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EXTREME DROUGHT TRENDS IN PUEBLA: CLIMATE AND SOCIOECONOMIC INDICES WITH IMPLICATIONS FOR WATER MANAGEMENT

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ABSTRACT

Droughts have caused damage in most of the state, generating economic, social and environmental consequences. This has caused social and political tensions and conflicts over the use of water at the local and municipal level. Therefore, it is important to generate knowledge about the current status and the evolution of droughts and their effects, due to the impact they have on various human activities and other areas. The objective of this study, is to analyze the principal databases to identify the state of Puebla's exposure to drought as an important component of vulnerability and risk. The methodology used was quantitative through the exploration of the CONAGUA drought monitor, the RClimDex software based on monthly time series of climate indices to analyze trends of meteorological variables, as well as socioeconomic indicators from databases of government institutions to identify factors of exposure and sensitivity and which, together with the adaptive capacity, determine the degree of vulnerability. The results indicate that in recent years, the periods of drought affecting various municipalities, mostly in the North and Northeast Sierra as well as the Mixteca region in Puebla have increased, with an effect on climate vulnerability from drought, primarily from the event of El Niño-Southern Oscillation. This represents an interesting contribution since there are few studies at the state level that analyze these databases, which are important in the detection of vulnerability to drought. In addition, it benefits decision makers in the adequate management of the water resource.

Keywords: CONAGUA drought monitor, RClimDex, risk management.

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INTRODUCTION

The Intergovernmental Panel on Climate Change (IPCC, 2023) mentions that in recent years, in different countries, there has been a significant increase in the frequency, magnitude and duration of drought events in comparison to the records made at the beginning of the 20th century. The climate scenarios (RCP8,5) estimate with an intermediate level of confidence that by the end of the 21st century, several dry regions will experience a decrease in soil moisture and higher risk of agricultural drought due to the increase in superficial temperatures. In large countries, a drought does not affect the entire territory; however, the regions affected do have important impacts on the economy and society (IPCC, 2013). Therefore, there is strong scientific and social interest in understanding the factors that lead to extreme events to increase the management of risks associated with threats such as droughts (Felsche and Ludwig, 2021).

These are characterized by a decrease in rainfall compared to a normal value (climatological mean) that increases its environmental, economic and social impact when the duration is extremely prolonged. This phenomenon happens with the alteration of patterns of general atmospheric and oceanic circulation, which in turn affects the tropical regions, influenced by the Inter-Tropical Convergence Zone (ITCZ) and events such as El Niño-Southern Oscillation (ENSO). For South America, the Andes mountain range also intervenes as another climate forcer. In addition, human activities influence climate change and extreme events such as drought, derived from deforestation, changes in land use, and the increase in concentration of Greenhouse Gases (GHGs), factors that provoke degradation, erosion and desertification (Matailo *et al.*, 2019).

With regards to the availability of databases, there is the Drought Atlas for Latin America and the Caribbean, which generates a reference on the frequency of the phenomenon. Through the generation of more solid climate information for decision making, the Atlas directly supports the proactive management of droughts in the region (Núñez and Verbist 2018). In Mexico, there is the Drought Monitor of the National Waters Commission (*Comisión Nacional del Agua*, CONAGUA) and the National Meteorological Service (*Servicio Meteorológico Nacional*, SMN), based on the United States Drought Monitor (USDM) (2023), which identifies drought areas and labels them based on intensity. The map uses four categories of drought, from D1, the least intense, to D4, the most intense. It provides information on the land to help better understand the local conditions and to identify areas that could need more attention. The objective of the research was to analyze the main databases to identify the drought exposure of the state of Puebla.

THEORETICAL FRAMEWORK

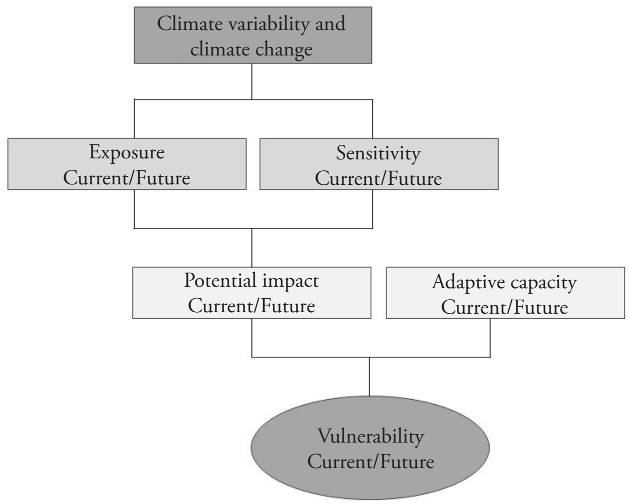
Drought is defined as a period of abnormally dry conditions that persist long enough to cause a serious hydrological imbalance (OMM, 1992). This term is relative, since it lacks a universal definition and its classification varies according to diverse criteria and authors. Any study about the deficit in rainfall should consider the specific activity related to the type of precipitation being examined. Wilhite and Glantz (1985) classified drought in function of the scientific discipline studying it, and they distinguish between meteorological, agricultural, hydrological and socioeconomic drought. Any period with abnormal rainfall deficit is defined as meteorological drought (IPCC, 2018), while in agricultural drought there will be a humidity deficit in the soil that impacts crop production or the function of ecosystems in general, and during the runoff and percolation season it primarily affects water contributions (hydrological drought). The humidity and the underground waters stored by the soil, are also affected by the increase in real evapotranspiration and by decreases in rainfall. Finally, socioeconomic drought emerges as consequence of the types of drought mentioned before, generating unfavorable effects in the social and economic spheres (Mishra and Sing, 2010; Coronel, 2013).

The problems produced by droughts are not only reflected in the production, productivity and economic yields, but also can lead to the decrease in standard of living and health, and the increase in poverty or migration (Calvo-Solano *et al.*, 2018; Nuñez and Verbist, 2018). In parallel, problems with natural resources are also generated, such as soil degradation and, therefore, loss of biodiversity. These effects are known jointly as desertification, and they are happening with more intensity and frequency due to climate change and the repeated occurrence of extreme atmospheric events that are attributable to the anthropogenic activities that alter the atmospheric composition (Matailo, Luna, Cervantes, & Vega, 2019). The impact of droughts is magnified when authorities do not show a firm commitment to adopt new government guidelines that may face and mitigate the effects of the water deficit (ONU, 2019).

Under such circumstances, the social and political conflicts derived from water scarcity tend to become exacerbated. Evidence suggests that the frequency, duration and intensity of droughts has increased, especially in the tropics and subtropics, since the last half of the 20th century in response to global climate change (IPCC, 2012). In 2009, Mexico experienced what is considered to be the second worst drought in sixty years, which was followed by a much more severe episode in 2011. This last event covered approximately 80% of the national territory prolonging it until 2013, increasing its coverage to 90%. The agricultural and livestock production sectors were affected primarily by water scarcity, which resulted in losses for a total of 7,751 million pesos (approximately $700 million USD at 2011 prices), according to data from the National Center for the Prevention of Disasters (CENAPRED, 2012; CONAGUA, 2019; and Méndez, 2013). Therefore, vulnerability in the presence of drought is linked not only with the duration and the geographic coverage of the event, but also to the capacity of society to anticipate, face, resist and recover from its effects. Vulnerability is influenced by the nature, magnitude and speed of climate variations to which a system is exposed, as well as by its sensitivity and adaptability (PECC, 2014).

It is important to mention that the lack of a concrete definition of vulnerability, especially regarding drought, is due to the different ways in which it has been conceptualized according to the objectives and methods for its analysis, as well as specific contexts (Zarafshani *et al.*, 2016). In Mexico, the definition of vulnerability to climate change established by the IPCC (2014) has been adopted in the national legislation. This definition emphasizes that the analysis of vulnerability of a system must take into account three essential elements: exposure, sensitivity and adaptability (Figure 1).

Exposure refers to the character, magnitude and speed of change and climate variation that affects a system. Sensitivity is related with the degree in which such as system is affected by the variability and climate change, which is influenced by the characteristics that define it. On the other hand, adaptability is based on the resources, both human and institutional, which make possible the establishment of adjustment processes in face of a climate problem in particular (IPCC, 2007). In other words, these are elements of collective nature that may reduce the potential impact. Therefore, this study is focused on drought intensity (exposure) from the dimension of temporal reference, as well as in identifying factors that have an impact on the sensitivity of municipalities which back risk



Source: INECC (2016).
Figure 1. Components of the current and future Vulnerability Model according to the IPCC concept (2007).

management. The results are fundamental to support risk management, which refers to the probability that a drought happening that affects the integrity and development of an object or specific social phenomenon (Varela, Oquendo and Romero, 2020).

In this sense, Lobato *et al*. (2019) suggest implementing a database to forecast and predict drought and to generate robust information related with different time scales (monthly, seasonal, among others), similar to the program in the United States called National Integrated Drought Information System (NIDIS, 2007). This system can help the users to make informed decisions to reduce the risks associated with drought. Therefore, an early alert system in face of drought that contemplates the methodological analysis of the possible impacts under realistic scenarios can greatly help official institutions, the private sector, and users to act before the occurrence and, therefore, reduce the risks associated (Lobato *et al*., 2019).

METHODOLOGY

Three development phases were considered for this study. In the first, the monthly records of the Mexican Drought Monitor (MDM) were reviewed, corresponding to the period of January 2003 to December 2020 for the state of Puebla. The absolute frequencies of the different conditions of meteorological drought that were presented monthly at the municipal level were obtained, and the municipalities with highest incidence of extreme drought were mapped using Geographic Information Systems (GIS). It is important to highlight that the MDM is based on obtaining and interpreting various drought indices or indicators. Among them, there are the following: Standard Precipitation Index (SPI), the Anomaly in the Normal Percentage of Rainfall, the Satellite Vegetation Health

Index (VHI), the Soil Humidity Leaky Bucket Model (*Centro de Predicciones Climáticas. Oficina Nacional de Administración Oceánica y Atmosférica*, CPC-NOAA), the Normalized Difference Vegetation Index (NDVI), the Average Temperature Anomaly, the Water Availability Percentage in the country's dam, and the contribution of local experts. These elements are used to classify drought according to its intensity, that is, the degree in which humidity conditions differ from normal. This classification is based on the standards used by the United States Drought Monitor (USDM) and the North American Drought Monitor (NADM) (Table 1).

The second phase, consisted in analyzing the meteorological variables of the CONAGUA stations through the RClimDex software, for those municipalities that presented extreme drought in the year 2019 (Francisco Mena, Jalpan, Pantepec, Tlacuilcotepec, Xicotepec, Zihuateutla and Venustiano Carranza), and which had an active meteorological station. However, only Pantepec and Xicotepec had complete data while Jalpan and Francisco Mena had missing years in their records. In the third phase, the study reviewed socioeconomic characteristics such as total population, educational backwardness, poverty and degree of marginalization of the municipalities mentioned before, using the databases from the National Statistics and Geography Institute (*Instituto Nacional de Estadística y Geografía*, INEGI), the National Population Commission (*Comisión Nacional de Población*,

Table 1. Classification of drought according to its conditions, intensity, and probabilities.

Category	Intensity	Condition of drought	Probability in percentile
D0	Abnormally dry	It is not considered a category of drought but rather a condition of dryness present at the beginning and at the end of a period of drought. At the beginning it can cause a delay in sowing of annual crops, limiting the growth of crops or grasses, and a risk of fires. At the end, the water deficit can persist and grasses and crops may not recover completely.	20 to ≤ 30
D1	Moderate drought	Some damages in grasses and crops are present, risk of fires, low levels in streams, reservoirs, rivers, watering holes, and wells; voluntary restriction is suggested.	10 to ≤ 20
D2	Severe drought	Probable losses in crops or grasses, high risk of fires, water scarcity; restrictions on water use must be imposed.	5 to ≤ 10
D3	Extreme drought	Major losses in crops and grasses, extreme risk of forest fires; restrictions on water use are generalized due to scarcity.	2 to ≤ 5
D4	Exceptional drought	Exceptional and generalized losses of grasses and crops, exceptional risk of fires, water scarcity in streams, reservoirs and wells. Probable emergency situation due to absence of water.	≤ 2

Note: each category is associated with the probability of occurrence of the percentile for a return period of 100 years.
Source: prepared by the authors based on Lobato (2016) and MSM (2023).

CONAPO), and the National Commission for Social Development Policy Evaluation (*Comisión Nacional de Evaluación de la Política de Desarrollo Social*, CONEVAL). The results were represented spatially with the purpose of identifying the municipalities where these characteristics have an impact on the sensitivity and adaptability and on their vulnerability. This approach agrees with the concept of vulnerability defined by the IPCC (2012a). This concept refers to the propensity or predisposition to be negatively affected and involves diverse aspects. Among these aspects, there is sensitivity or susceptibility to damage, as well as the lack of capacity to respond and adapt.

RESULTS AND DISCUSSION

Impact of drought at the municipal level according to the Mexican Drought Monitor

According to the data provided by the Mexican Drought Monitor, during the period of January 2003 to December 2022, different degrees of drought have been reported in the state of Puebla. They range from abnormally dry drought (D0) to extreme drought (D3), and no exceptional drought events have been reported in this period (Table 2).

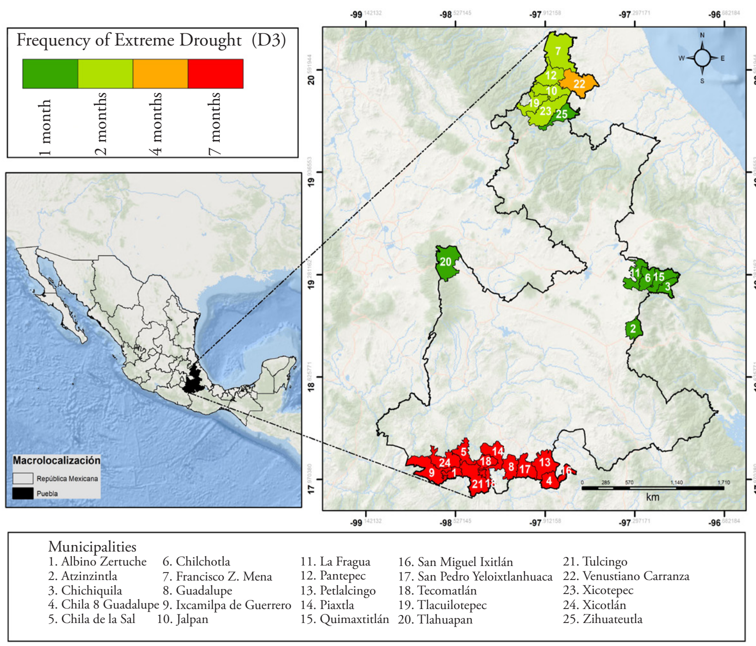
The study found that the 217 municipalities that make up the state (100% of the territory of Puebla) have presented the abnormally dry degree, as well as moderate drought in different moments of the period from 2003 to 2022. It is important to highlight that although the condition called abnormally dry is not a category of drought, it is relevant because it happens at the beginning and the end of drought. On the other hand, severe drought has happened in nearly all the municipalities of the state, except Coxcatlán and Coyomeapan. This means that 215 municipalities have experienced this type of drought. In the case of extreme drought, it took place in the municipalities of Albino Zertuche, Atzitzintla, Chichiquila, Chila, Chila de la Sal, Chilchotla, Francisco Z. Mena, Guadalupe, Ixcamilpa de Guerrero, Jalpan, Lafragua, Pantepec, Petlalcingo, Piaxtla, Quimixtlán, San Miguel Ixitlán, San Pedro Yeloixtlahuaca, Tecomatlán, Tlacuilotepec, Tlahuapan, Tulcingo, Venustiano Carranza, Xicotepec, Xicotlán and Zihuateutla. These represented 12% of the municipalities in the state of Puebla (Figure 2).

According to Figure 2, the municipalities that reported extreme drought are located in the regions of Sierra Norte, Valle Serdán, Angelópolis and the Mixteca region. In

Table 2. Drought classification in municipalities of Puebla.

Degrees of drought	Category	Percentage of municipalities (%)
Abnormally dry	D0	100
Moderate	D1	100
Severe	D2	99
Extreme	D3	12

*Percentage of municipalities in the territory that have presented the degree of drought mentioned during some month or months of the 2003-2020 period.
Source: prepared by the authors with data from the Mexican Drought Monitor [MDM] (2023).



Source: prepared by the authors with data from the Mexican Drought Monitor [MDM] (2023).

Figure 2. Location of the municipalities with report of extreme drought and its frequency in months.

the latter, the drought lasted longer, up to 7 months, which affected 12 municipalities during 2003. In Valle Serdán, this degree of drought was seen in 2011 with a shorter duration in 5 municipalities, in addition to the municipality of Tlahuapan of the Angelópolis region. By the year 2019, extreme drought was present in the Sierra Norte in the municipalities of Francisco Z. Mena, Jalpan, Pantepec, Tlacuilotepec, Venustiano Carranza, Xicotepec and Zihuateutla. The importance of identifying (extreme) drought in these municipalities lies in that it was characterized by having greater losses in crops and grasses and extreme risk of forest fires, so the use of water must be restricted because of its scarcity.

Although the degree of drought entails certain severity, the increase in frequency and intensity generates impacts from exposure to these episodes. This frequency is represented in the following graphs (Figure 3).

The scenarios of drought events have varied by region. Moderate droughts have happened in most of the territory during different years from 2003 to 2022 (except in the municipalities of Coxcatlán and Coyomeapan). In the region of Angelópolis and in the Valley of Atlixco and Matamoros, the frequency of occurrence of moderate drought was lower than in other regions. Meanwhile, severe drought and extreme drought was not frequent, and it was not reported for the region of Angelópolis. In contrast, the North, Northeast, Tehuacán and Sierra Negra regions reported a higher frequency of abnormally

Source: prepared by the authors with data from the Mexican Drought Monitor [MDM], (2023).
Figure 3. Frequency of drought events in Puebla by region and municipality from 2003 to 2022.

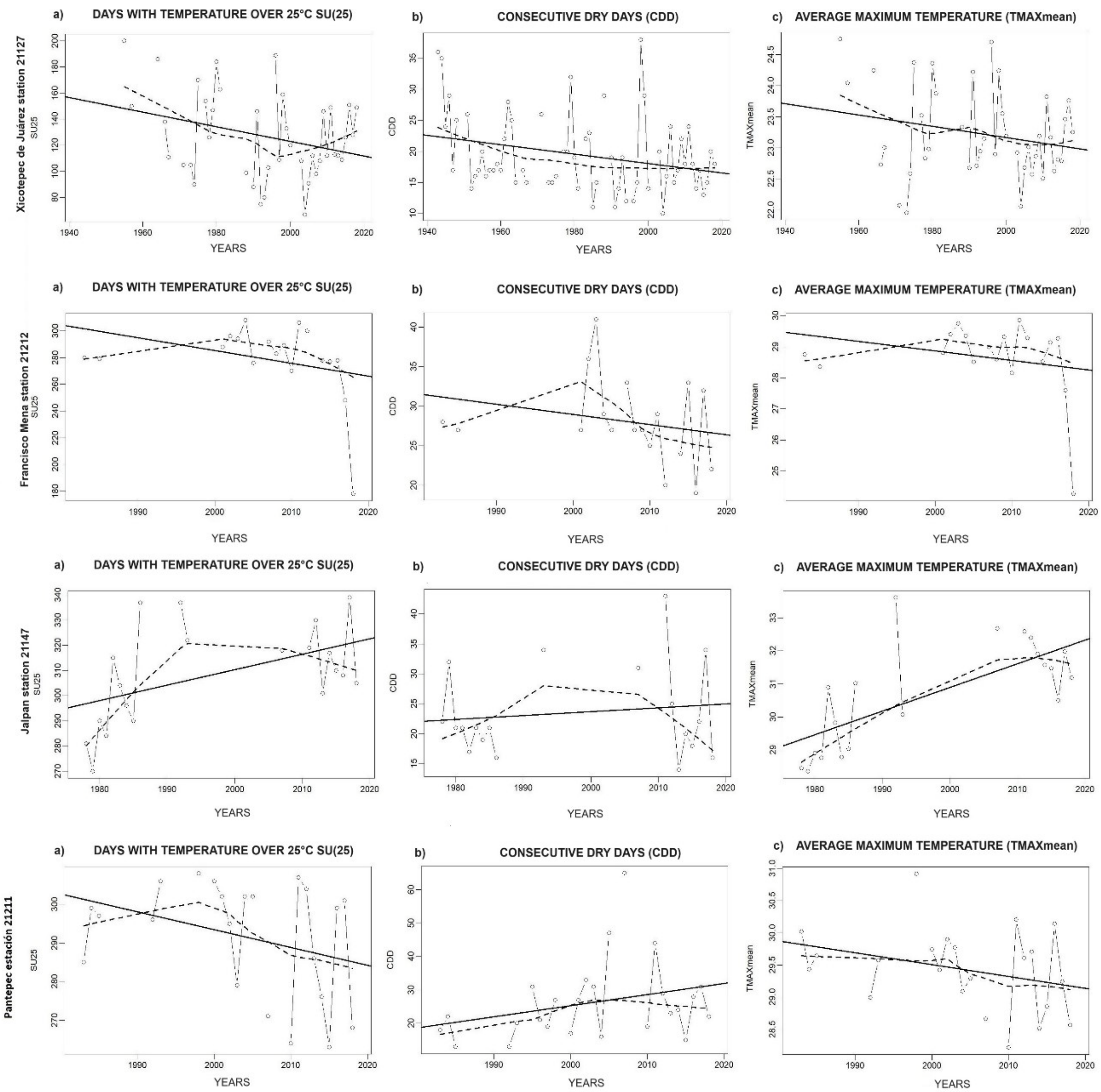
dry periods. In the first, two there were moderate droughts and in the case of the Sierra Norte extreme droughts were reported.

For its part, the Mixteca region in Puebla shows the greatest effect from the frequency of drought events. When contrasting the results of this analysis from the drought monitor to others, it was found that there are few at the state level and for Puebla they were not found; these are fundamental data for the application of more complete initiatives to reduce the risks and impacts associated to droughts (Lobato, 2016). In this sense, it is essential to approach the development of drought indices and predictive models based on reliable meteorological data. The creation of specific indices for the state of Puebla would allow a more accurate and contextualized evaluation of the drought conditions, providing valuable information for informed decision making. Prediction models based on reliable meteorological data can provide early forecasts of potential droughts, which are essential for planning and preparation (Nandgude, 2023).

Drought indices estimated with RClimDex

The results show a historical series of climate indices that start in 1947, 1977 and 1982 until 2020; however, in some seasons there are only records with 60% of the data. The RClimDex software provides 27 climate indices, of which 3 were selected for this study (Velasco *et al.*, 2015). They are SU25, which represents the days when the temperature is higher than 25 °C; the CDD index indicates the consecutive dry days; and the TMAXman index refers to the average of maximum temperature. Figure 4 shows linear and non-linear slopes with positive and negative trends that describe the behavior of three climate indices and which contribute to complementing the information from the Mexican Drought Monitor (MDM), in order to identify climate behavior patterns that influence exposure and vulnerability. For the municipality of Xicontepec, in (a), a high variability is shown where the non-linear trend describes the behavior related with temperature increases, while in the other indices there is a decreasing trend. In the municipality of Francisco Z. Mena, the three climate indices show a decreasing trend. It is interesting that in the consecutive dry days there are relevant years such as 2004 and 2011. On the other hand, in the municipality of Jalpan, there are increasing trends in the three climate indices. Regarding the municipality of Pantepec, an increase is seen in consecutive days and a decrease is observed in the SU25 and TMAXmean indices.

The analysis of these trends does not show significant differences. Therefore, it is likely the El Niño-Southern Oscillation (ENSO) event is present, which considerably affects wind patterns, the ocean's superficial temperature, and rainfall on the Tropical Pacific. Its effects influence the climate of the entire region of the Pacific and of many other parts of the world, through teleconnections that extend throughout the planet (IPCC, 2018). An early alert system for drought, which contemplates the methodological analysis of the possible impacts under realistic scenarios, can greatly help official institutions, the private sector and other users. This would allow taking preventive measures before the drought happens and reducing the risks associated (Cortez *et al.*, 2020). These climate events can



Source: prepared by the authors with data from CONAGUA (2023).
Figure 4. Results from the treatment of databases from meteorological stations with RClimDex.

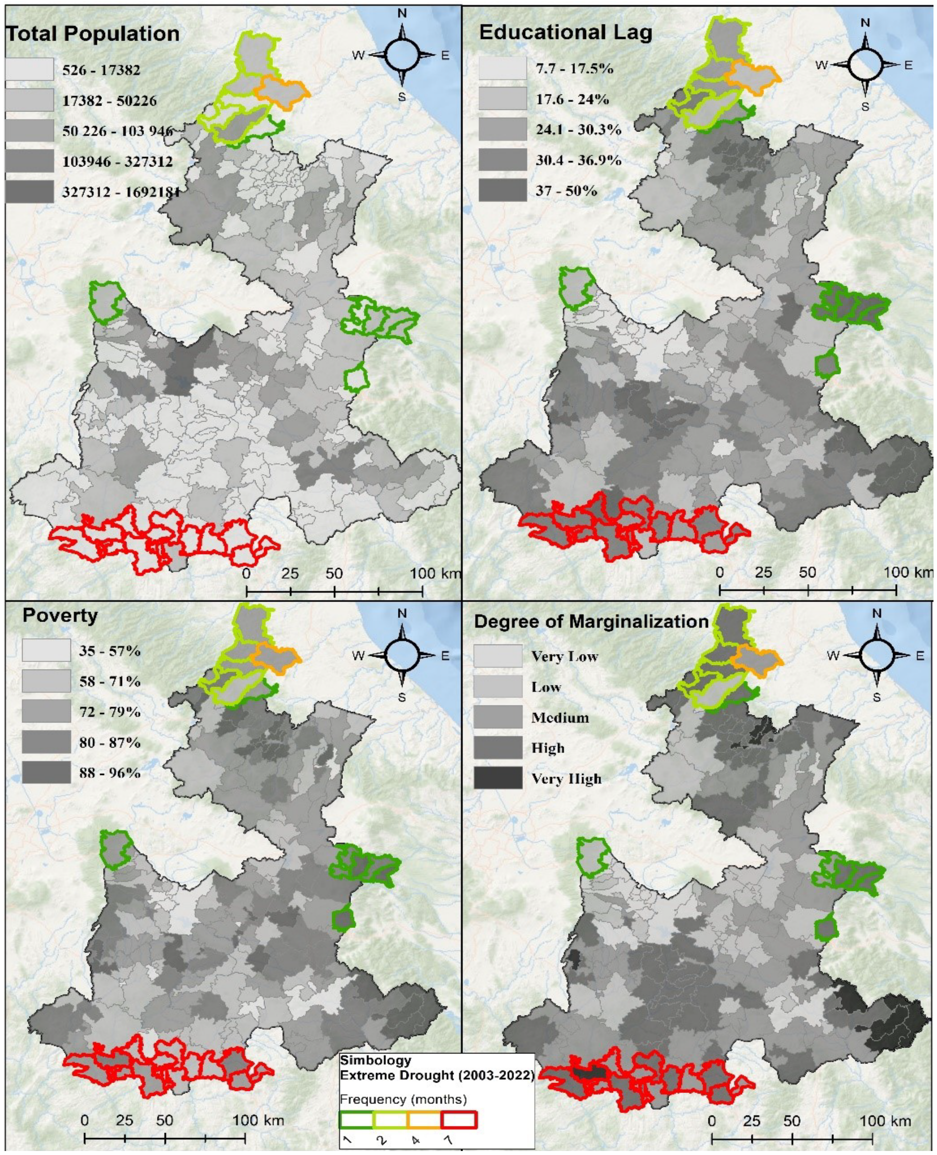
have severe implications in the use of irrigation water, cause physiological stress in crops, increase the impact of respiratory and cardiac diseases, and favor insect reproduction cycles and populations (Ruíz *et al.*, 2020). There are studies that show an integration of remote sensing data, meteorological observations, hydrological models, and climate indices to improve the accuracy in predicting droughts (Nandgude *et al.*, 2023). Therefore, it is likely that there are teleconnections, because there are trends of decreasing values in the climate indices of the SU25, CDD and TMAXmean variables that do not correspond to the variability of the databases of the meteorological stations. Thus, Lazcarro *et al*. (2020) warn that although the application of the RClimDex software allows understanding in detail the climate indicators to better comprehend the consequences of climate variability, with the exception of a predominance of extreme climate conditions, as has been the case of this study. It should be mentioned that the municipality of Tlacuilotepec does not have a meteorological station and the municipality of Zihuateutla did not have enough data to apply the RClimDex software. This underlines the importance of increasing the number of meteorological stations, especially in regions where droughts are recurrent and climate information is scarce (Lobato, 2016). To approach droughts effectively, the local, state and federal authorities must coordinate to deal with droughts as continuous phenomena that result from meteorological changes, water management, and economic and social variability. In addition, policies such as the local or state risk atlas, and technologies such as irrigation systems could help to prevent and respond to the negative effects of droughts (Robles, 2022).

Socioeconomic indicators

The total population of the state is 6,583,278, occupying the fifth place by number of inhabitants at the national level, with the municipality of Puebla as the one that concentrates the largest population (1,692,181), followed by Tehuacán (327,312), San Martín Texmelucan (155,738), San Andrés Cholula (154,448), Atlixco (141,793), San Pedro Cholula (138,433), Cuautlancingo (137,435) and Amozoc (125,876) (INEGI, 2020; CONAPO, 2020), which implies a high demand of the water resource.

The Marginalization Index covers characteristics of the distribution of population, housing, education and income from work. On the other hand, educational backwardness is the condition of a person older than 15 years who has not finished their basic education, while poverty analyzes two large approaches: welfare and social rights. These factors were considered because they refer to the degree of sensitivity and vulnerability of the population to extreme events and to climate change.

However, Figure 5 evidences that these factors work against municipalities from the North, Northeast, Mixteca and Sierra Negra regions by decreasing the adaptive capacity and increasing their vulnerability. It is seen that there are municipalities where the socioeconomic characteristics of marginalization, educational backwardness, and poverty are relevant factors in the sensitivity of the municipality to drought events. For the case of the municipalities that have experienced extreme drought, it was identified that the municipality of Coyomeapan presents a high percentage in backwardness and poverty (44.9 and 48.7, respectively). Among the municipalities that have a high degree of marginalization, as well as a high percentage in backwardness, there are Piaxtla, Tulcingo. Other municipalities present a high degree of marginalization such as Ixtacamaxtitlán, Jonotla, Zihuateutla and Cuetzalan del Progreso; while some that present high educational backwardness are Axutla, Albino Zertuche, Quecholac, Xicotlán, General Felipe Ángeles



Source: prepared by the authors with data from CONAPO and CONEVAL, 2023.
Figure 5. Frequency of extreme drought and socioeconomic variables.

and Los Reyes de Juárez. All of this generates a restriction in the access to resources and opportunities, which increases the vulnerability from drought. In this regard, González de la Rocha and Saraví (2018) and Toscana and Günther (2021) mention that the vulnerability is in function not only of the deficit in rainfall, but also of the demand for water from the systems and the characteristics of the population and the communities such as marginalization, poverty, social backwardness, and the human development index. In a study performed in Estado de México, it was found that the municipalities with presence of soils with degradation and a tendency to desertification, together with high marginalization indices and with the modality of seasonal sowing, are the ones that have a higher degree of vulnerability (Espinosa *et al.*, 2022). Within the framework of this expected social transformation is where efforts by institutions, peasant organization and academics are found, which contribute to strengthening the local capacities to face such challenges as those that an increasing drought trend presents (Bocco *et al.*, 2021).

CONCLUSIONS

When it comes to the exposure to drought events, the analysis of databases from the Mexican Drought Monitor revealed that in the state of Puebla there have been moderate, severe and extreme droughts; moderate droughts were present in the entire state, while severe in 99%, and extreme in only 12% of the municipalities. The latter, of low frequency, were reported in the years 2003, 2011 and 2019. Because droughts vary in intensity, duration and extension, and with this their effects are diverse, it was important to recognize that most of the territory in Puebla has presented high frequency of severe and moderate droughts, which implicates more planning for the use of resources in the long term. Regarding the socioeconomic indicators of population density, marginalization index, educational backwardness and poverty, the municipalities located in the North, Northeast, Mixteca and Sierra Negra regions increase their sensitivity because they have high degrees, and with that they acquire greater vulnerability; among them, the ones that stand out are Coyomeapan, Piaxtla, Tulcingo, Ixtacamaxtitlán, Jonotla, Zihuateutla, Cuetzalan del Progreso, Axutla, Albino Zertuche, Quecholac, Xicotlán, General Felipe Ángeles and Los Reyes de Juárez. Good risk management is necessary to strengthen coping with problems, developing and building resilience; therefore, the strategies to face these events will be different in terms of resource management and strengthening of their adaptive capacity to confront backwardness in socioeconomic and institutional capacity. For this purpose, studies at the local level such as this study are necessary, which support improving decision making of key stakeholders.

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