricultural activity that consumes 80% of the available water, demands public policies for sustainable management and responsible use by users. Otherwise, there is a risk of experiencing adverse effects and a decrease in water availability in Chihuahua's state for the near future, not only for resource users but also for the environment. Because the aggravated effects of droughts and water scarcity are presented by natural causes and social factors where management policies and sustainable use of water reserves are relevant (FAO, 2013).

6. Conclusions

The results obtained with the Mann Kendall trend test indicate an alteration of the rainfall regime in the state of Chihuahua with a significantly decreasing trend in the southern and southeastern part of the state, mainly during September, and a not considerably increasing trend in the northwest. This fact makes it possible to determine that the droughts of recent years are a consequence of Climate Change rather than a natural variability of the climate. On the other hand, three of the extreme climatic precipitation indices proposed by the ETCCDI determined that the increase in the intensities of extraordinary storms can be attributed to Climate Change, according to the annual precipitation indices of extremely humid days (R99P), maximum precipitation in one day (RX1DAY) and maximum precipitation in five days (RX5DAY). In addition, the annual precipitation index for very humid days (PRCPTOT), in correspondence with the Mann Kendall test, indicates a decrease in annual precipitation in the south of the state.

Faced with the alteration of the rainfall regime in the state of Chihuahua, it is imperative to maintain constant monitoring of the variable's behavior, which leads to the rehabilitation of weather stations that are out of operation even to implement new automatic weather stations that provide greater detail.

Likewise, the changes in the frequency and intensity of rainfall in the state of Chihuahua demand the development and application of a plan for adaptation to Climate Change in the main socio-economic activities, which allow adjusting the demands of water resources sustainably.

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