Observed trends in daily extreme precipitation indices in Aguascalientes, Mexico

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Abstract
Precipitation and its distribution greatly influence the evolution of ecosystems and the development of society. The objective was to analyse trends in extreme precipitation indices at 25 weather stations of Aguascalientes State. Eleven extreme precipitation indices were obtained. The time series of these indices were analysed with the non-parametric Mann–Kendall test. The number of days above 50 mm, consecutive wet days, and extremely wet days did not have significant trends at any of the weather stations. Each of the indices maximum 1 day precipitation amount, maximum 5 day precipitation amount and number of very heavy precipitation days showed a significant positive trend at 12% of the weather stations; both the number of heavy precipitation days and the number of very wet days had significant positive trends at 8% of the weather stations; the simple daily intensity index, consecutive dry days and annual total wet-day precipitation showed significant positive trends at 20%, 36% and 4% of weather stations, respectively. The intensity index was the only one that showed a significant negative trend, which happened at 4% of the weather stations. In a small part of Aguascalientes, the precipitation intensity, the number of rainy days and the accumulated total increased in short periods. Also, in a reduced region, daily precipitation intensity decreased; and in another very small area the number of dry days increased. For mitigating the effects of these phenomena, it is suggested that water be used more efficiently for sustained agricultural production systems and ecosystem management. The results of the present study will be of great importance in future economic planning in the Aguascalientes State.

KEYWORDS
climate change, climate variability, extreme indices, global warming, Mann–Kendall, non-parametric, Theil–Sen estimator

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1 | INTRODUCTION

Currently, one of the most significant challenges is to understand climate change and mitigate its adverse effects. It is believed that during the period 1880–2012 the average global warming was 0.85°C, and its leading causes were attributed to anthropogenic activities, especially those related to the excessive burning of fossil fuel (IPCC, 2014; Allen et al., 2018). However, it is also estimated that, today, between 20% and 40% of the world population lives in regions with warming even higher than the average mentioned above (Allen et al., 2018).

Climate change, climate variability and extreme events are of great interest to society. Climate change is a statistically significant variation either in the mean state of the climate or its variability, persisting for an extended period (decades or more). It can be caused by internal natural processes or external forcing, or by persistent anthropogenic changes in the composition of the atmosphere or land use (WMO, 2017). In the last decades, important advances have been made in the field of climatology and studies have been focused predominantly on variables of the hydrological cycle (e.g. precipitation, temperature and evaporation) either monthly or the annual average (Ceballos et al., 2004; Kothawale and Kumar, 2005; Mandal et al., 2013). However, extreme events have received relatively limited attention. An extreme meteorological event is a climatic or meteorological phenomenon that is rare at a particular place or time of the year, e.g. heat waves, cold waves, heavy rain, droughts, floods and severe storms (National Academies of Sciences, Engineering and Medicine, 2016). These events are produced by climatic variability, which is defined as the variation in the mean state and other statistics (standard deviation, the occurrence of extremes etc.) of the climate on all temporal and spatial scales beyond that of individual weather events (WMO, 2017). Differently, an extreme precipitation event is an event in which precipitation in a specific period exceeds some threshold either at a point (i.e. measured by just one rain indicator) or on average over some spatial region (National Academies of Sciences, Engineering and Medicine, 2016). Extreme precipitation is associated with a series of meteorological processes, such as tropical cyclones, extratropical cyclones, monsoons, atmospheric rivers or localized convection (Kunkel et al., 2013).

In the past two decades, extreme indices have received great attention. Although rain is beneficial for humanity and environmental and hydrological processes, its frequent extremes are associated with adverse effects such as high runoff, floods and erosion. Nevertheless, low and erratic precipitation events lead to droughts and significant agricultural damage. For the study of extremes, the Expert Team on Climate Change Detection Monitoring and Indices (ETCCDMI) sponsored by the Commission for Climatology (CCI) of the World Meteorological Organization and the Climate Variability and Predictability Project (CLIVAR) developed 27 extreme meteorological indices associated with precipitation and temperature (Peterson et al., 2001; ETCCDMI, see http://www.etcddi.pacificclimate.org). Currently, these indices constitute a methodological guide accepted globally to analyse climate change, and they have been used at regional and global levels in different studies related to extreme meteorological events (Vincent et al., 2005; Zhang et al., 2005; Haylock et al., 2006).

Worldwide a great variety of studies focusing on extreme precipitation events have been carried out. Zhang et al. (2005) considered 10 extreme precipitation indices in a survey carried out in 15 countries of the Middle East. They found significant positive trends in the number of days with precipitation and on the average precipitation intensity. In a study of trends in 10 extreme precipitation events in 14 countries from South and West Africa, New et al. (2006) found significant increases in daily rainfall intensity, dry spell duration and 1 day rainfall. Similarly, Santos et al. (2011) studied nine extreme precipitation indices in Utah and found that the precipitation trend was diverse over the state; they found increases in 1 day precipitation, total precipitation in five consecutive days and accumulated annual precipitation. Likewise, Shrestha et al. (2017) investigated trends and changes in 11 extreme precipitation indices over the Koshi River basin, India, and reported an increase in accumulated annual precipitation and the number of consecutive dry days. Similarly, in a study of changes in precipitation extremes in Central America and northern South America, including south and southeast of Mexico, Aguilar et al. (2005) analysed 10 precipitation indices developed by the ETCCDMI and did not find a significant increase in total precipitation. However, they reported significant positive trends in daily precipitation amount and the number of wet days confirming the idea of a trend towards more humid conditions in that area of study. Moreover, Alexander et al. (2006) studied global changes in daily climatic extremes of precipitation during the period 1901–2003. They found a significant increase in the majority of precipitation indices, except dry days and consecutive wet days, and so they suggested that there exists more tendency to more humid conditions. Similarly, Arriaga-Ramirez and Cavazos (2010) investigated the seasonal and annual trend in 10 precipitation indices in six regions of northwest Mexico and southwest of the United States. On an annual scale, they found significant negative trends in rainy days but significant positive trends in the annual amount of precipitation. Differently, at a seasonal scale, summer showed significant positive trends in total precipitation and simple daily intensity index; instead, in winter, total precipitation and the number of heavy
precipitation days and very wet days showed significant positive trends, and only the maximum 5 day precipitation amount had a significant negative trend. In the same way, Brown et al. (2010) studied 10 precipitation indices at 40 weather stations in northeastern United States. In general, they found significant positive trends in intensity and amount of precipitation. Because of the major prevalence of significant positive trends associated with precipitation indices, these authors emphasized that the region showed a tendency toward wetter conditions. Similarly, Boot et al. (2012) considered four precipitation indices in a study of climate change for western North America during 1950–2005. In many parts of the territory, they found a moderate increase in both amount and intensity of precipitation, and commented that stronger precipitation trends occurred in regions with climate controlled by air masses coming from the Gulf of Mexico. Also, Insaf et al. (2013) examined trends in 11 precipitation indices in New York State in the period 1948–2008 and indicated that the number of days with heavy precipitation, the number of consecutive wet days, the total wet day precipitation and the simple daily intensity index were the indices that showed the highest significant positive trends. Moreover, total wet day precipitation and the simple daily intensity index revealed a significant increase at most of the stations. For North America, Peterson et al. (2008) evaluated changes in extreme events derived from daily precipitation for 1950–2000. They found that heavy precipitation and total precipitation increased in the second half of the last century; they also indicated that these increases were consistent with the warming that the planet is experiencing. Likewise, Powell and Keim (2015) investigated the trend in extreme precipitation in the southeast United States during 1948–2012. They found a significant increase in both intensity and magnitude of extreme precipitation except at those locations located further east. Also, they showed that autumn is getting significantly wetter, while spring and summer are getting drier. Moreover, Skansi et al. (2013) investigated the signal in the degree of wetting through an analysis of nine extreme precipitation indices in South America during the period 1950–2010. They observed significant trends in maximum 1 day precipitation amount, maximum 5 day precipitation amount, the number of very heavy precipitation days, consecutive dry days, very wet days and extremely wet days, the simple daily intensity index and the annual total wet-day precipitation. In the same way, Stephenson et al. (2014) analysed changes in extreme precipitation in the Caribbean during 1961–2010. They suggested that changes in rainfall were little consistent and that in general trends were weak. They also reported short significant positive trends in annual total precipitation, daily intensity index, maximum number of consecutive dry days and heavy rainfall events, and related precipitation extremes with the Atlantic Multidecadal Oscillation. Also, Zandonadi et al. (2015) used the 11 extreme precipitation indices of the ETCCDMI in a study of precipitation variation in Brazil during 1986–2011. They observed an increase in total precipitation at almost all weather stations and attributed it to extreme precipitation. In the north centre of the country, the increase in total annual rainfall was related to high rates of heavy precipitation, and also to the highest precipitation event which was above 10 mm. Instead, in the north, they reported a decrease in extreme precipitation, which was caused mainly by a reduction in precipitation greater than the 95th percentile. Also, they added that a positive precipitation trend could cause floods which suggests the necessity of implementing urban planning more efficiently for the future.

In Mexico, the majority of climatic studies have been focused on the analysis of average trends in some variables of the hydrological cycle. However, studies of the pattern of extreme precipitation events are required to provide information for different sectors of society (Nowreen et al., 2015), such as the agricultural sector. For example, the Aguascalientes State has preponderant and competitive agriculture, where the main crops are corn (grain and forage), beans, oats, sorghum and vegetables both in irrigated conditions and rainfed (INIFAP, 1998). This state is already facing adverse environmental problems, such as contamination and depletion of aquifers (CNA-WMO, 2006), and essential changes in the patterns of temperature and evaporation (Ruiz et al., 2016, 2018), which increase even more the risk of productive activities.

The objective of this research, therefore, was to analyse trends in 11 extreme precipitation indices at 25 weather stations of Aguascalientes State using the methodology suggested by the ETCCDMI for a period of 34 years (1980–2013). The results of this work will help determine the areas of Aguascalientes that are affected by climate change and construct a picture of the spatial distribution of extreme precipitation events which will help generate or adapt technology and production systems according to current conditions.

2 | MATERIALS AND METHODS

2.1 | Area of study

Aguascalientes State is located between 22 ° 27 ’ and 21 ° 38 ’ N latitude and 101 ° 53 ’ and 102 ° 52 ’ W longitude in the north-central region of Mexico (Figure 1a). It has a territorial area of 5,617.8 km² and adjoins Zacatecas on the north, northeast and west, with Jalisco on the south and east. According to García’s classification, this state has three different climates: semi-dry temperate (BS1k), semi-dry warm
(BS1h) and temperate sub-humid (Cw); in these climates, the average annual temperature is 17.1, 20.1 and 14.5°C, respectively (García, 1973). Previous studies indicate that average annual precipitation has a unimodal regime and varies from 3.4 mm in March to 130.4 mm in July (Ruíz et al., 2018). The total annual precipitation is around 516.8 mm, and average monthly evaporation oscillates between 113.7 mm in December and 235.5 mm in May, summing to an annual total of approximately 1958.5 mm (Ruíz et al., 2018). The lands of this state are semi-arid, and the ratio of precipitation and potential evapotranspiration is equal to 0.35 (Ruíz et al., 2018).

### 2.2 Meteorological data

Uninterrupted daily precipitation data for 34 years (1980–2013) from 25 weather stations of the National Meteorological Service belonging to the Comision Nacional del Agua were used (Table 1 and Figure 1b). Before starting the study, the database was subjected to quality control analysis, carried out by the staff of the National Meteorological Service, consisting of identifying daily outliers, i.e., those daily measurements that were outside an interval (upper and lower limit) were deleted. This interval was defined by two allowable thresholds (maximum and minimum) (Adolfo Portocarrero Resendiz, Servicio Meteorologico Nacional, personal communication).

### 2.3 Software and data quality analysis

The RClimdex 1.0 software, developed by the Climate Research Branch of the Meteorological Service of Canada, was used. This software provides an easy interface for computing the 27 primary indices suggested by the CCI/CLIVAR/ETCCDMI expert team for detection and monitoring of climate change (ETCCDMI) as well as for calculating other temperature and precipitation indices with thresholds defined by the user (Zhang and Yang, 2004). A second quality control phase was performed before estimating the indices, which is a prerequisite of the software and consists of the following phases (Zhang et al., 2015): (1) replacing all missing observations (coded as −99.9) in an internal format (NA) recognized by the software, (2) replacing all unreasonable values by NA, and (3) identifying daily precipitation values higher than the upper limit defined by the user (Zhang et al., 2015). It is important to
The estimation of extreme precipitation indices was carried out with the RClimdex 1.0 software according to recommendations published by Zhang and Yang (2004) and Zhang et al. (2015). This study also considered a wide variety of publications where the use of this software has been reported (Vincent et al., 2005; Zhang et al., 2011; Shresta et al., 2017; Ye et al., 2018). In total, 11 extreme precipitation indices were estimated. These indices were chosen because they are more related to the climatology of our study area (Table 2). Also, to establish the behaviour of precipitation variation, the interquartile range (IQR) of daily precipitation for each month was estimated (Trenary et al., 2015).

2.4 Calculation of extreme precipitation indices and their statistical analysis

After obtaining the extreme indices and the IQR for each weather station, the resulting time series were subjected to a statistical analysis to determine the presence or absence of trends and determine their statistical significance ($p \leq 0.05$). This analysis was carried out with the non-parametric Mann–Kendall test (Mann, 1945; Kendall, 1975; Rio et al., 2005). This test is robust and is not affected when missing values exist in the time series. Furthermore, it does not require that observations follow a

| ID   | Weather station       | Latitude (N) | Longitude (W) | Elevation (m) | Duration of data | ATP  | MD  |
|------|-----------------------|--------------|---------------|---------------|------------------|------|-----|
| 1004 | Cañada Honda          | 22° 00' 0"   | 102° 11' 56" | 1.925         | 1980–2013        | 496  | 0.22|
| 1005 | Presa El Niagara      | 21° 46' 44"  | 102° 22' 19" | 1.828         | 1980–2013        | 545  | 0.02|
| 1008 | Puerto de La Concepción| 22° 12' 7"   | 102° 08' 6"  | 2.300         | 1980–2013        | 547.7| 0.01|
| 1010 | La Tinaja             | 22° 09' 50"  | 102° 33' 14" | 2.425         | 1980–2013        | 656.5| 0.27|
| 1011 | Malpaso               | 21° 51' 36"  | 102° 39' 50" | 1.775         | 1980–2013        | 551.1| 0.51|
| 1012 | Presa Media Luna      | 21° 47' 38"  | 102° 48' 7"  | 1.585         | 1980–2013        | 636.1| 0.26|
| 1013 | Mesillas              | 22° 18' 47"  | 102° 09' 58" | 1.990         | 1980–2013        | 394.7| 0.47|
| 1015 | Palo Alto             | 21° 54' 58"  | 101° 58' 8"  | 2.015         | 1980–2013        | 525.4| 0.27|
| 1017 | Presa Potrerillos      | 22° 13' 59"  | 102° 26' 38" | 2.090         | 1980–2013        | 503.2| 1.48|
| 1018 | Presa Plutarco Elias Calles | 22° 08' 28" | 102° 24' 54" | 2.020         | 1980–2013        | 491.6| 0.10|
| 1019 | Presa Jocoque         | 22° 07' 41"  | 102° 21' 32" | 1.970         | 1980–2013        | 470.9| 0.00|
| 1020 | Presa La Codorniz     | 21° 59' 49"  | 102° 40' 26" | 1.783         | 1980–2013        | 593.5| 0.34|
| 1021 | Rancho Viejo          | 22° 07' 23"  | 102° 30' 40" | 2.090         | 1980–2013        | 569.4| 0.72|
| 1022 | San Bartolo           | 21° 44' 53"  | 102° 10' 12" | 1.965         | 1980–2013        | 527.6| 0.09|
| 1023 | Calvillo              | 21° 50' 13"  | 102° 42' 43" | 1.665         | 1980–2013        | 605.6| 0.10|
| 1024 | San Isidro            | 21° 46' 41"  | 102° 6' 14"  | 1.895         | 1980–2013        | 432.4| 0.19|
| 1026 | Tepezala              | 22° 13' 23"  | 102° 10' 8"  | 2.110         | 1980–2013        | 426.4| 0.06|
| 1027 | Venadero              | 21° 52' 37"  | 102° 27' 47" | 1.995         | 1980–2013        | 515.4| 1.25|
| 1028 | Villa Juarez          | 22° 06' 4"   | 102° 04' 5"  | 1.970         | 1980–2013        | 474  | 0.05|
| 1030 | Aguascalientes        | 21° 53' 42"  | 102° 18' 29" | 1.865         | 1980–2013        | 506.3| 0.02|
| 1031 | El Novillo            | 22° 01' 8"   | 101° 59' 56" | 2.010         | 1980–2013        | 513.7| 0.65|
| 1032 | Las Fraguas           | 22° 02' 20"  | 101° 53' 31" | 2.020         | 1980–2013        | 439.5| 1.32|
| 1033 | Los Conos             | 21° 53' 49"  | 101° 59' 31" | 2.015         | 1980–2013        | 490.4| 0.25|
| 1034 | Sandovales            | 21° 53' 6"   | 102° 06' 32" | 2.000         | 1980–2013        | 454.2| 0.01|
| 1045 | El Tule               | 22° 04' 59"  | 102° 05' 28" | 1.960         | 1980–2013        | 460.6| 0.96|

**ATP**, annual total precipitation (mm); **MD**, missing data (%).
Table 2: Extreme precipitation indices, suggested by the ETCCDMI, used in the present study

| Index | Indicator name | Definition | Units |
|-------|----------------|------------|-------|
| RX1day | Max 1 day precipitation amount | Monthly maximum 1 day precipitation | mm |
| RX5day | Max 5 day precipitation amount | Monthly maximum consecutive 5 day precipitation | mm |
| SDII | Simple daily intensity index | Annual total precipitation divided by the number of wet days (defined as PRCP ≥ 1.0 mm) in the year | mm/day |
| R10 | Number of heavy precipitation days | Annual count of days when PRCP ≥ 10 mm | days |
| R20 | Number of very heavy precipitation days | Annual count of days when PRCP ≥ 20 mm | days |
| R50 | Number of days above 50 mm | Annual count of days when PRCP ≥ 50 mm | days |
| CDD | Consecutive dry days | Maximum number of consecutive days with RR < 1 mm | days |
| CWD | Consecutive wet days | Maximum number of consecutive days with RR ≥ 1 mm | days |
| R95p | Very wet days | Annual total PRCP when RR > 95th percentile | mm |
| R99p | Extremely wet days | Annual total PRCP when RR > 99th percentile | mm |
| PRCPTOT | Annual total wet-day precipitation | Annual total PRCP in wet days (RR ≥ 1 mm) | mm |

PRCP, precipitation; RR, daily rainfall.

Graphical illustration of trends

Once all trends of precipitation indices were estimated, spatial distribution maps were generated for graphical illustration purposes using the inverse distance weighting interpolation method (Shepard, 1968). This method assumes that the nearby values contribute more to the interpolated values than distant observations. The advantage of inverse distance weighting over other geostatistical methods is that it is intuitive, efficient, and does not require an a priori investigation of spatial variability (Berndt and Haberlandt, 2018).

Relationship between elevation and extreme precipitation indices

Topography plays a vital role in the distribution of precipitation indices. Several studies indicate that a relationship exists between elevation and extreme precipitation indices (Zhang et al., 2014; Yao et al., 2016; Ding et al., 2019). For measuring this relationship, the Pearson correlation coefficient is used. This statistic measures the degree of compactness of the relationship between two variables (Ding et al., 2019). The two variables are positively correlated when the correlation coefficient is greater than 0 and are negatively correlated when the coefficient is less than 0 (Ding et al., 2019). An absolute value of the correlation coefficient that is nearer 1 indicates a stronger correlation between the two variables, whereas a correlation coefficient value nearer zero shows a weak correlation (Ding et al., 2019). A correlation coefficient equal to zero indicates that no linear relationship exists (Lyman and Longnecker, 2001; Ding et al., 2019). For Aguascalientes, a correlation analysis was carried out between the magnitude of precipitation extreme index trends and altitude. This analysis was made, as suggested by Ding et al. (2019) and Yao et al. (2016), by establishing different ranges of elevation: 1,585–1,990, 1,995–2,425 and 1,585–2,425 m.

Results and Discussion

The trends of 11 extreme precipitation indices at 25 weather stations of Aguascalientes, Mexico, are presented. From the total of the studied indices, the results for those that showed statistically significant trends (p ≤ 0.05) at at least one weather station are discussed.

Extreme precipitation indices

3.1 RX1day and RX5day

The maximum 1 day precipitation amount (RX1day) and the maximum 5 day precipitation amount (RX5day) seemed to...

distribution function (Gilbert, 1987). In the same way, the rate of change of the extreme indices and IQR through time was obtained with Theil–Sen’s trend estimator (Theil, 1950; Sen, 1968). In global warming studies, it is essential to know the sign of extreme indices; this makes it possible to predict other indices intended for applications related to climate change impacts (Almazroui et al., 2014). For this reason and for understanding interrelations among all precipitation indices, a correlation matrix was obtained. The Pearson correlation coefficient was calculated between all indices and for each weather station (Lyman and Longnecker, 2001).
| ID  | Station name          | RX1day | RX5day | SDII | R10 | R20 | R50 | CDD | CWD | R95p | R99p | PRCPTOT |
|-----|-----------------------|--------|--------|------|-----|-----|-----|-----|-----|------|------|---------|
| 1004| Cañada Honda          | −0.948 | 0.255  | 0.204| 0.000| 0.000| 0.000| 9.167| 0.000| 0.000| 0.000| −8.411 |
| 1005| Presa El Niagra       | 3.043  | 3.571  | 0.867*| 1.667| 1.538*| 0.000| 12.500| 0.000| 22.750| 0.000| 44.933  |
| 1008| Puerto de La Concepción| −0.115 | −3.300 | −1.200*| −1.667| −0.769| 0.000| 7.857| 0.000| −0.087| 0.000| −47.034 |
| 1010| La Tinaja             | 0.705  | −0.689 | −0.125| −0.690| 0.000| 0.000| 9.438| 0.000| 8.258 | 0.000| −12.194 |
| 1011| Malpaso               | 2.065  | 1.540  | 0.400| 1.111| 0.167| 0.000| 12.639| 0.000| 21.906| 0.000| 25.086  |
| 1012| Presa Media Luna      | 0.517  | 1.919  | 0.500| 0.556| 0.607| 0.000| 16.754*| 0.000| 20.300| 0.000| 20.104  |
| 1013| Mesillas              | 5.340* | 15.568*| 0.625| 0.923| 0.000| 0.000| 12.487| 0.000| 37.143*| 0.000| 37.969  |
| 1015| Palo Alto             | 5.607* | 10.428*| 1.592*| 1.429| 0.627| 0.000| 12.427| 0.000| 37.143*| 0.000| 37.969  |
| 1017| Presa Potreroillos    | −1.429 | 0.688  | 0.151| −0.185| 0.000| 0.000| 12.727*| 0.000| 14.316| 0.000| 7.371   |
| 1018| Presa Plutarco Elias Calles | −1.648 | −4.149 | −0.538| −0.435| 0.000| 0.000| 8.621 | 0.000| −3.875| 0.000| −11.933|
| 1019| Presa Jocoque         | 0.857  | −0.267 | 0.286| 1.250| 0.417| 0.000| 10.690| 0.000| 9.667 | 0.000| 16.435  |
| 1020| Presa La Coordiniz    | 1.948  | 3.378  | 0.277| 0.000| 0.000| 0.000| 15.486*| 0.000| 6.796 | 0.000| 6.108   |
| 1021| Rancho Viejo          | 2.000  | 3.125  | 0.348| 1.111| 0.000| 0.000| 15.000*| 0.000| 22.500| 0.000| 40.769  |
| 1022| San Bartolo           | 5.000  | 5.513  | 0.467| 0.625| 0.000| 0.000| 14.000*| 0.000| 25.050| 0.000| 6.625   |
| 1023| Calvillo              | −3.442 | −6.073 | −0.111| −1.667| 0.000| 0.000| 22.308*| 0.000| −17.320| 0.000| −25.261|
| 1024| San Isidro            | 0.261  | 0.942  | 0.071| −1.176| 0.000| 0.000| 13.333| 0.000| 1.077 | 0.000| −21.200|
| 1026| Tepezula              | 0.885  | 0.559  | −0.529| −1.000| 0.000| 0.000| 19.000*| 0.455| 0.000 | 0.000| −15.238|
| 1027| Venadero              | 2.158  | −0.317 | 0.218| −0.625| 0.000| 0.000| 10.000| 0.000| 1.270 | 0.000| −12.914|
| 1028| Villa Juarez          | 2.053  | 5.196  | 0.857*| 0.833| 0.000| 0.000| 14.000*| −0.476| 19.333| 0.000| 20.588  |
| 1030| Aguascalientes        | 0.357  | 0.903  | 0.208| 1.000| 0.000| 0.000| 14.400*| 0.000| 13.250| 0.000| 17.267  |
| 1031| El Novillo            | 0.000  | −1.933 | −0.286| 0.000| 0.417| 0.000| 6.000 | 0.357| 0.000 | 0.000| −8.417  |
| 1032| Las Fraguas           | 0.938  | 1.000  | 0.222| 0.000| 0.313| 0.000| 8.462 | 0.000| 6.842 | 0.000| 1.778   |
| 1033| Los Conos             | 5.861* | 12.887*| 0.413| 1.144| 1.000| 0.000| 10.945| 0.000| 33.493*| 0.000| 44.000  |
| 1034| Sandovales            | 1.176  | 8.640  | 0.824*| 2.414*| 1.111*| 0.000| 3.462 | 0.000| 18.889| 0.000| 67.500* |
| 1045| El Tule               | 3.000  | 10.000 | 0.875*| 2.174*| 1.579*| 0.000| 15.833| 0.000| 18.750| 0.000| 42.500  |

**Summary**

- Not statistically significant: 22 22 19 23 22 25 16 25 23 25 24
- Significant positive trends: 3 3 5 2 3 0 9 0 2 0 1
- Significant negative trends: 0 0 1 0 0 0 0 0 0 0 0
- Total: 25 25 25 25 25 25 25 25 25 25 25

*Significant at 95% level ($p \leq 0.05$).
be increasing just in a small part of Aguascalientes. The RX1day index showed statistically significant \((p \leq 0.05)\) trends only at three weather stations. The magnitudes of these trends were 5.340, 5.607 and 5.861 mm/decade in Mesillas, Palo Alto and Los Conos respectively (Table 3) in the north, east and southeast of the study area (Figure 2a). For this index, the trends fell within the interval reported in previous studies. For instance, some authors showed a range of 2.410 to 8.900 mm/decade (Beharry et al., 2015; Croitoru et al., 2016). Others described magnitudes different from ours, such as Santos et al. (2011) who reported a range that was from 1.140 to 1.640 mm/decade. Also, Shresta et al. (2017) described trends with a value of 34.600 mm/decade. In Figure 3, an example is presented of a time series for the RX1day index at the Los Conos weather station, where the analysis was statistically significant \((p \leq 0.05)\) and the rate of change was 5.861 mm/decade. The positive trend in the RX1day in the north, east and southeast of the state (Figure 2a) indicated that, at these locations, the monthly maximum 1 day precipitation was increasing. The increases for the RX1day may be linked to global warming, changes in the moisture close to the terrestrial surface and coincidental circulation (O’Gorman and Schneider, 2009), as well as an increase in the interannual variability of the monsoon in response to the duplication of carbon dioxide (Meehl and Washington, 1993). These increases in precipitation are of great environmental importance, since they improve runoff and recharge of the aquifers (Nowreen et al., 2015). Also, at
these three locations and their nearby regions, the increases in the RX1day can improve soil moisture conditions and favour rainfed agriculture particularly during the crop growth period known as spring–summer in which corn, beans and alfalfa are cultivated. In addition, a detrimental effect associated with the increases in the RX1day is the increase in the frequency of massive floods (Nowreen et al., 2015). In the same way, the RX5day had a statistically significant ($p \leq 0.05$) trend only at the same three weather stations, Palo Alto, Los Conos and Mesillas (Table 3) in the east, southeast and north of the state (Figure 2b), with magnitudes of 10.428, 12.887 and 15.568 mm/decade respectively. The magnitudes of our trends were higher than those reported by other studies, such as that of Beharry et al. (2015) who found values between 7.760 and 8.600 mm/decade. Studies such as Santos et al. (2011) and Croitoru et al. (2016) found trends substantially smaller with magnitudes between 1.150 and 5.420 mm/decade. Also, Shresta et al. (2017) reported trends considerably higher than ours; these were between 55.300 and 61.000 mm/decade. It is important to highlight that the weather stations with a significant positive trend in the RX5day are the same as those that showed a significant positive trend in the RX1day (Table 3), corroborating that at these locations the maximum precipitation of short periods is increasing. According to Frich et al. (2002), the increase in the RX5day is caused by the forcing of greenhouse gases; thus, the greater quantity of water vapour available for condensation led to an increase in the maximum quantity of total precipitation with a notably improved hydrological cycle. In this way, the increase in the RX5day confirmed the idea set before by the RX1day about one optimistic scenario for the environment and rainfed agriculture at these three locations; however, these increases could also bring flash floods with them (Frich et al., 2002; Nowreen et al., 2015). In summary, relative to these indices the perceived scenario for the nearby zones of these three locations shows that the climate tends to offer a greater availability of moisture coming from rain.

3.1.2 Simple daily intensity index (SDII)

Analysis of the SDII also manifested changes in one small part of the study area. This index showed a statistically significant trend ($p \leq 0.05$) at six weather stations of which five had a positive trend and one had a negative trend (Table 3). The positive significant trends varied between 0.824 and 1.592 mm day$^{-1}$ decade$^{-1}$ in Sandovales and Palo Alto, respectively (Table 3), and were distributed in the south (Presa El Niágara), east (Palo Alto), northeast (Villa Juárez and El Tule) and southeast (Sandovales) of the state (Figure 4). These positive trends were within the values reported by Shresta et al. (2017), who obtained a range from 0.600 to 2.400 mm day$^{-1}$ decade$^{-1}$; however, the magnitudes were higher than those obtained by Croitoru et al. (2016) and Santos et al. (2011) who obtained trends between 0.110 and 0.320 mm day$^{-1}$ decade$^{-1}$. On the other hand, the only negative significant trend occurred at the Puerto de La Concepción weather station in the northeast of Aguascalientes (Figure 4) and had a magnitude of $-1.200$ mm day$^{-1}$ decade$^{-1}$ (Table 3). This negative trend was slightly higher than the values of Shresta et al. (2017), who found an interval that was from $-2.100$ to $-1.700$ mm day$^{-1}$ decade$^{-1}$. In Figure 5, a time series example is presented for the SDII index at the Puerto de La Concepción weather station where the analysis was statistically significant ($p \leq 0.05$) and the rate of change was $-1.200$ mm day$^{-1}$ decade$^{-1}$. Our results showed that in Aguascalientes the SDII just affected a relatively small area; for the most part it increased, and in a very little area it decreased; in other words, in most of the area the annual total precipitation divided by the number of wet days increased, and in a small area it decreased. The increase in SDII in the majority of climate models is directly related to greenhouse gas forcing (Frich et al., 2002). The implications of the increase in this index relate to the positive effects of the RX1day and RX5day, particularly the intensification of the hydrological cycle.
3.1.3 | Number of heavy precipitation days (R10 and R20)

The number of heavy precipitation days (R10 and R20) only showed changes in a small part of the study area. The R10 index showed a statistically significant ($p \leq 0.05$) trend only at two weather stations (Table 3), with magnitudes of 2.174 and 2.414 days/decade at El Tule and Sandovales (Table 3) in the northeast and southeast of Aguascalientes (Figure 6a), respectively. For this index, previous studies reported rather heterogeneous magnitudes. Nevertheless, our trends were within these ranges; for example, for this index, trends oscillated between 0.420 and 5.900 days/decade (Arriaga-Ramirez and Cavazos, 2010; Santos et al., 2011; Croitoru et al., 2016; Shresta et al., 2017). Our results indicated that the number of days in the year with precipitation ≥10 mm was increasing just in a small part of the state. According to Frich et al. (2002), this indicator is a direct measure of the number of very wet days, and it is highly correlated with annual total precipitation in almost all types of climates. The R10 increase is produced by climatic perturbations caused by the forcing of greenhouse gases, which provoke a greater availability of water vapour for condensation and, in turn, permit a clear increase in the number of days with heavy precipitation (Frich et al., 2002). In soils with slope and low hydraulic conductivity, the increase in R10 could bring with it an increase in erosion risk, mostly at the beginning of the growing season when the crop does not provide enough cover (Haan et al., 1994). It is important to mention that Sandovales and El Tule (sites with an increase in R10) are locations with a high tradition in bean and corn production. For these crops, farmers have started to adopt inexpensive techniques for conserving soil and harvesting water from

FIGURE 5 | Time series example for SDII in the Puerto de La Concepción weather station ($p \leq 0.05$)

FIGURE 6 | Spatial distribution of R10 (a) and R20 (b) in Aguascalientes, Mexico
rain. This avoids the loss of water by runoff and reduces erosion of plots. At the same time, this practice permits water infiltration to be increased, improving the soil agronomic properties and increasing crop productivity (Jones and Clark, 1987). Nevertheless, R20 showed a statistically significant (p ≤ 0.05) trend just at three weather stations (Table 3); the magnitudes were 1.111, 1.538 and 1.579 days/decade at Sandovales, Presa El Niagara and El Tule (Table 3) in the southeast, south and northeast of Aguascalientes, respectively (Figure 6b). For this index, the reported trends for other parts of the world varied importantly; however, the magnitudes of our trends were within that interval. Some authors comment that globally these trends are between 0.270 and 10.910 days/decade (Croitoru et al., 2016; Shresta et al., 2017; Barry et al., 2018). Our findings indicate that the number of days with precipitation ≥20 mm is increasing just in a small area of the state. The increase in R20 is associated with the forcing of greenhouse gases (Frich et al., 2002). The problems related to the increase in this index are linked to the erosion of both agricultural and non-agricultural soils, so that at Sandovales, Presa El Niagara and El Tule some strategies to prevent damage associated with this type of rain might be the same as those recommended for R10, besides the establishment of contours, terraces, runoff control works and reforestation of the lower lands for lessening the destructive force of runoff.

3.1.4 Number of consecutive dry days (CDD)

Analysis of the number of consecutive dry days (CDD) indicated notable changes in the moisture regime in one part of the state. The CDD index had statistically significant (p ≤ 0.05) trends at nine weather stations (Table 3). These trends varied between 12.727 and 22.308 days/decade at Presa Potrerillos and Calvillo (Table 3), respectively. Thus, the increases in CDD were distributed in the southwest (Presa Media Luna and Calvillo), northwest (Presa Potrerillos and Rancho Viejo), west (Presa La Codorniz), southeast (San Bartolo), northeast (Tepezala and Villa Juarez) and south-central region (Aguascalientes) of Aguascalientes (Figure 7). The trends obtained in the present study were quite similar to those reported in other studies. Croitoru et al. (2016) observed a range from 0.490 to 1.330 days/decade; other researchers reported trends between 10.200 and 18.700 days/decade (Shresta et al., 2017; Nkemelang et al., 2018) which are more similar to ours. These results indicated that in an important part of Aguascalientes the maximum number of consecutive days with precipitation <1 mm occurred with more frequency. In other words, at these locations the number of dry days increased. According to the National Academies of Sciences, Engineering and Medicine (2016), an increase in drought occurrences is caused by the influence of anthropogenic activities. Similarly, Rosenfeld et al. (2001) indicated that dust has an inhibitive effect on precipitation in the properties of clouds. This effect is less compared to the combustion of vegetation or anthropogenic gases, but what is important is the abundance of dust that deserts release to the atmosphere. The precipitation reduction in clouds affected by desert dust causes soil dryness, which in turn increases the dust forming a feedback loop that decreases precipitation even more (Rosenfeld et al., 2001). The implications of this phenomenon could be a moisture deficit in the first soil horizon, reduction of crop yield and reduction of natural vegetation. When this phenomenon is combined with an evaporation increase, it can lead to a desertification increase (Frich et al., 2002). On the other hand, Nkemelang et al. (2018) indicated that the increase in CDD implicated a longer dry season and late-onset of rains and their early end. This is particularly important at the Presa Media Luna weather station for which significant evaporation increases have been reported (Ruiz et al., 2018), which could put even more pressure on water resources of the region.

3.1.5 Number of very wet days (R95p)

The number of very wet days (R95p) is changing in a very small surface area of the state. The R95p index had statistically significant (p ≤ 0.05) trends, only positive, at two weather stations (Table 3). The magnitudes were 33.493 and 37.143 mm/decade at Los Conos and Palo Alto (Table 3) in the southeast and east of the study area, respectively (Figure 8). In connection with this index, our trend values were within the range reported for other parts of the world. Some authors have found magnitudes lower than ours, such as Arriaga-Ramirez and Cavazos (2010) who obtained trends between 7.300 and 10.000 mm/decade. Similarly, Croitoru et al. (2016) reported a range from 11.720 to 17.510 mm/decade. In other studies, trends relatively higher than ours were reported; e.g. Shresta et al. (2017) found trends between 65.300 and 152.900 mm/decade. Also, Barry et al. (2018) reported a regional average trend of about 28.070 mm/decade, which is quite close to that found here. Our results indicated that the very wet days, i.e. annual total precipitation when the daily rainfall (RR) is >95th percentile, increased in a small part of the state (Figure 8). According to climate models, increases in R95p are also a consequence of the forcing of greenhouse gas (Frich et al., 2002). The increases in R95p in this area of Aguascalientes could have significant environmental and economic effects, such as greater moisture availability to maintain the dynamism of the ecosystem and hydrological cycle, and higher soil moisture availability during the growing season. The scenario for the region of influence of the Palo Alto weather station improves even more when considering the evaporation decreases that have been reported for this place (Ruiz et al., 2018). Another important benefit of the increase in
R95p is that, in regions where irrigation is practised, pumping and the pressure in the use of water could decrease.

### 3.1.6 Annual total wet-day precipitation (PRCPTOT)

The PRCPTOT also indicated changes in a small area of Aguascalientes. The PRCPTOT index showed a statistically significant ($p \leq 0.05$) trend only at one weather station (Table 3); its value was 67.500 mm/decade at Sandovales in the southeast of the state (Figure 9). For this index, previous studies have reported very heterogeneous magnitudes, but the range of these encompassed the trend values obtained in the present work. For example, Croitoru et al. (2016) reported trends between 14.470 and 28.560 mm/decade and Santos et al. (2011) reported positive trends from 8.320 to 26.690 mm/decade. On the other hand, Shresta et al. (2017) found positive trends which were considerably higher, between 131.800 and 261.500 mm/decade. Nevertheless, Barry et al. (2018) reported a regional average trend of about 61.430 mm/decade, which is quite close to the trend in the present work. According to the National Academies of Sciences, Engineering and Medicine (2016), the previous heterogeneity in the positive trends of PRCPTOT is because the extreme indices present high variability among the different sites of meteorological monitoring. Our results indicated that PRCPTOT increases in a small area of the state, while the more significant part did not show changes; in other words, the Sandovales weather station (southeast) is the only site where PRCP was increasing. The increases in precipitation are related to the forcing associated with strong vertical movement and the significant increase of water vapour derived from warming (Hartmann et al., 2013; Westra et al., 2014). As a consequence, the increases in PRCPTOT in Sandovales could bring with them an increase of runoff and recharge, increase in vegetation, improvement in the hydrological cycle, aridity index reduction and higher soil moisture availability.

### 3.1.7 Summary of significant vs. not significant trends of extreme precipitation indices

The R50, consecutive wet days (CWD) and R99p indices did not show statistically significant trends ($p \leq 0.05$) at any
of the weather stations considered in the study. At the bottom of Table 3, a résumé of the number of weather stations with no significant trends, with significant positive trends and with significant negative trends is presented. For all indices, most of the weather stations did not show significant trends: as indicated above R50, CWD and R99p did not experience significant trends at any weather station. A small number of weather stations had significant positive trends in most indices, and SDII was the only index with a significant negative trend in only one weather station. This information is presented in Table 4 also, but in this case information is shown as a percentage of weather stations.

3.2 | Correlation analysis of extreme precipitation indices

A correlation is essential to understand the existing interrelation between all extreme indices. Except for the pairs CDD–RX1day, CDD–R50, R95p–CDD and R99p–CDD, all pairs of extreme precipitation indices showed a statistically significant correlation ($p \leq 0.05$) at the weather stations considered (Table 5). All statistically significant correlations had a negative sign (Table 5) except for the pairs CDD–RX5day, CDD–R10, CDD–R20, CWD–CDD and PRCPTOT–CDD (Table 5). Finally, the range of variation of all correlations was $-0.5301 \pm 0.9830$ and was given by the pairs R10–CDD and R50–R99p, respectively (Table 5).

3.3 | Trend of the interquartile range of monthly daily precipitation

No important changes were noted in the IQR of daily monthly precipitation. The IQR was estimated in 300 time series, i.e. for 12 months and 25 weather stations. However, for this statistic, values greater than zero were obtained only in wet months (June, July, August and September). Out of 300 time series, a significant trend was only obtained in September at Puerto de La Concepción weather station; the magnitude was 0.196 mm/decade. Thus, in the majority of weather stations and months, the variability of monthly precipitation is quite stable through the years, i.e. no trends of IQR exist through time. In Figure 10, two examples of IQR time series are shown: Figure 10a corresponds to August at Presa El Niagara weather station (no significant trend), and Figure 10b corresponds to September at Puerto de La Concepción weather station (significant trend).

3.4 | Microclimate effect in the spatial distribution of precipitation indices

The spatial distribution of the sign and magnitude of precipitation index trends is related to differences in local climate and vegetation characteristics. According to Chattopadhyay et al. (2017), the spatial variation of extreme precipitation indices, amongst other things, is caused by microclimate and
### Table 5
Correlation matrix for the precipitation extreme indices in Aguascalientes, Mexico, during the period 1980–2013

|          | RX1day | RX5day | SDII  | R10   | R20   | R50   | CDD  | CWD  | R95p  | R99p  | PRCPTOT |
|----------|--------|--------|-------|-------|-------|-------|------|------|-------|-------|---------|
| RX1day   | 1      |        |       |       |       |       |      |      |       |       |         |
| RX5day   | +0.4115 + 0.907 \(^a\) | 1      |       |       |       |       |      |      |       |       |         |
|          | 100\(^b\) |       |       |       |       |       |      |      |       |       |         |
| SDII     | +0.3559 + 0.7495 + 0.3912 + 0.8091 | 1      |       |       |       |       |      |      |       |       |         |
|          | 96     | 100    |       |       |       |       |      |      |       |       |         |
| R10      | +0.3486 + 0.4950 + 0.3752 + 0.7898 + 0.3503 + 0.7823 | 1      |       |       |       |       |      |      |       |       |         |
|          | 24     | 92     | 92    |       |       |       |      |      |       |       |         |
| R20      | +0.3446 + 0.6474 + 0.4254 + 0.8140 + 0.4631 + 0.8731 + 0.5455 + 0.8793 | 1      |       |       |       |       |      |      |       |       |         |
|          | 56     | 100    | 100   | 100   |       |       |      |      |       |       |         |
| R50      | +0.4497 + 0.8395 + 0.3479 + 0.7305 + 0.3634 + 0.7298 + 0.3500 + 0.4474 + 0.3505 + 0.5962 | 1      |       |       |       |       |      |      |       |       |         |
|          | 100    | 92     | 84    | 28    | 56    |       |      |      |       |       |         |
| CDD      | =      | −0.3484 |       | +0.3931 + 0.4924 −0.5301 − 0.3430 −0.3839 −0.3470 = | 1      |       |       |       |       |         |
|          |      | 4      | 8     | 28    | 12    |       |      |      |       |       |         |
| CWD      | +0.3788 + 0.4487 + 0.3430 + 0.6446 + 0.3703 + 0.6183 + 0.3947 + 0.7617 + 0.3625 + 0.6091 + 0.4436 + 0.5826 −0.4308 | 1      |       |       |       |       |      |      |       |       | −0.3967 |
|          | 8     | 72     | 20    | 92    | 56    | 12    | 8    |      |       |       |         |
| R95p     | +0.4457 + 0.8743 + 0.4032 + 0.8635 + 0.5164 + 0.8510 + 0.4471 + 0.6837 + 0.4637 + 0.8801 + 0.4578 + 0.8289 | + 0.3489 |       |       |       |       |      |      |       |       | +0.5347 |
|          | 96    | 100    | 100   | 88    | 100   | 100   | 56   | 100  |       |       |         |
| R99p     | +0.4517 + 0.8941 + 0.3484 + 0.7664 + 0.3934 + 0.7159 + 0.3921 + 0.4644 + 0.3616 + 0.5786 + 0.7717 + 0.9830 | + 0.3687 | + 0.4731 |       |       |       |      |      |       |       | +0.7954 |
|          | 100   | 92     | 88    | 16    | 44    | 100   | 16   | 100  |       |       |         |
| PRCPTOT  | +0.3585 + 0.7469 + 0.4399 + 0.8080 + 0.3669 + 0.8177 + 0.3505 + 0.5962 + 0.6842 + 0.9060 + 0.3506 + 0.6124 −0.5047 | + 0.4079 | + 0.5519 | + 0.3664 |       |       |      |      |       |       | +0.6405 |
|          | 80    | 100    | 100   | 56    | 100   | 84    | 60   | 96   | 100   | 80    |         |

\(^a\)These numbers represent the correlation range for those weather stations where the correlation analysis was statistically significant \((p \leq 0.05)\).

\(^b\)These numbers indicate the percentage of weather stations that were statistically significant \((p \leq 0.05)\) in the correlation analysis for this pair of indices.

\(^=\)correlation was not statistically significant \((p \leq 0.05)\).
the characteristics of the local vegetation. They commented that significant trends were distributed mainly in lands covered by pasture/hay and in urban zones. In Aguascalientes, the three significant positive trends in the RX1day and RX5day occurred at sites (Mesillas, Palo Alto and Los Conos) where irrigated agriculture is practised. One of these sites (Los Conos) is located near to secondary bushy vegetation. On the other hand, four (Presa El Niagra, Palo Alto, Villa Juarez and El Tule) out of five significant positive trends of the SDII occurred in irrigated lands, and one (Sandovales) occurred in lands with rainfed agriculture near to secondary bushy vegetation. The only (Puerto de La Concepción) significant negative trend in the SDII was located in an area with scrub. Similarly, out of three significant positive trends in R10, one (Presa El Niagra) occurred in irrigated soils, another R20 positive trend (El Tule) also occurred in irrigated soils but near lands with secondary bushy vegetation, and another (Sandovales) in lands with secondary bushy vegetation and close to soils where rainfed agriculture is practised. Out of nine significant positive trends in CDD, four (Presa Media Luna, Presa La Codorniz, Calvillo and Villa Juarez) were at sites of irrigated agriculture, two of these (Presa Media Luna and Presa La Codorniz) were also located very close to secondary bushy vegetation, and another weather station (Calvillo) was close to the limit of Calvillo city which has shown an accelerated growth in the last decades. Another trend (Rancho Viejo) took place in soils with rainfed agriculture near soils covered by grassland. Three more (Presa Potrerillos, San Bartolo and Tepezala) occurred in grasslands but, of these, one (San Bartolo) was close to the limits of irrigated lands and another (Tepezala) was close to the limit of scrub. Finally, another significant positive trend was located in the urban zone of Aguascalientes city. This is the only index with more magnitude variability in those stations with a significant positive trend (Table 3). The magnitudes of significant positive trends for this index increased in the following order: grassland, grassland and close to irrigated soils, irrigated lands, urban area, rainfed agriculture and close to the limits of grassland, secondary bushy vegetation near to irrigated soils, irrigated crops and close to secondary bushy vegetation, grassland and near to the limit of scrub, irrigated agriculture and on the limits of urban growth. In the same way, both (Palo Alto and Los Conos) significant positive trends in R10 occurred in regions with irrigated agriculture, but one of them (Los Conos) was also close to secondary bushy vegetation. Similarly, the only significant positive trend in R95p was at a site (Sandovales) with secondary bushy vegetation, very close to the limits with rainfed agriculture. In Aguascalientes, for all indices, the existence/absence of uniformity in both sign and magnitude of significant trends could be related to the similarity/difference of microclimate and the characteristics of vegetation. Roque-Malo and Kumar (2017) investigated the potential microclimate role as an explanatory variable of changes in precipitation indices patterns; they found that the climate diversity or microclimate was responsible for the lack of uniformity in the trends found in their study area. They added that the extent of the uniformity of trends was also influenced by how the changes and rotation in the vegetation covered and land use occurred (Roque-Malo and Kumar, 2017). In this regard, it is important to highlight that between 1985 and 2014 important changes in land use occurred in Aguascalientes. The total surface covered by bodies of water increased by 180.62%, i.e. there was an increment of 30.03 km²; the forest area was reduced by 64.19%, which is equivalent to a loss of 686.74 km²; the area covered by grassland grew by 9.72%,
which equals an increase of 135.97 km²; the urban area increased 983.25%, i.e., it had a growth of 190.24 km²; the surface of scrub grew 19.37%, which equals 162.60 km²; also the agricultural area increased by 7.31%, i.e. 166.63 km² (INEGI, 1990, 2016). In Aguascalientes, the local microclimate and characteristics of the vegetation at each weather station could be significant contributors in the spatial pattern of extreme index trends.

### 3.5 Relationship between elevation and extreme precipitation indices

It is considered that there exists a relation between elevation and extreme precipitation indices. Extreme rainfall index trends are much less consistent spatially than other meteorological factors due to the complexity of topography and geomorphology in a mountain region (Alexander et al., 2006), which impacts cloud thickness and water content, as a result of which the amount of precipitation is affected (Ding et al., 2019). Studies show evidence of a correlation between elevation and extreme precipitation indices. In a study that encompassed an altitudinal range of 1,245–4,200 m, Zhang et al. (2014) found a significant correlation (p ≤ 0.05) between elevation and the magnitude of six extreme indices (NW, CDD, CWD, R20, R25 and SDII). Ding et al. (2019) analysed the relationship between topography and extreme precipitation through correlation analysis at different gradients of height; they found that the RX1day was significantly correlated with the height of weather stations at less than 500 m; on the other hand, the RX1day, RX5day, R5mm and PRCPTOT trends were significant and positively correlated above 3,500 m; there was no significant correlation in stations located between 500 and 3,500 m. According to the correlation analysis, in Aguascalientes the relationship between extreme precipitation indices and elevation was not obvious, since for each range of elevation only one significant (p ≤ 0.05) correlation was obtained (Table 6). For the range 1,585–1,990 m, most of the correlations were positive and oscillated between moderate and weak. Only CWD and CDD were negative, the first being weakly correlated and the other between moderate and strong. However, CDD is a unique index with a significant correlation in this range of altitude (Table 6). The significant negative correlation between CDD and elevation indicates that CDD decreases while height increases. This reduction in CDD is coherent with the precipitation increase that occurs when elevation increases (Yao et al., 2016). Other studies have also found a significant correlation between CDD and elevation (Zhang et al., 2014; Gao and Wang, 2017). In the same way, for the range 1,995–2,425 m, the majority of correlations were negative and varied from moderate to weak; the unique index with a positive correlation was CDD, which was weak (Table 6). In this range, R20 was a unique index with significant correlation and oscillated between moderate and strong; furthermore, it was negative (Table 6). This means that, as height increases, the negative trend in R20 is smaller, i.e. when height is increased R20 stops decreasing, which is also coherent with the positive pattern of rainfall through elevation (Yao et al., 2016). Also, a significant negative correlation for R20 has been reported by Gao and Wang (2017). In the range 1,585–2,425 m, RX5day, SDII, R10, R20, CDD and PRCPTOT had a negative correlation between moderate and weak (Table 6). Similarly, RX1day, CWD and R95p were positive and weakly correlated with elevation (Table 6). Thus, for this range, CDD was the only index with significant correlation, which means that CDD decreases as elevation increases. Also, other studies have shown the sensitivity of CDD with respect to elevation (Zhang et al., 2014; Gao and Wang, 2017). The fact that correlations in all ranges were not significant in the majority of indices could be because our ranges of elevation were not too wide; for the complete elevation range (1,585–2,425 m) the difference in elevation between the weather station located at the highest elevation and the weather station located at the lowest elevation was just 840 m. Some work where more correlation was reported between extreme indices and elevation considered greater differences in elevation (Zhang et al., 2014; Ding et al., 2019). In the present study, the indices that showed greater sensitivity to elevation were CDD and R20.

### 4 CONCLUSIONS

Analysis of trends in 11 extreme precipitation indices at 25 weather stations of Aguascalientes State was carried out.
In small zones in the east and north of the state, precipitation in 1 and 5 days increases; in the east and south, both rainfall intensity and the number of days with heavy precipitation increase; in a very small zone to the east annual total precipitation also shows evidence of an increase. This is an indicator that in these parts of the state more inclination to wetter conditions exists. On the other hand, at a specific site in the northeast precipitation intensity decreases; in the north, west, central and southeast regions dry days show evidence of an increase. This suggests that in these places traits of drier conditions prevail.

In those regions where precipitation increased both in intensity and annual accumulated total, to lower the erosion risk it is recommended that the use of soil management technology both in agricultural lands and in land with natural vegetation is intensified. On the other hand, at sites with increases in the number of dry days, production systems that use water more efficiently should be adopted. The harvesting of water using furrow dykes could be a useful technique whose use should be intensified. Also, deficit irrigation could constitute a potential strategy for producing more food under a scenario of water deficit.

This line of research should continue with the analysis of extreme precipitation events using data from climate model outputs both for present climate and the future; these results will benefit society in long-term socioeconomic planning.

The changes found in extreme precipitation indices in the present study could also be part of climate change effects that face other parts of the watershed to which Aguaescalientes belongs.

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