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Articles

Hydrological drought risk assessment in urban areas of Mexico: Guadalajara and Monterrey

Evaluación del riesgo por sequía hidrológica en áreas urbanas de México: Guadalajara y Monterrey

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Abstract

Despite its importance, there is relatively little research focused on drought risk in cities. Therefore, the present work aims to propose a methodology for the evaluation of hydrological drought risk in urban areas of Mexico and their respective drinking water, sewerage and sanitation operating organizations (OOAPAS, by its Spanish acronym). This methodology was applied in two of the most important urban areas of the country: The Monterrey hydropolitan area (AHM), and the Guadalajara metropolitan area (AMG). The study period was 2008-2018. For the risk assessment, the contextual approach was adopted, which defines this concept based on the hazard, exposure and vulnerability of the analyzed system. To calculate the hazard, the Streamflow Drought Index (SDI-12) was used, and socioeconomic, environmental, and institutional management indicators were used to assess vulnerability and exposure. The results indicate that the study areas are very sensitive to hydrological droughts, that is, to the deficit of surface runoff that enters their sources of water supply. The vulnerability index trend in these areas is downward. Regarding the drought exposure and risk index, the trend is to increase in both areas. The results obtained showed that the proposed methodology is feasible and useful in assessing of drought risk in the study areas, and can be applied in other urban areas of the country.

Keyword: Hydrological drought, drinking water, cities, vulnerability, exposure, adaptive capacity, Guadalajara, Monterrey.

Resumen

A pesar de su importancia, existe relativamente poca investigación centrada en el riesgo por sequía en las ciudades. Por ello, el presente trabajo tiene como objetivo proponer una metodología para la evaluación del riesgo por sequía hidrológica en áreas urbanas de México y sus respectivos organismos operadores de agua potable, alcantarillado y saneamiento (OOAPAS). Esta metodología se aplicó en dos de las zonas urbanas más importantes del país: el área hidropolitana de Monterrey (AHM), y el área metropolitana de Guadalajara (AMG). El periodo de estudio fue de 2008-2018. Para la evaluación del riesgo se adoptó el enfoque contextual, que define este concepto en función de la amenaza, exposición y vulnerabilidad del sistema analizado. Para el cálculo de la amenaza se utilizó el índice de sequía de los caudales fluviales (SDI-12), y para la evaluación de la vulnerabilidad y la exposición se emplearon indicadores socioeconómicos, ambientales y de gestión institucional. Los resultados indican que las áreas de estudio son muy sensibles a las sequías hidrológicas, es decir, al déficit de escurrimientos superficiales que ingresan a sus fuentes de abastecimiento de agua. La tendencia del índice de vulnerabilidad en estas áreas va a la baja. Con respecto al índice de exposición y riesgo por sequía, la tendencia es ir en aumento en ambas áreas. Los resultados obtenidos demostraron que la metodología propuesta es factible y útil en la evaluación del riesgo por sequía en las áreas de estudio, y puede ser aplicada en otras zonas urbanas del país.

Palabra clave: sequía hidrológica, agua potable, ciudades, vulnerabilidad, exposición, capacidad de adaptación, Guadalajara, Monterrey.

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Introduction

In recent decades, Mexico has faced severe episodes of drought, with negative impacts on various socio-economic sectors (Conagua, 2014; Esparza, 2014; Torres-Lima, 2015; Breña-Naranjo, 2021). Due to the significant population growth in urban areas, these areas are becoming increasingly sensitive to hydrological droughts, which occur when the precipitation deficit in contributing basins persists over time and combines with anthropogenic pressures for surface and groundwater demand, leading to a considerable reduction in the supply of water sources (rivers, lakes, springs, reservoirs, and aquifers). Consequently, some cities constantly require new water sources and the development of hydraulic infrastructure, especially those experiencing chronic water scarcity (where demand exceeds supply), such as Mexico City, Guadalajara, and Monterrey (García, Benítez, & Gaudiano, 2012; Torres & Barajas, 2013; Aguilar-Barajas, Sisto, & Ramírez, 2015; FAMM, 2018). Thus, cities face recurrent reductions in available water caused by frequent droughts, the effects of which are exacerbated by inadequate water resource management and extensive urban growth (Pineda-Pablos & Salazar-Adams, 2016).

The attention to drought phenomena in recent decades has been based on a reactive approach rather than risk management (Ortega-Gaucin & Velasco, 2013). Drought risk assessments constitute the first step in identifying the causes that generate impacts, thus facilitating a paradigm shift towards the implementation of prevention and mitigation measures (Knutson, Hayes, & Philips, 1998). In this regard, various studies have proposed methods to measure drought risk. In summary, Blauhut's work (Blauhut, 2020) reviews 82 international articles related to drought risk, along with an additional 26 articles consulted on the same topic, all compiled in the study by Castellano-Bahena and Ortega-Gaucin (2022). The total number of reviewed articles was 108 from the period 2001-2021, where it is observed that 67 % are related to agriculture, 25 % to multiple hazards, only 2 % to hydrological drought, and the remaining 6 % to topics associated with forestry, electricity, water deficit stress, and health (Castellano-Bahena & Ortega-Gaucin, 2022). However, despite the growing number of these studies, it was noted that there is very little research on urban drought risk methodologies. Of the reviewed works, only five of them indirectly involve the urban area. These works were carried out by Welle and Birkmann (2015); Neri and Magaña (2016); Sena, Ebi, Freitas, Corvalan and Barcellos (2017); Ortega-Gaucin, De-la-Cruz-Bartolón and Castellano-Bahena (2018), and Ahmadalipour, Moradkhani, Castelletti and Magliocca (2019).

Therefore, considering the areas of opportunity and knowledge gaps identified on the subject, this work developed a methodology to assess hydrological drought risk in urban areas of Mexico. The study areas where this methodology was applied include the Metropolitan Hydrological Area of Monterrey (AHM) and the Metropolitan Area of Guadalajara (AMG), including their respective Drinking Water, Sewerage, and Sanitation Operating Organizations (OOAPAS), namely, the Water and Drainage Services of Monterrey (SADM) and the Intermunicipal System of Drinking Water and Sewerage Services of Guadalajara (SIAPA). Drought risk in these study areas was assessed by determining risk indices calculated from the combination of hazard, exposure, and vulnerability indices to drought, as described in the following section.

Materials and methods

Research area

AHM

The Metropolitan Area of Monterrey comprises thirteen municipalities, and the "hydropolitan" region is a set of geopolitical and power relations historically shaped by an ideal of development and modernization that places cities as priority spaces in meeting basic needs, namely, drinking water, sanitation, and electricity services (Perló & González, 2005). On the other hand, this set of political power relations has concrete manifestations in the production of urban space (Raffestin, 1993). SADM delimited the hydropolitan area to nine municipalities: Monterrey, Apodaca, García, San Pedro Garza García, General Escobedo, Guadalupe, Juárez, San Nicolás de los Garza, and Santa Catarina (Conagua, 2015c) (Figure 1a). SADM provides drinking water, sanitary drainage, and sanitation services to the AHM (Conagua, 2015a). The water supply to the AHM comes from approximately 68 % surface sources, consisting of three reservoirs: La Boca, Cerro Prieto, and El Cuchillo, while the remaining 32 % comes from groundwater (Semarnat, 2011; Ortega-Gaucin, 2012; Torres & Barajas, 2013; FAMM, 2018) (Figure 1b and 1c).

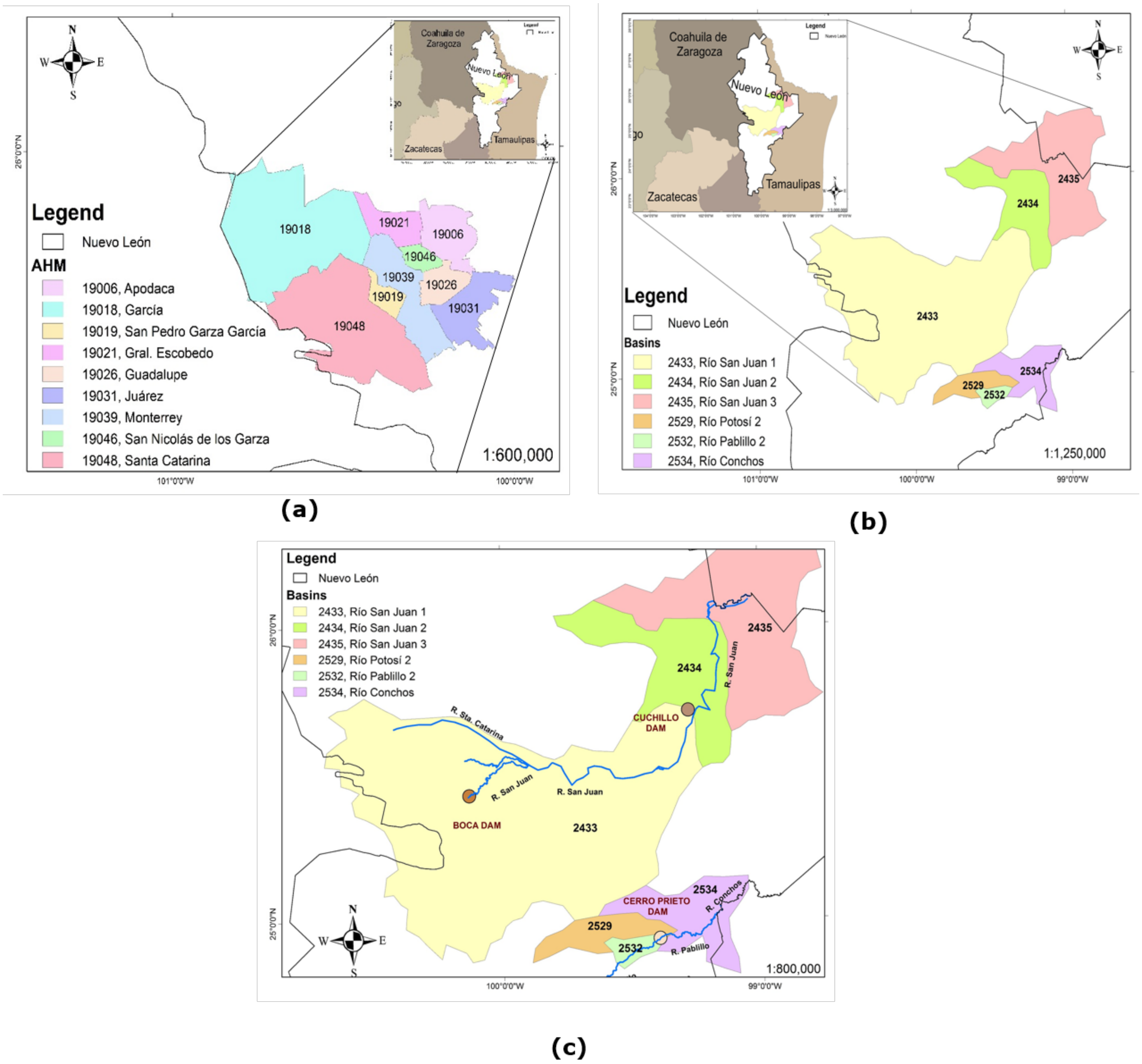
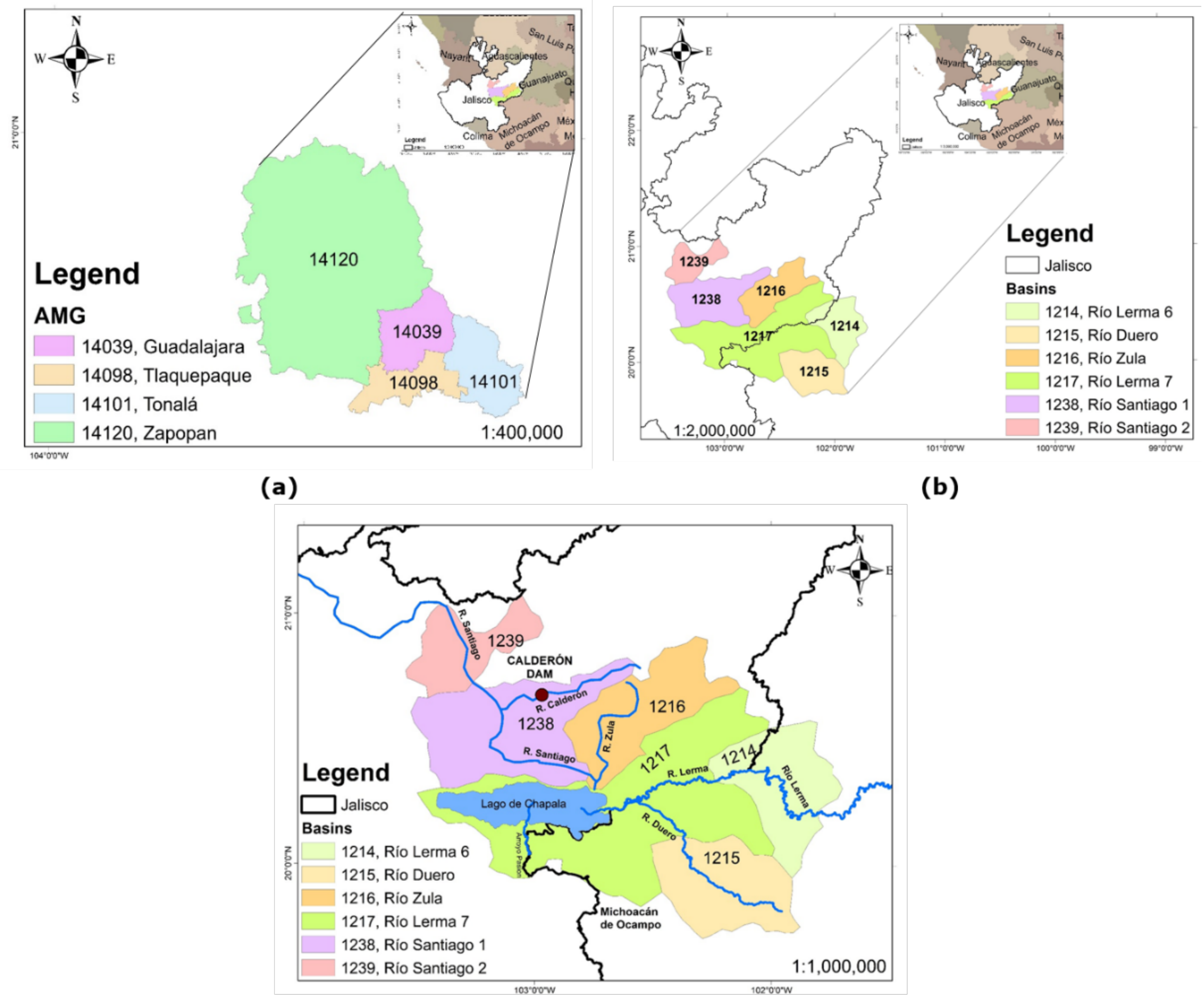


Figure 1. AHM study area: (a) municipalities comprising the AHM; (b) basins where surface water sources are located; (c) surface water supply.

The AHM is located in a semi-arid zone, according to the Köppen climate classification, and therefore faces low natural availability of water resources. The historical rainfall patterns in the AHM and surrounding areas exhibit a high degree of inter-annual variability, with rainfall occasionally falling below the average (622 mm), while at times, relatively abundant rainfall has been recorded, exceeding 1,000 mm (Aguilar-Barajas *et al*., 2015). An analysis of the historical rainfall patterns in the study region revealed that, in the period from 1980 to 2018, there were 11 years with below-average rainfall (28.1 %). The driest year during this period was 2011, with a precipitation deficit of 25.28 % compared to the average, while the wettest year was 2010 with 1 331 mm of rainfall.

AMG

According to the Decree 25400 (Gobierno del Estado de Jalisco, 2015) of the state government of Jalisco, the AMG is composed of 9 municipalities. However, for the provision of potable water, sewerage, and sanitation services by SIAPA, there is an agreement to provide these services only to the municipalities of Guadalajara, Zapopan, San Pedro Tlaquepaque, and Tonalá (Decree 24805/LX/13) (Gobierno del Estado de Jalisco, 2013). Therefore, only these municipalities were considered (Figure 2a) as the study area for this project. The water supply for public-urban use in the AMG comes from Lake Chapala, the Calderón dam, and a set of deep well systems (Conagua, 2009a) (Figure 2b and 2c).



(a)

(b)

(c)

Figure 2. AMG study area: (a) municipalities included in the agreement with SIAPA; (b) basins where surface water sources are located; (c) surface water supply.

68 % of the territory of the state of Jalisco has a subhumid warm climate, along the coast and central areas; 18 % has a subhumid temperate climate, in the high parts of the mountains, and 14 % is dry and semiarid, in the north and northeast of the state (INEGI, 2013). The average annual precipitation in AMG is 865 mm, which is 12 % higher than the national average of 772 mm (Conagua, 2009a). An analysis of historical rainfall patterns in the study region revealed that from 1980 to 2018, there were 20 years with below-average rainfall (51.3 %); the driest year during this period was 2011, with a precipitation deficit of 45.6 % compared to the average, and the rainiest year was 1992 with 1 122 mm.

Drought Hydrological risk assessment

Risk, in general, is defined as the anticipated consequence of an adverse event. More specifically, in the scientific field of natural hazards, risk can be defined as a real or existing hazard to a system (life, health, property, infrastructure, economy, and environment) given its current exposure and vulnerability (Tsakiris, 2007). Risk assessment can be conducted using the following general formulation (UNDRO, 1979; IPCC, 2014):

$$Risk = f(Hazard * Exposure * Vulnerability) \quad (1)$$

In the specific case of drought, the hazard is commonly assessed using historical climatic or hydrological information, which is utilized to determine its probability of occurrence (Ortega-Gaucin, Ceballos-Tavares, Ordoñez, & Castellano-Bahena, 2021). In this scenario, since the main water supply sources in the analyzed cities are rivers, lakes, and storage reservoirs, the hazard is determined through hydrological drought indices, specifically the Streamflow Drought Index (SDI). The assessment of exposure and vulnerability is carried out using socioeconomic and environmental indicators that help comprehend the different dimensions of these variables. This understanding proves highly valuable for decision-making aimed at risk management (Castellano-Bahena & Ortega-Gaucin, 2022).

However, Khoshnazar, Corzo and Diaz (2021) point out that the traditional calculation of the risk index by multiplying the indices of hazard, exposure, and vulnerability (as described in equation 1) has a drawback. When the values of each component are high, the resulting risk index value should also be high. However, in practice, when this operation is performed, the risk index value turns out to be low, which seems unreasonable. To overcome this limitation, various methodologies for integrating risk components have been proposed. These methodologies include principal component analysis, weighting methods, and aggregation methods (MacKenzie, 2014; Nardo *et al*., 2005). In this study, the geometric aggregation method was used because it facilitates the interpretation of results and the analysis of the final ranking of the analyzed units. It allows for a lower degree of trade-off between indicators

(Blancas-Peral, Contreras-Rubio, & Ramírez-Hurtado, 2011). The formula is as follows (Bas-Cerda, 2014):

$$IC_c = \prod_{q=1}^{Q} (I_{qc})^{W_q} \tag{2}$$

Where:

IC_c = geometric aggregation

w_q = weight of the indicator

I_{qc} = normalized value of analysis unit *c* concerning indicator *q*, for *q* = 1,..., *Q,* and *c* = 1,..., *M*

Khoshnazar *et al*. (2021) modified equation 2 to calculate the risk index as follows:

$$DRI = \left(\prod_{1}^{n} I_i\right)^{\frac{1}{n}} = \sqrt[n]{I_1 I_2 \dots I_n} \tag{3}$$

Where:

DRI = drought risk index

I_i = i-th component (index) contributing to the risk index

n = total number of components

According to the description above, equation 1 is modified to:

$$DRI = HI * EI * VI \tag{4}$$

Where:

DRI = drought risk index

HI = hazard index

EI = exposure index

VI = vulnerability index

In Figure 3, the proposed flowchart for evaluating drought risk components in the study areas (AHM and AMG) is presented. The hazard analysis is based on the severity analysis of hydrological drought and its probability of occurrence. This analysis considered the runoff records from the main rivers supplying the water sources (dams and lakes) for the analyzed cities over the last 38 years (1980-2018). Exposure and vulnerability were calculated using socioeconomic, environmental, and institutional management indicators from the period 2008-2018. The following points provide a detailed description of each stage of the methodology.

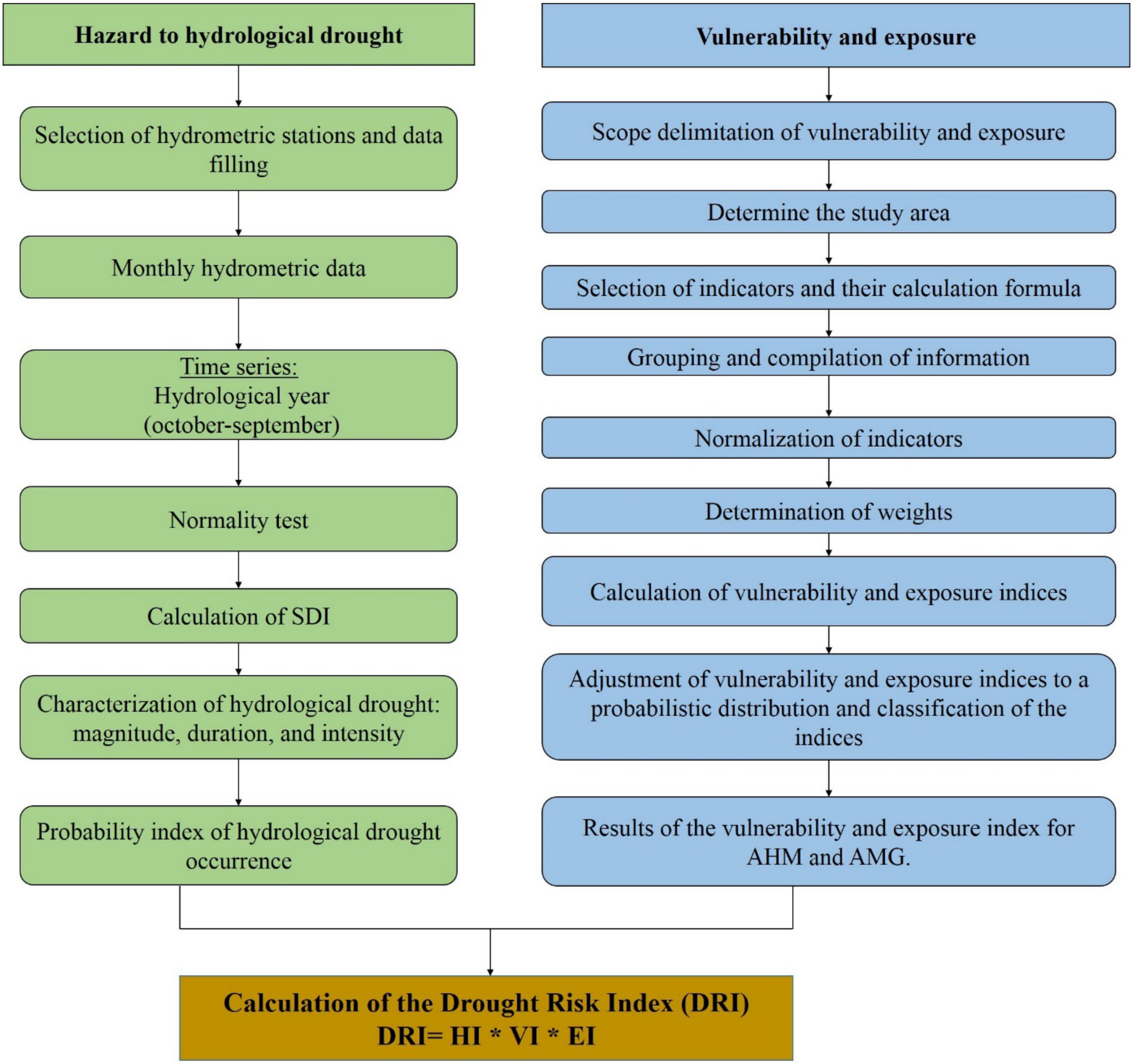


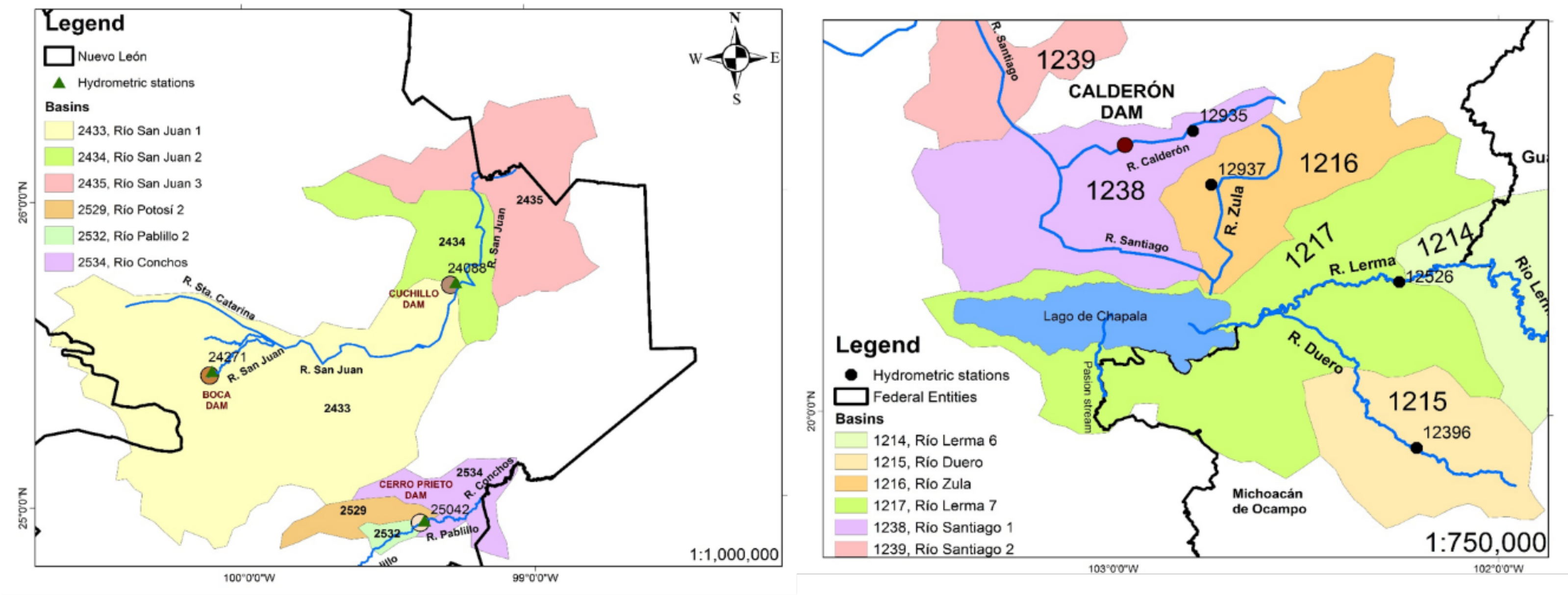
Figure 3. Flowchart of the methodology to assess drought risk in the urban areas under study.

Drought hazard index (DHI)

The procedure for determining the Drought Hazard Index involves the following activities:

a) Selection of hydrometric stations and filling in missing data

The selection of hydrometric stations was based on the availability of hydrological data provided by Conagua. Stations that had more than 80 % of daily data within the recording period were chosen. To fill in the missing data, the values were completed with the average of nearby conventional hydrometric stations using the Inverse Distance Weighting (IDW) method (Wise, 2000). IDW is available in Geographic Information Systems (GIS) software (Pérez & Mas, 2009). Data was sourced from the National Bank of Surface Water Data (Bandas), and the data recording period ranged from 1980 to 2018. For AHM, three stations were selected: 24271-La Boca, 24088-El Cuchillo, and 25042-Cerro Prieto (Figure 4a). In the case of AMG, four stations were selected: 12396-Camécuaro, 12526-Yurécuaro II, 12935-Calderón, and 12937-Zula (Figure 4b).



(a)

(b)

Figure 4. Selected hydrometric stations: (a) AHM and (b) AMG.

b) Obtaining monthly hydrometric data and time serie

The original daily flow data in m^3/s were aggregated into monthly volumes, and then grouped according to the 12-month hydrological year (October-September) over a period of 38 years (445 months), from 1980 to 2018. Subsequently, normality tests were applied to these time series.

c) Normality test

The probability density function (PDF) of streamflows is often skewed and, therefore, may require normalization using distributions such as Gamma or Log-normal (Batelis & Nalbantis, 2014). In this study, the data for the hydrological year were normalized using the mentioned PDFs, and then the Kolmogorov-Smirnov (KS) test was applied to select the one that best fits the data. The test results showed that the Gamma distribution fits well across 100 % of the evaluated time scale (October-September). Therefore, it was decided to use the Gamma distribution for the analysis.

d) Calculation of the River Flow Drought Index (SDI)

To characterize hydrological drought, Nalbantis and Tsakiris (2009) developed the SDI considering the value of the monthly flow ($Q_{i,j}$), where *i* represents the hydrological year and *j* represents the month within that hydrological year. Based on this series, the following is obtained:

$$V_{i,k} = \sum_{J=1}^{3k} Q_{i,j}\,; \;\; i = 1,2,3,\dots\,, \;\; j = 1,2,3,\dots,12, \;\; k = 1,2,3,4 \tag{5}$$

Where:

$V_{i,k}$ = accumulated flow volume for the *i-th* hydrological year and the *k-th* reference period

For the 3 month SDI, the value of *k= 1*; similarly, k=2, k=3 y k=4 For 6 months, 9 months, and 12 months, respectively. The SDI is defined based on the accumulated flow volumes $V_{i,k}$ for each reference period *k* of the *i-th* hydrological year, as follows:

$$SDI_{i,k} = \frac{V_{i,k} - \overline{V}_k}{s_k}; \;\; i = 1,2,\dots \;\; k = 1,2,3,4 \tag{6}$$

Where:

$\bar{V}_k$ = mean of the accumulated flow volumes during the reference period k, as estimated over an extended period of time

S_k = standard deviation of the accumulated flow volumes during the reference period k, as estimated over an extended period of time

In this definition, the truncation level is set at $\bar{V}_k$, although other values could be used (Nalbantis, 2008; Nalbantis & Tsakiris, 2009).

According to the index creators, different states or degrees of hydrological drought can be defined using the results obtained from the calculation of the SDI in each time period (Table 1).

Table 1. Definition of hydrological drought states based on the SDI.

States	Description	Criterian
0	No drought	SDI greater than 0.0
1	Mild drought	-1.0 ≤ SDI <0.0
2	Moderate drought	-1.5 ≤ SDI <-1.0
3	Severe drought	-2.0 ≤ SDI <-1.5
4	Extreme drought	SDI <-2.0

Source: Nalbantis & Tsakiris (2009).

The SDI was calculated using the DrinC® software. This software is designed to assess drought indices and is suitable for meteorological, hydrological, and agricultural drought analysis. The software is user-friendly. The primary reference period in DrinC is the hydrological year (October-September) (Tigkas, Vangelis, & Tsakiris, 2015). For this study and based on the results of the KS test, the Gamma distribution was used. Finally, its probability of occurrence was calculated by obtaining a relative frequency (Malik, Kumar, Salih, & Yaseen, 2021), as indicated below.

e) Calculation of the hydrological drought hazard index

This index was determined based on the probability of occurrence of moderate, severe, and extreme hydrological drought events in the AHM and AMG, as follows:

$$HI = \frac{MS}{TMS} \tag{7}$$

Where:

HI = hydrological drought hazard index

MS = number of months of the moderate, severe, and extreme drought event (in this case, mild, moderate, severe, and extreme droughts were considered)

TMS = total number of months (with and without drought)

Vulnerability and exposure Index (VI and EI)

The concepts of vulnerability and exposure applied in this study are those proposed by the Intergovernmental Panel on Climate Change (IPCC, 2014). In the case of vulnerability, it is defined as the propensity or predisposition to be negatively affected. Vulnerability encompasses a variety of concepts and elements, including sensitivity or susceptibility to damage and lack of capacity for response and adaptation. The formula used in this study is presented below:

$$Vulnerability = f(Sensitivity - Adaptive\ Capacity) \quad (8)$$

Sensitivity or susceptibility to damage refers to the degree to which a system is affected, either adversely or beneficially, by stimuli from climate change (IPCC, 2001; IPCC, 2014). Adaptive capacity is defined as the process of adjusting to actual or projected climate and its effects. According to the IPCC (2001), the main characteristics determining the adaptive capacity of a region or community include economic wealth, technology, information, knowledge, infrastructure, institutions, and equity.

In addition to the previous concepts, this study considers three basic types of vulnerability: socioeconomic, institutional management, and environmental, which together give rise to overall vulnerability (Figure 5).


Socioeconomic vulnerability:

Socioeconomic sensitivity captures the characteristics of a community that influence its likelihood of experiencing harm while undergoing a drought episode. Socioeconomic adaptive capacity is a function of two asset-based components of a community, such as wealth and human capital, that help predict how individuals can be flexible in anticipating, responding to, and recovering from the effects of drought (Carrao *et al*., 2016)

Institutional management vulnerability:

When the administrative and financial structure, the infrastructure of operating entities, and the technological processes involved in their functioning are too weak to protect the population from the impacts of a drought, it becomes impossible to promote the rational management of the service for users. This prevents meeting the requirements of quantity, continuity, quality, reliability, and cost (Adapted from Buenfil, 2000).

Environmental vulnerability:

It is related to the intrinsic susceptibility of the environment or natural resources to suffer damage due to a lack of water, as all living beings require certain environmental conditions for development. In the event of deterioration of nature through the destruction of environmental reserves, ecosystems become highly vulnerable to threats such as drought (Ortega-Gaucin *et al*., 2018).

Figure 5. Types of vulnerability analyzed in this research.

The formulas used to calculate the socioeconomic vulnerability index (SEVI), institutional management vulnerability index (IMVI), and environmental vulnerability index (EVI) are as follows:

$$SEVI = SESI - SEASI \tag{9}$$

$$IMVI = IMSI - IMACI \tag{10}$$

$$EVI = ESI - EACI \tag{11}$$

Where:

$SESI$ = Socioeconomic Sensitivity Index

$SEACI$ = Socioeconomic Adaptive Capacity Index

$IMSI$ = Institutional Management Sensitivity Index

$IMACI$ = Institutional Management Adaptive Capacity Index

ESI = Environmental Sensitivity Index

$EACI$ = Environmental Adaptive Capacity Index

From the aforementioned indices, the general vulnerability index (*GVI*) is determined through:

$$GVI = SEVI + IMVI + EVI \tag{12}$$

On the other hand, regarding exposure, IPCC (2014) defines it as the presence of people; livelihoods; species or ecosystems; functions, services, and environmental resources; infrastructure; or economic, social, or cultural assets in places and environments that could be negatively affected. Here, the following formula is proposed to calculate the general exposure index (*GEI*):

$$GEI = SEEI + IMEI + EEI \tag{13}$$

Where:

SEEI = Socioeconomic Exposure Index

IMEI = Institutional Management Exposure Index

EEI = Environmental Exposure Index

The procedure for constructing the vulnerability and exposure indices consists of nine steps, which are described below:

1. Delimitation of the scope of vulnerability and exposure analysis

To establish the vulnerability issues, Füssel (2004) suggests formulating the questions shown in Figure 6, which, in the case of this research, are answered there as well.

Dimension	Question	Project Vulnerability and Exposure
System	¿Who or what is vulnerable?	SADM y SIAPA
	¿Who or what is exposed?	The population of AHM and AMG.
Danger (or hazards or stress factors)	¿Vulnerable to what?	Hydrological droughts
	¿Exposed to what?	
The consequences (or effects or valued attributes or variables of interest)	¿What is at risk?	Lack of capacity of the OOAPAS to supply drinking water to the population
Temporal and spatial scale	¿What time horizon?	Historical: 2008-2018
	¿Which region?	AHM y AMG

Figure 6. Fundamental dimensions describing a situation of vulnerability and exposure. Source: Developed by the authors based on Füssel (2004).

2. Selection of indicators and formulas for their calculation

The calculation of the indices described earlier is based on socioeconomic, environmental, and institutional management indicators. For the selection of indicators in this project, 24 articles related to climate change and droughts at the national and international levels from the period 2003-2019 were consulted. The indicators from these articles were analyzed, and a set of 29 indicators was selected. The selection of these indicators was based on the following criteria: a) relevance of the variable to drought, b) availability of information, and c) historical data availability (2008-2018). Subsequently, the 29 indicators were reviewed by experts from SADM and SIAPA, and finally, 16 indicators were chosen for evaluating vulnerability and exposure to drought in the socioeconomic, environmental, and institutional management sectors. These selected indicators are presented in Table 2. Additionally, Table 3 shows the formulas for calculating them and the sources of information for each indicator.

Table 2. Indicators of vulnerability and exposure to drought, and their impact on water supply.

Indicator	Type of indicator	Definition	Impacto n Water Supply
Population density (resident/km^2)	Socioeconomic	The relationship between a specific space and the number of people inhabiting it (INEGI)	The population growth, urbanization, and migration have contributed to increasing population density asymmetrically across the national territory. These factors exacerbate the challenges of providing basic urban services (Mitchell, 2006; Kraas, 2008; Martínez *et al*., 2010; Semarnat, 2016)

Indicator	Type of indicator	Definition	Impacto n Water Supply
Unemployed economically active population (UEAP) (%)	Socioeconomic	People aged 15 and older, who provide the available workforce for the production of goods and/or services targeted at the market and who are actively seeking employment, having worked before, or are seeking employment for the first time (INEE, 2016)	People living in poverty, lacking the income and other necessary resources to meet life's basic needs, find it particularly challenging to cope with the impacts of drought (UNCCD, 2013)
Population in poverty conditions (%)	Socioeconomic	When a person has at least one social deprivation and their income is insufficient to acquire the goods and services necessary to satisfy their food and non-food needs (Coneval, 2018a)	
Annual per capita income (thousands of Mexican pesos / year)	Socioeconomic	The relationship between the total value of all final goods and services generated during a year by the economy of a nation or entity and its population size in that year (INEE, 2016)	The largest net pressure on national water resources in Mexico comes from entities with lower human development values compared to other entities (Semarnat, 2016)

Indicator	Type of indicator	Definition	Impacto n Water Supply
Volume of surface and groundwater produced (m^3).	Institutional management	Total volume of water produced in a year, including unmeasured extractions based on previous studies. This reported volume should be prior to the purification processes (Hansen & Alcocer, 2014)	Drought is assessed by the greater or lesser volume of water available in reservoirs to meet current demands (Morales, Olcina, & Rico, 2000). The impact of drought in the city is mediated by the reservoir storage capacity, the volume of aquifer recharge, and the total storage capacity of the aquifer (Pineda-Pablos & Salazar-Adams, 2016)
Housing units without piped water, drainage, or toilet facilities (%)	Institutional management	Number of occupants in private households without piped water, drainage, or toilet facilities, as a percentage of the total occupants in private households, minus the occupants in private households who did not specify the availability of piped water and sanitary drainage (Conapo, 2015a; Conapo, 2015b)	It is an indicator that is part of the social deprivation index and directly reflects the vulnerability to which the population is exposed due to the lack of basic services. Therefore, in the presence of a drought event, the susceptibility to health damage increases (Ortega-Gaucin *et al*., 2018)

Indicator	Type of indicator	Definition	Impacto n Water Supply
Physical efficiency (%)	Institutional management	Assess the efficiency between the volume of water billed and produced by the OOAPAS (Hansen & Alcocer, 2014)	Minimizing physical water losses in distribution and improving the efficiency of the distribution network (Pineda-Pablos & Salazar-Adams, 2016) is indicative not only of the administrative capacity of the OOPAS but also of losses in the distribution system, both due to the poor condition of the network and to theft and unaccounted water (Camacho, 2012)
Micro and macro measurement (%)	Institutional management	The ability to measure water consumed by users, as well as the actual knowledge of the water delivered (Hansen & Alcocer, 2014)	Having micro measurement allows for knowing the consumption of each user and enables the fair billing based on the authorized tariff. Additionally, it facilitates the easier identification of leaks in households through consumption spikes and provides knowledge of the total volume being delivered for consumption. As for macro measurement, the goal to aim for is 100 %, as this accurately determines the produced volume used to carry out the hydraulic balance (Conagua, 2011)

Indicator	Type of indicator	Definition	Impacto n Water Supply
Tariff-cost ratio	Institutional management	Describe the connection between water service rates and the costs associated with its supply. This includes expenses related to maintenance, operation, and administration. (Camacho, 2012)	Since the tariffs don’t necessarily reflect the cost for OOAPAS to deliver a determined volumen of water, they reflect the degree to which domestic tariffs are subsidized, and it could be that when faced with climate change events, there could be an increase in the operating costs and induce an incorrect use of this resource (Camacho 2012)
Commercial efficiency (%)	Institutional management	Evaluates the efficiency between billing and payment (Hansen & Alcocer, 2014)	It encompasses all types of actions that allow defining appropriate tariffs, billing them, and collecting them from service users to ensure the financial self-sufficiency of the operating organization (SEAPAL, 2019)
Consumption (l/resident/d)	Institutional management	Actual water consumption without taking into account losses due to leaks in the network and household connections (Hansen & Alcocer, 2014)	Considering the impact of future climate changes, an increase in water demand translates to higher operating costs, compounded by the issue of water scarcity and population growth (Camacho, 2012)
Continuous water service hours (%)	Institutional management	Number of hours users have access to continuous water service (Hansen & Alcocer, 2014)	

Indicator	Type of indicator	Definition	Impacto n Water Supply
Treated volume (%)	Institutional management	This indicator represents the percentage of wastewater treated from the collected sewage network, based on 70 % of the produced volume (Hansen & Alcocer, 2014)	Drought does not have a direct impact on treated wastewater, but it can be used as a first-hand resource in drought-prone areas. Additionally, the lack of treatment systems has affected the habitat of flora and fauna in the region (Díaz-Cuenca, Alvarado-Granados, & Camacho-Calzada, 2012)
Surface water quality (BOD_5, mg/l)	Environmental	Water quality is an attribute that measures the physical, chemical, and biological properties of the liquid (Peters, Campoy-Favela, & Flessa, 2009). Biochemical oxygen demand (BOD5) is an indicator of pollution from municipal and domestic sources (Conagua, 2010)	The deterioration of water supply sources directly impacts the level of present sanitary risk and the type of treatment required for its reduction. Evaluating water quality allows for control and mitigation actions, ensuring the supply of safe water (Torres, Cruz, & Patiño, 2009)
Groundwater quality (TDS, mg/l)	Environmental	Total Dissolved Solids (TDS) can be organic and/or inorganic, originating from various domestic, commercial, and industrial activities (Chibinda, Arada-Pérez, & Pérez-Pompa, 2017)	Water quality is affected by human activity, overexploitation of groundwater aquifers, and prolonged droughts. This has led to decreased groundwater levels to the extent that the mineralogy of the deposit in contact with water changes in its characteristics, and high levels of metals are detected in waters that originally had no appreciable values of these metals (Rocha, 2010)

Indicator	Type of indicator	Definition	Impacto n Water Supply
Degree of water resource pressure (%)	Environmental	It is a percentage indicator of the pressure to which the water resource is subjected, obtained by dividing the total volume of granted water concessions by the renewable water (Conagua, 2017)	It is considered that if the percentage is higher than 40 %, there is a high or very high degree of pressure (Conagua, 2017). In arid ecosystems, excessive pressure on water and its impacts on natural systems hazarden overall sustainability in such areas (Martínez, 2006)

Table 3. Formulas of the indicators for calculating drought vulnerability and exposure indices.

Indicator	Formula	Information source	Formula source
Population density (resident/km^2)	$PD = \frac{Popultation}{Area\ (km^2)}$	Conapo and area of municipalities within AM (2008-2018)	Conapo (2015b)
Unemployed economically active population (UEAP) (%)	$UEAP = \frac{EAP\ Unemployed}{EAP\ total} * 100$	ICU y SNIM (2008-2018)	INEGI (2020)
Population in poverty conditions (%)	Multivariable	Coneval (2010-2015)	Coneval (2018b)
Annual per capita income (thousands of mexican pesos/ year)	$IPCA = \frac{Anual\ GDP}{Population}$	ICU y Conapo (2008-2018)	INEE (2016)

Indicator	Formula	Information source	Formula source
Volume of potable water produced (m^3)	The production volume data is the result of macro measurement at the collection sources	Data provided by SIAPA y SADM (2008-2018)	Hansen and Alcocer (2014)
Housing units without piped water, drainage, or toilet facilities (%)	$HWPWDT = \frac{NoHWPW + NoHWDT}{Total\ No\ of\ housing} * 100$ NoHWPW: Number of housing units without piped water service. NoHWDT: Number of housing units without drainage and toilet facilities	Conapo (2010-2015)	Conapo (2015b)
Physical efficiency (%)	$E_{FIS} = \frac{V_{BW}}{V_{VPWP}} * 100$ V_{BW}: Vol. of billed water (m^3) A_{VPWP}: Annual vol. of potable water produced (m^3).	Data provided by por SIAPA y SADM (2008-2018)	Conagua (2011), and Hansen and Alcocer (2014)
Micro and macro measurement (%)	$MICROMACRO = \frac{\left(\left({}^{M_{IC}}/_{T_{REG}}\right) + \left({}^{M_{AC}}/_{C_{APT}}\right)\right) * 100}{2}$ M_{IC}: No. of functioning micrometers T_{REG}: Total number of registered water taps M_{AC}: No. of functioning macrometers at collection points C_{APT}: No. of collection points	Data provided by SIAPA y SADM (2008-2018)	Conagua (2011), and Hansen and Alcocer (2014)
Tariff-cost ratio (Dimensionless)	$R_{TC=\frac{T_{MD}}{C_{VP}}}$ T_{MD}: Average household tariff ($) C_{VP}: Cost per produced volume ($)	Data provided by por SIAPA y SADM (2008-2018)	Hansen and Alcocer (2014)
Commercial efficiency (%)	$E_{COM} = \frac{V_{AP}}{V_{AF}} * 100$ V_{AP}: Paid water volume (m^3) V_{AF}: Billed water volume (m^3)	Data provided by por SIAPA y SADM (2008-2018)	Conagua (2011), and Hansen and Alcocer (2014)

Indicator	**Formula**	**Information source**	**Formula source**
Consumption (l/resident/day)	$Consumption = \frac{V_{con} * 1000}{365 * Pop}$ V_{con}: Volume of water consumed (m^3/year) Pop: Population	Data provided by por SIAPA y SADM (2008-2018)	Hansen and Alcocer (2014)
Continuous water service hours (%)	The number of hours with 24/7 water service	Data provided by por SIAPA y SADM (2008-2018)	SIAPA (2010), SIAPA (2017), SIAPA (2018), SADM (2010), SADM (2013), SADM (2014), SADM (2015), SADM (2017)
Treated volume (%)	$V_{TRAT} = \frac{V_{ART}}{V_{APP} * 0.70} * 100$ V_{ART}: Annual volume of treated wastewater (m^3) V_{APP}: Annual volume of produced drinking water (m^3)	Data provided by por SIAPA y SADM (2008-2018)	Hansen and Alcocer (2014)
Surface water quality (BOD_5, mg/L)	$BOD_5 = IDO - DO_5$ BOD_5: Biochemical oxygen demand IDO (mg/l): Initial dissolved oxygen DO_5 (mg/l): Dissolved oxygen at the fifth day	SIAPA y SINA (2008-2018)	Norma Mexicana (NMX-AA-028-SCFI) (2001) and Conagua (2016)
Groundwater quality (TDS, mg/l)	$TDS = (TS) - (TSS)$ TDS: Total dissolved solids TS: Total solids TSS:Total suspended solids	SIAPA y Conagua (2008-2018)	Norma Mexicana (NMX-AA-034-SCFI-2015) (2015) and Conagua (2016)

Indicator	Formula	Information source	Formula source
Degree of water resource pressure (%)	$\frac{TVGW}{RWV} * 100$ *TVGW*: Total volume of granted water, surface, and groundwater (hm^3) *RWV:* Renewable water volume (hm^3)	Conagua (2008-2018)	Conagua (2017)

3. Grouping and compilation of information

For the grouping of indicators, IPCC (2014) proposes that they be grouped based on the category of their two components: sensitivity and adaptive capacity. Patnaik and Narayanan (2009) suggest a method where they are grouped according to types of vulnerability. In this project, these two proposals are combined, and the collected data are arranged in the form of a rectangular matrix, with rows representing the indicators based on the type of vulnerability and exposure, and columns representing the components of vulnerability (Table 4 and Table 5).

Table 4. Grouping of Indicators for Calculating the Drought Vulnerability Index.

Type of Vulnerability		**Components of Vulnerability**	
		Sensitivity (S)	**Adaptation Capacity (AC)**
General	**Socioeconomic**	-Unemployed economically active population (UEAP) (%)] -Population in poverty conditions (%)	-Annual per capita income (thousands of mexican pesos /year)
	Institutional management	-Tariff-cost ratio (units) -Consumption (l/resident/d) -Housing units without piped water, drainage, or toilet facilities (%)	-Physical efficiency (%) -Commercial efficiency (%) -Micro and macro measurement (%)
	Environmental	-Surface water quality (BOD_5) (mg/l) -Groundwater quality (TDS) (mg/l)	-Treated volume (%)

Table 5. Grouping of Indicators for Calculating the Drought Exposure Index.

Type of Exposure		**Indicators**
General	**Socioeconomic**	-Population density (resident/km^2)
	Institutional management	-Volume of water produced (m^3) -Continuous water service hours (24 hours) (%)
	Environmental	-Degree of water resource pressure (%)

After compiling the information from the selected indicators in an Excel® database, a multicollinearity analysis was conducted using the SPSS® software. This software is user-friendly and has a free trial period (Castro, 2010; Abreu, Velázquez, & Velázquez, 2021). SPSS employs various procedures to detect multicollinearity among independent variables, such as tolerance and the variance inflation factor (Baños, Torrado-Fonseca, & Álvarez, 2019). Multicollinearity analysis helps to avoid the over-representation of selected indicators. This occurs when variables involved in a model provide redundant information, and the information from one or more variables is also provided by others; that is, there are independent variables that are strongly correlated with each other (Gujarati, 2010). The most common technique used to detect the presence of multicollinearity is the analysis of the correlation matrix using the Pearson correlation coefficient (*r*) (Astorga, 2014). If two sets of data have values showing an r coefficient greater than 0.90 (in the case of positive correlation) or less than -0.90 (in the case of negative correlation), at least one of the involved variables should be eliminated, or both should be grouped to create a new indicator (Pértegas & Pita, 2001). The evaluation of r in this study was conducted by type of vulnerability and exposure (socioeconomic, institutional management, and environmental). Therefore, only the relationship of variables for each of these types was considered independently. Indicators with a correlation greater than 0.90 or less than -0.90 were discarded, and the condition for removing them was that the correlation existed in both the AMG and the AHM. Based on the analysis of the r coefficient in the study areas, it was decided to eliminate only one indicator, which was the total population, as it is the only variable with a perfect positive correlation in both case studies.

4. Normalization of Indicators

The objectives of normalization techniques are to adjust the data so that they do not have different units of measurement and ranges of variation, and to adjust the data in the case they follow an asymmetric distribution or in the presence of outliers (Bas-Cerda, 2014). There are various normalization methods. For the purposes of this work, the rescaling normalization method was chosen as it is robust and one of the most commonly used. This technique was defined by Drewnowski and Scott (1966) and is widely used in the construction of numerous synthetic social and economic indices (Actis-di-Pasquale & Balsa, 2017). For a positive correlation (↑), the formula is as follows:

$$X_{ij} = \frac{X_i - Min X_j}{Max\, X_j - Min\, X_j} \tag{14}$$

Where:

X_{ij} = normalized value of indicator (*j*) for year (i)

X_i = actual value of the indicator for year *(i)*

$MinX_J$ y $MaxX_J$ = minimum and maximum values, respectively, of indicator *(j)* across all years.

In the case of an inverse relationship between the indicator and the theoretical construct, for example, the illiteracy rate and well-being, the calculation will be as follows, incorporating a directional change (Actis-di-Pasquale & Balsa, 2017), meaning a negative correlation (↓):

$$X_{ij} = \frac{Max\ X_j - X_i}{Max\ X_j - Min\ X_j} \tag{15}$$

Where:

X_{ij} = normalized value of indicator (*j*) for year (i)

X_i = actual value of the indicator for year *(i)*

MinXJ y *MaxXJ* = minimum and maximum values, respectively, of indicator *(j)* across all years

A normalized data point (*x*) is considered an outlier when the score X_{ij} is greater than 1 or when dealing with negative values.

5. Determination of indicator weights

Weighting involves assigning each individual indicator a weight, often interpreted as a measure of the indicator's relative importance in constructing the composite index (Saltelli *et al*., 2008). In this study, one of the weighting methods based on statistical models was used, specifically the method proposed by Iyengar and Sudarshan (1982). With this method, each indicator is assigned a weighted score based on all indicators evaluated through the variance statistic using the following expression:

$$P_{i=\frac{1}{(\sigma_i)(\sum_{i=1}^{n}\frac{1}{\sigma_i})}} \tag{16}$$

Where:

P_i = weighted score of indicator *i*

σ_i = standard deviation of the set of values for indicator *i*

n = number of selected indicators

This weighting method ensures that significant variations in one or more indicators do not dominate the contribution of the remaining indicators.

6. Calculation of vulnerability and exposure indices

Regarding the aggregation rule, there are no objective criteria available to choose the most appropriate method (Kang, 2002). Weighted additive aggregation (WAA), also known as the weighted sum method (Blancas-Peral *et al*., 2011), refers to the most commonly used linear aggregation method in constructing a composite index (CI) (Bandura & Martin, 2006; Nardo *et al*., 2005). The formula is as follows:

$$IC_c = \sum_{q=1}^{Q} w_q \, I_{qc} \qquad (17)$$

Where:

w_q = weight of indicator q

I_{qc} = normalized value of analytical unit *c* with respect to indicator q, for *q* = 1,..., *Q an* c = 1,..., *M*

7. Adjustment of Vulnerability and Exposure Indices to a Probabilistic Distribution

Goodness-of-fit tests help verify what type of distribution the data follows (Romero-Saldaña, 2016). The probabilistic distribution will be useful to avoid arbitrary classification of synthetic index results where the boundaries between categories are not clearly defined (Ortega-Gaucin *et al*., 2018). In this study, the extended Shapiro-Wilk test (Shapiro & Wilk, 1965) was used, as it can be applied to any number of data points (*n*) in the range 3 ≤ n ≤ 5000. The methodology of this test can be found in the work of Razali and Wah (2011). Real Statistics® software was used to conduct the extended Shapiro-Wilk test. This software is free and expands the statistical capabilities integrated into Excel (Zaiontz, 2024). The results indicated that the vulnerability and exposure indices of AMG and AHM follow a standard normal distribution.

8. Classification of vulnerability and exposure indices

Once the distribution function was obtained, the vulnerability and exposure indices were classified into five levels based on percentiles, as shown in Table 6.

Table 6. Degrees of vulnerability and exposure.

Degree of vulnerability and exposure	Percentile value
Very low	$0 < I_{vi} \leq 20$
Low	$20 < I_{vi} \leq 40$
Moderate	$40 < I_{vi} \leq 60$
High	$60 < I_{vi} \leq 80$
Very high	$80 < I_{vi} \leq 100$

Source: Adapted from Iyengar and Sudarshan (1982).

Drought risk index (DRI)

To determine the drought risk indices (DRI), Equation 4 was used. Subsequently, the DRI values were adjusted to the extended Shapiro-Wilk goodness-of-fit test (described earlier) to assess the normality of the data. Lastly, they were classified into five risk levels (Very Low, Low, Moderate, High, and Very High), similar to the vulnerability and exposure indices (Table 6).

Results

Drought hazard index (DHI)

The SDI was estimated at the research stations for the 12-month hydrological year (October-September) over a period of 38 years (445 months), and the results are presented in Table 7.

Table 7. Percentage of months recorded with drought (1981-2018).

Area of study	Code	Station	% of months with drought recorded	% of months with mild drought	% of months with moderate drought	% of months with severe drought	% of months with extreme drought
AHM	24271	La Boca	64	80	18	2	0
	24088	El Cuchillo	53	71	24	5	0
	25042	Cerro Prieto	65	83	8	5	4
AMG	12396	Camécuaro	55	67	26	6	0
	12526	Yurécuaro II	47	59	22	14	4
	2935	Calderón	51	61	37	2	0
	12937	Zula	50	58	27	13	2

The most critical months for each of the stations belonging to AHM are as follows: In La Boca, the months of Sep.-Oct. 1987, Sep. 1990, and Sep.-Oct. 1991 recorded severe drought (Figure 7a). In El Cuchillo, the months of Dec.94-Feb.95, Sep.-Dec.95, Jun.-Jul.99, and Jul.-Aug.03 recorded severe drought (Figure 7b). And in Cerro Prieto, the months of Sep.90-Mar.91 and Aug.-Dec.93 recorded extreme drought (Figure 7c).

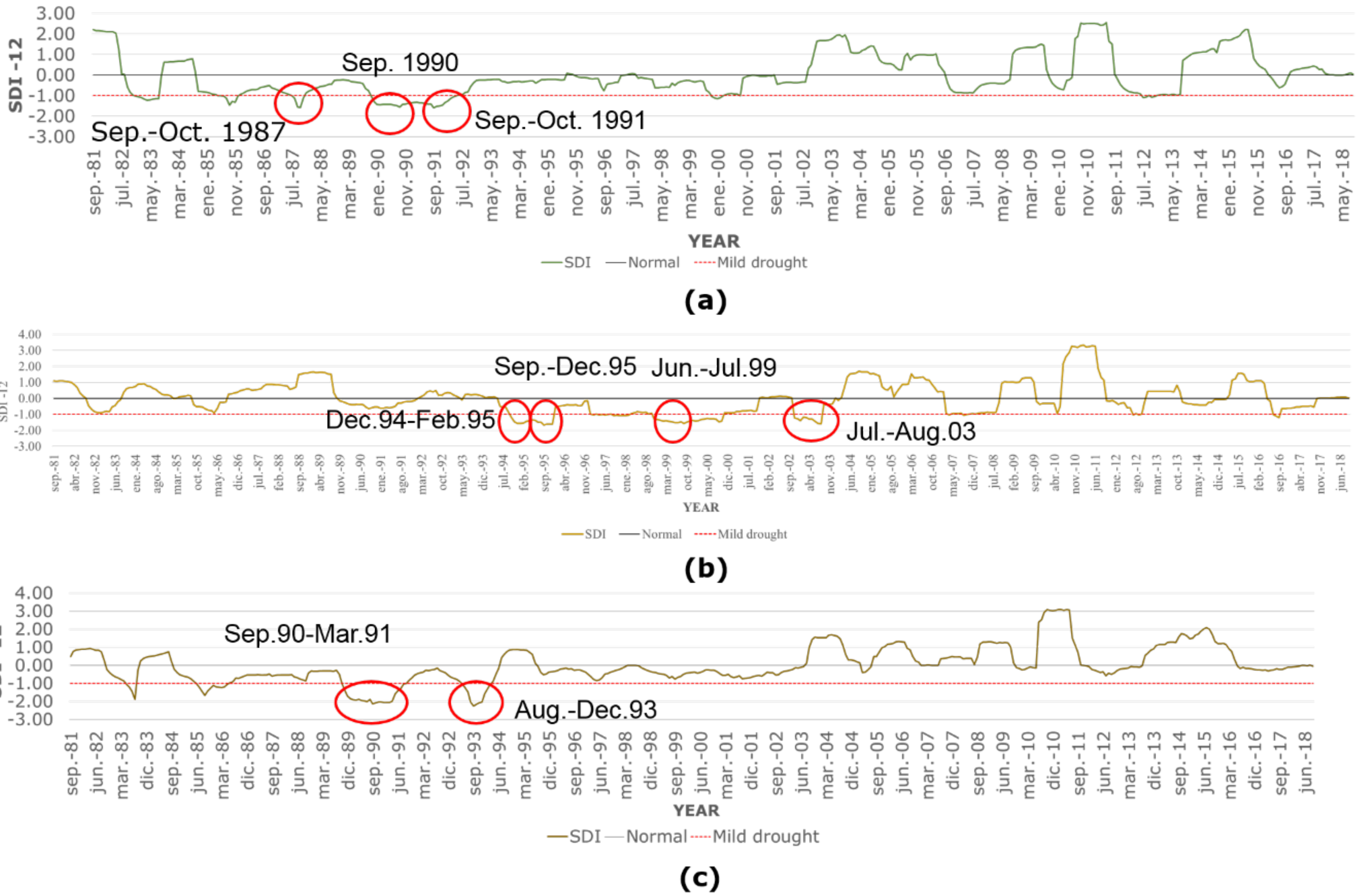


Figure 7. SDI of the hydrometric stations of AHM (1981-2018): (a) La Boca, (b) El Cuchillo, and (c) Cerro Prieto.

The most critical months for each of the stations belonging to AMG are as follows: In Camécuaro, the months of Sep.-Dec. '83 and Mar.-Dec. '13 recorded severe drought (Figure 8a). In Yurécuaro II, the months of Jul. '89-Oct. '90 and Nov. '00-Aug. '01 experienced severe drought; and Oct. '11-Jun. '12 had extreme drought (Figure 8b). In Calderón, the months of Mar.-Apr. '01 and Jul.-Sep. '13 recorded severe drought (Figure 8c). In Zula, the months of Apr.-Jul. '90, Oct. '86-May. '87, Oct. '00-Jun. '01, and Jul.-Aug. '06 experienced severe drought, and Oct. '11-Jan. '12 recorded extreme drought (Figure 8d). The classification of drought states (mild, moderate, severe, extreme) was based on the definition of hydrological drought states using the SDI, proposed by Nalbantis and Tsakiris (2009) (Table 1). The definition of different types of drought can be found in the works of Wilhite (2000), and Castellano-Bahena and Ortega-Gaucin (2022).

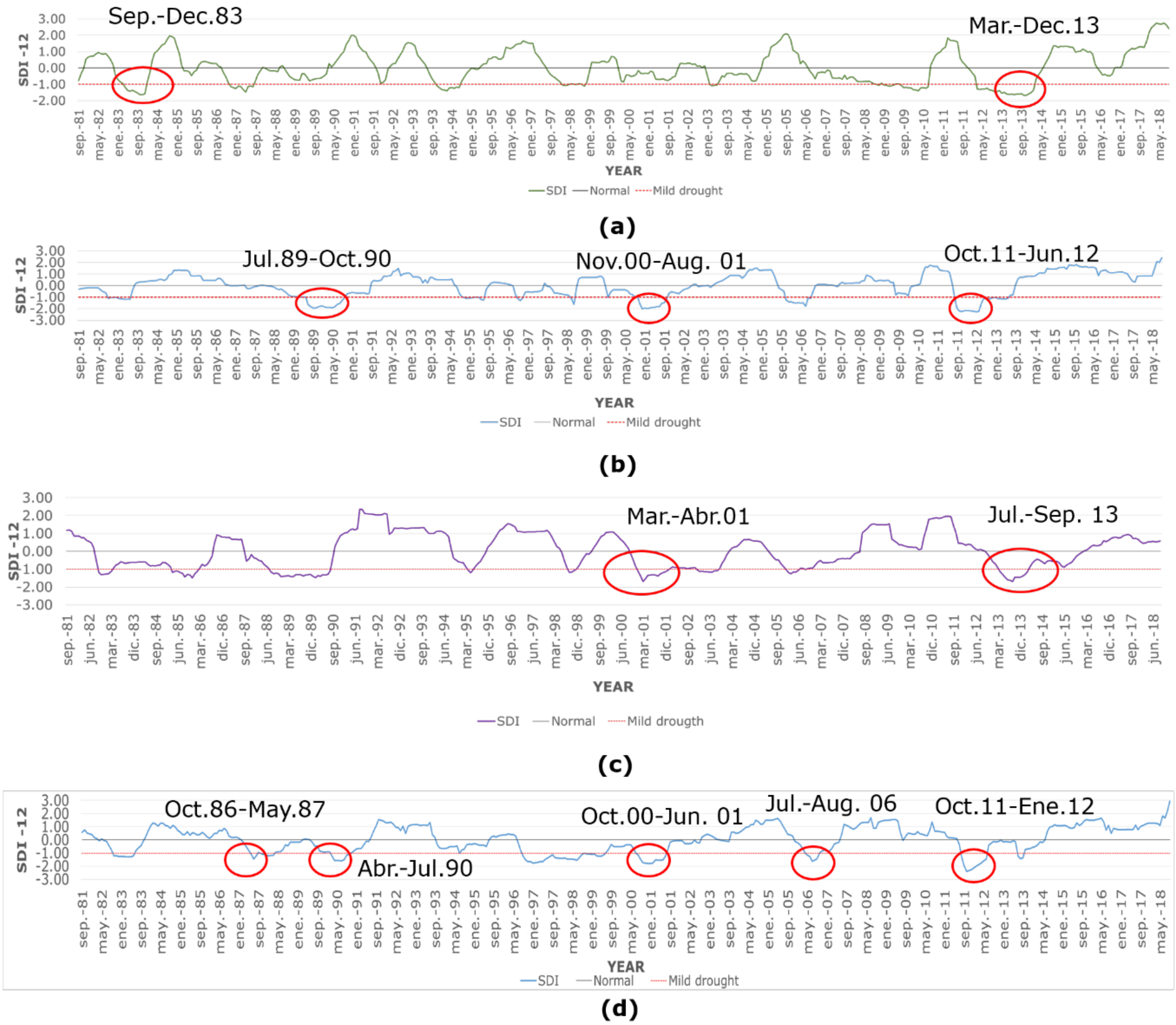


Figure 8. SDI of the hydrometric stations of AMG (1981-2018): (a) Camécuaro, (b) Yurécuaro II, (c) Calderón, and (d) Zula.

Hydrological drought hazard index

The Drought Hazard Index (IA) was obtained for the period 2008-2018. To calculate the IA for each year, the total months from 1981 to the year under evaluation were considered, along with the months recorded with drought (mild, moderate, severe, and extreme) from the hydrometric stations under study. Table 8 and Table 9 show the IA values for AHM and AMG for the study period. It is observed that AHM has slightly higher IA values than AMG. Among the AHM stations, La Boca has the highest IA, while in the case of AMG, it is the Camécuaro station. Regarding the years when IA increased in both areas, these were the years 2008 and 2012-2013.

Table 8. Hydrological Drought Hazard Index (HDHI) based on SDI-12 in the AHM.

Year	IA by station			Average IA
	La Boca	El Cuchillo	Cerro Prieto	
2008	0.75	0.54	0.71	**0.67**
2009	0.72	0.53	0.69	**0.64**
2010	0.72	0.53	0.68	**0.65**
2011	0.70	0.52	0.66	**0.63**
2012	0.71	0.53	0.67	**0.64**
2013	0.71	0.52	0.68	**0.64**
2014	0.69	0.53	0.66	**0.63**
2015	0.67	0.53	0.64	**0.61**
2016	0.67	0.52	0.63	**0.61**
2017	0.65	0.54	0.64	**0.61**
2018	0.64	0.53	0.65	**0.60**

Table 9. Hydrological Drought Hazard Index (HDHI) based on SDI-12 in the AMG.

Year	IA by station				Average IA
	Camécuaro	Yurécuaro	Calderón	Zula	
2008	0.57	0.54	0.58	0.58	**0.57**
2009	0.58	0.53	0.56	0.56	**0.56**
2010	0.59	0.53	0.54	0.54	**0.55**
2011	0.57	0.52	0.52	0.53	**0.53**
2012	0.58	0.53	0.50	0.54	**0.54**
2013	0.59	0.54	0.52	0.56	**0.55**
2014	0.59	0.53	0.53	0.56	**0.55**
2015	0.58	0.51	0.55	0.55	**0.55**
2016	0.57	0.50	0.54	0.53	**0.54**
2017	0.56	0.48	0.52	0.52	**0.52**
2018	0.55	0.47	0.51	0.50	**0.51**

Vulnerability and Exposure index (VI e EI)

a) General vulnerability index (GVI)

The General Vulnerability Index (GVI) was obtained based on the SEVI, IMVI, and EVI indices. The results of this index for the AHM show that the general vulnerability trend is decreasing over the study period. On the other hand, the results for the AMG vary from year to year, although in recent years, there is a tendency for it to decrease (Figure 9). This is attributed to the behavior of the indices that make up the GVI: The results of the SEVI in the AHM and AMG showed a decreasing trend, which was due to a decrease in the economically active unemployed population and the population in conditions of poverty, while the annual per capita income increased during the study period. These results are consistent with Cedillo's observations (Cedillo, 2017) regarding Nuevo León and Jalisco, which are among the entities that contribute the most to the national GDP, ranking third and fourth, respectively (in 2014, they contributed a combined 13.61 %); and they also align with data from INEGI (2021), which reports that in 2020, their combined contribution was 15.3 % of the national GDP.

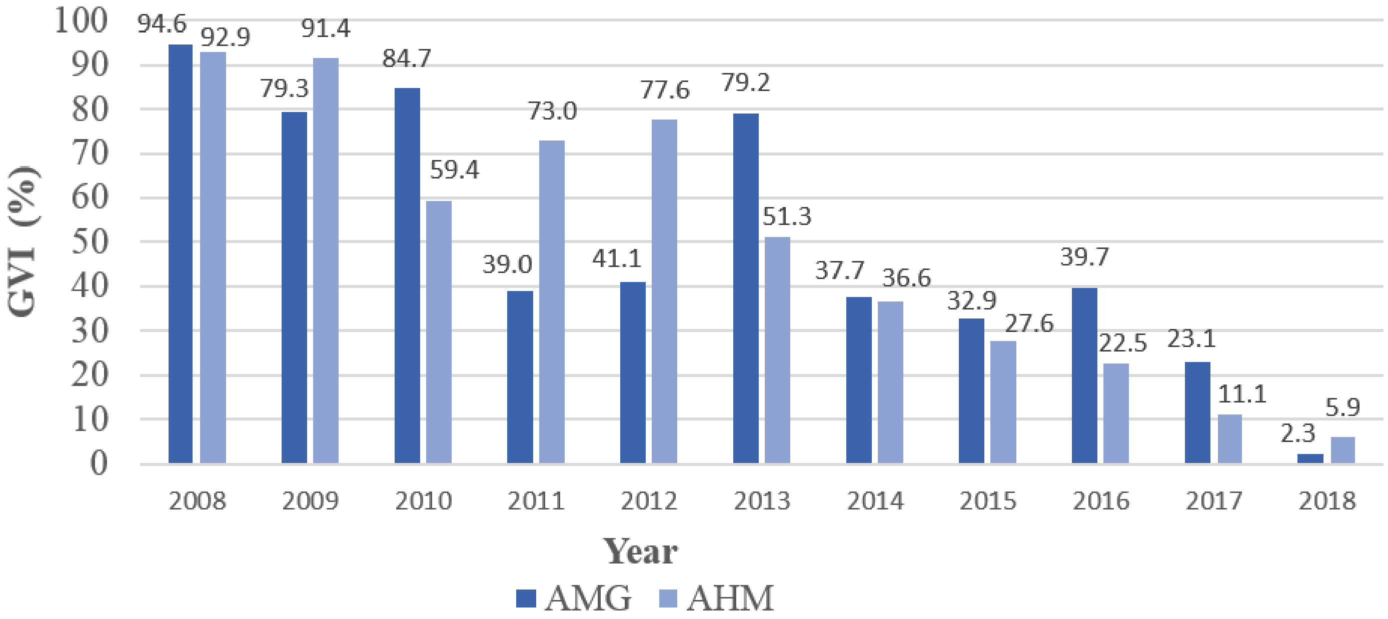


Figure 9. Evolution of the GVI in the AMG and AHM (2008-2018).

Regarding the AHM: The results of the IMVI concerning SADM (Metropolitan Water and Sanitation System) were very variable during the analysis period, without a specific trend. Its behavior was influenced by changes in physical efficiency, commercial efficiency, and consumption during the study period. The decrease in vulnerability could be attributed to actions taken by SADM in the AHM. For example, in 2009, it installed 19.6 kilometers of pipeline in six municipalities of the AHM. In 2013, it installed 2,241 macro-meters, resulting in a recovery of 904.47 liters per second. During the period 2014-2018, sectorization, leak repairs, increased coverage of drinking water, and improvement of physical efficiency in macro sectors were carried out (SADM, 2010; SADM, 2013; SADM, 2014; SADM, 2015; SADM, 2017). As for the increase in vulnerability, in 2011 and 2012, it went from high to very high, respectively. Conagua (2009b) mentions that factors contributing to decreasing physical efficiency include extraordinary allocations to areas with irregular settlements or to inhabitants affected by extreme climatic events. Regarding EVI, its trend is decreasing, attributed to SADM having 100 % of treated volume and a decrease in TDS, although water quality remains slightly brackish. , Alejandre, Valenzuela and Álvarez (2011) note that the AHM is located in an area with water scarcity, creating greater awareness of water use and treatment among the population.

In regards to the AMG: The results of the IMVI regarding the SIAPA, which manages the drinking water in the AMG, varied significantly during the analysis period, without a specific trend. Its behavior was due to fluctuations in physical efficiency and micro-measurement during that time. The decrease in IMVI in some periods was a result of SIAPA's efforts to reduce unaccounted water through the process of sectorization and meter installation (SIAPA, 2010; SIAPA, 2017; SIAPA, 2018). However, in other periods, the IMVI increased. McCulligh and Tetreault (2011) note that water losses due to leaks have long been a subject of concern for social and civil organizations. Regarding the EVI, it exhibited an extremely variable behavior from one year to another. This behavior is attributed to changes in the quality of surface water (BOD_5), groundwater (TDS), and treated volume. The increase in BOD_5 is consistent with what De Anda and Maniak (2007) mention about the quality of Lake Chapala, which has degraded due to wastewater discharges, reduced river flows, and water extractions for the supply to the AMG. Concerning the results of TDS, these increased considerably in the year 2012. This increase could be attributed to the drought of 2011 that affected most of Mexico (Ortega-Gaucin & Velasco, 2013). Finally, the results of the treated volume increased from the year 2011, with an average for the period 2011-2018 of 68 %. These results are consistent because during that period, two wastewater treatment macro-plants (WTP) were put into operation: El Ahogado, inaugurated in 2012, and Agua Prieta, inaugurated in 2014 (McCulligh, 2019).

b) General exposure index (GEI)

The General Exposure Index (*GEI*) was obtained from the indices of *SEEI*, *IMEI*, and *EEI*. The results of the GEI for the AMG and AHM show an increasing trend (Figure 10). This was due to the increase in all three indices: SEEI increased as the population density considerably grew during the study period. This is attributed to the lack of urban planning, as municipal and state governments carry out projects and works without prior coordination in development plans (Iracheta, 2010; Pacheco-Vega, 2014). IMEI increased due to the rise in the volume of produced drinking water. López, Garcia and Cortez (2014) note that an increase in population demands more spaces for housing, and these, in turn, require more services. Finally, EEI increased due to the higher pressure on the water resource. In the case of AHM, it can be observed that in the period 2013-2014 and in the AMG in 2014, the GEI is low, which could be due to the presence of Hurricane Ingrid in 2013, causing a potential decrease in the pressure on the water resource. In general, the behavior of EEI in the study areas can be explained by the regional strong pressure on the water resource in the central, northern, and northwest regions of the country (Conagua, 2017).

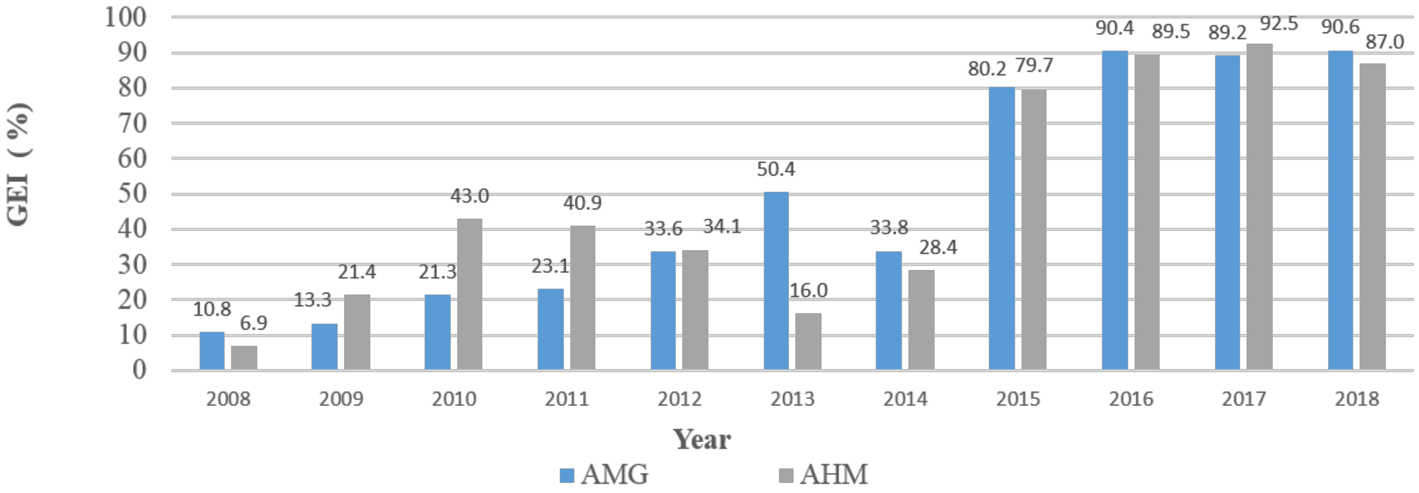


Figure 10. Evolution of the General Exposure Index (GEI) in the AMG and AHM (2008-2018).

Drought risk index (DRI)

The results of the Drought Risk Index (DRI) for the AMG and AHM show abrupt changes in some years of the analysis period, although there is a notable trend of increasing, especially in the AMG (Figure 11). It can be deduced that the study areas are highly sensitive to hydrological droughts. According to the results of the Hydrological Drought Hazard Index (HDHI), in both study areas, moderate drought was more significant than severe and extreme droughts. Additionally, in these areas, the General Exposure Index (GEI), represented by population density, volume of produced drinking water, and the degree of pressure on the water resource, tends to increase.

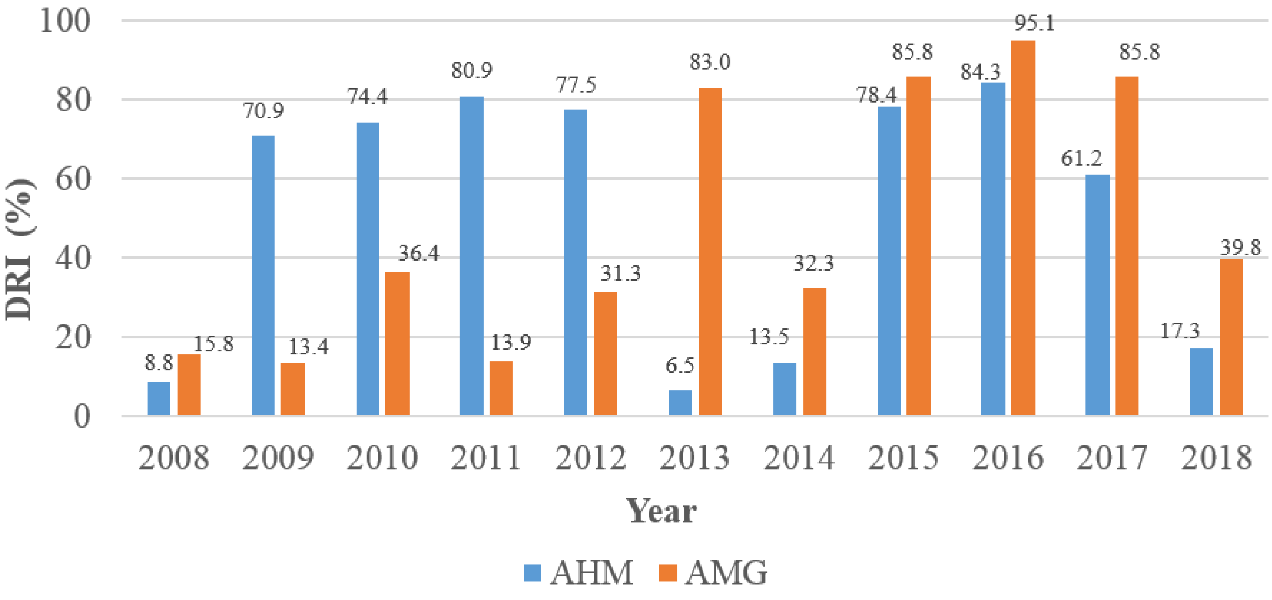


Figure 11. Evolution of DRI in the AHM and AMG (2008-2018).

With respect to the AHM: In the period from 2008 to 2011, the DRI went from very low to very high, and this was due to the GVI and specifically to the SEVI (poverty) and SEEI (population density) since they increased in that year. These results are consistent with those published by Coneval (2018a), where poverty at the national level increased by 1.8 percentage points as a result of the 2008-2009 financial crisis, and the volatility of food prices also increased. In the case of the 2013-2014 period, the DRI was very low, which was due to the decrease in EVI, as SADM has 100 % of treated volume, and TDS also decreased, although the water quality remains slightly brackish. Regarding IMVI, the results were highly variable from year to year without a specific trend, which was because physical efficiency did not increase in the analysis period, resulting in losses due to leaks. Aguilar and Monforte (2018) mention that the volume of unaccounted water in the AHM reached its maximum level in 2010 and has remained at that level since then, with an upward trend. It can also be observed that the meteorological drought that occurred in the 2011-2012 period, classified as severe drought, was not perceived in the AHM. This was due to the passage of Hurricane Alex in July 2010, where more than 60 hours of intense rain occurred, and the dams were completely filled (Sedesol, 2010). Aguilar-Barajas *et al*. (2015) note that the AHM has a highly vulnerable water supply system, highly dependent on the presence of hurricanes to fill the three dams that supply this area. For example, on September 1, 2013, the El Cuchillo and Cerro Prieto dams were at critical levels after two years of meteorological drought. The abundant rains on September 12 and 13 of that same year (due to the presence of Hurricane Ingrid) allowed the recovery of these reservoirs, thus hiding the degree of vulnerability to which the AHM is exposed.

In the case of the AMG: In 2013, the DRI went from low to very high, and this was due to an increase in the GVI and GEI, specifically the SEVI (increase in the economically inactive population and the population in poverty conditions). This happened as a result of the financial crisis (Coneval, 2018b), and to EVI and EEI (higher levels of TDS as well as an increase in the degree of pressure on the water resource). Regarding this, Flores-Elizondo (2016) states that several populations suffer environmental impact from uncontrolled wastewater discharges in the AMG without accountability for resulting health effects. In the case of IMVI, there is an up-and-down behavior throughout the study period, which was because in some years, adaptability (physical efficiency, commercial efficiency, micro and macro measurement) and sensitivity (consumption) increased, and in other years, they decreased. One of the problems with water availability is the limited storage capacity. The combination of geological, orographic characteristics, and the natural availability of rivers crossing the state results in limited suitable sites for storage infrastructure construction in Jalisco (Conagua, 2009b). Lake Chapala, due to the intense drought in 2012, was on the verge of turning into a desert (Huerta, Castañeda, & Mora, 2016).

Discussion

Discussion regarding the methodology

As mentioned in the introduction, there is relatively little research with regard to methodologies for assessing the risk of hydrological drought in urban areas. The difference between the methodology proposed in this work and others analyzed lies in the approach and purpose. In this study, the elements of drought risk are first evaluated separately (hazard, vulnerability, and exposure), and then they are analyzed together to calculate the degree of risk for the metropolitan areas under examination (AHM and AMG).

During the execution of this study, several limitations arose that hindered the analysis and interpretation of the obtained results. Among these, the following stand out:

- The assessment of drought hazard was limited by the availability of information on hydrometric data. Specifically, there is a lack of information on groundwater extractions, and in the case of surface waters, some hydrometric stations were omitted because more than 80 % of their records were incomplete, and it was not appropriate to fill them using any method. The selected hydrometric stations cover the study area.
- The sample size for the study period in evaluating vulnerability and exposure indices was only 11 years, as information for all proposed indicators in previous years was not found.

- Involvement of managers of the water and sanitation systems (OOAPAS) in the two study areas. Their participation was sought in the selection of indicators proposed for the assessment of vulnerability and exposure indices. However, due to the Covid-19 pandemic, it was impossible to meet again to determine the weights of these indicators. Instead, an alternate weighting method was chosen. This could have affected the level of importance given to each indicator, potentially influencing the vulnerability and exposure results.
- The assessment of drought risk in these two study areas is based on published data from different agencies, so the results may be biased by the quality of the indicators and weighting methods used.

Despite the aforementioned limitations, it is essential to highlight that the strength of this study lies in developing a methodology to calculate hydrological drought risk in urban areas. This methodology can be replicated in other regions, contributing to filling the gap in studies on the subject.

Discussion regarding the results

The results showed that, because in the study areas, more than half of the water supply comes from surface sources, they are highly sensitive to hydrological droughts, whose characteristics were determined through the SDI. It is observed that the AHM has HDHI slightly higher than the AMG.

The results of the DRI show that the trend in the AHM and AMG is increasing. Since the population in these areas has increased, demanding more water and experiencing water stress. It is observed that when the population in conditions of poverty increases along with the economically unemployed population, and per capita income decreases, the DRI is higher. Regarding the IMVI and IMEI, it is also observed that the trend is increasing, as the population increases, more water is being extracted in a continuous 24/7 service, and physical efficiency does not increase, resulting in losses due to leaks. Regarding the EEI in the AHM and AMG, there is a trend of increase, as the degree of pressure on the water resource has been on the rise. In the case of the AMG, the quality of surface water shows signs of contamination. The quality of groundwater is fresh (Conagua, 2016); however, it can be observed how the TDS increased considerably in the year 2012, which could be due to the drought of 2011 that occurred in most of Mexico.

The results of this research confirm Esparza's statements (Esparza, 2014) about the idea that the aggravated effects of droughts and water scarcity are not only due to natural causes but also because of social factors, highlighting poor policies for the management and use of water reserves. They also confirm what Pineda-Pablos and Salazar-Adams (2016) wrote, asserting that drought does not have a direct effect on urban water systems but is mediated by water infrastructure and management. The main obstacle for cities to carry out adaptive water management is the lack of reliable information systems. The findings align with Ahmadalipour *et al*. (2019), who consider controlling population growth essential to mitigate drought risk, as it improves socioeconomic vulnerability and reduces potential exposure to drought. Finally, they support Camacho's statement (Camacho, 2012) that the increase in vulnerability will force operators to adapt to new conditions imposed by climate change, associated not only with an increase in demand but also with greater pressure on water sources, reduced availability, changes in water quality, among others, thereby increasing operating and administrative costs proportionally.

The consequences of not having risk management strategies to reduce vulnerability and exposure were reflected in the intense drought crisis experienced in many parts of Mexico in 2021. Urban areas such as Monterrey and Mexico City faced severe restrictions in water availability and supply to their respective populations, as reported by Meléndez (2021b); Manuela (2021); Badillo (2021); Ramírez (2021); Martín (2021); Enciso, Davila, Partida, Nuñez and Chio (2021), and Flores (2021).

Conclusions

There is a wide range of approaches, methods, and tools to determine drought risk components; however, there are no universally applicable methods for conducting these assessments since the drought phenomenon depends on many contextual factors, and its effects vary in each case. From the analysis of 108 scientific articles on the topic, it was observed that there is very little research on urban drought risk methodologies. Of the works found, only five indirectly involve urban areas. Therefore, it is concluded that there are knowledge gaps and significant opportunities in the studies of hydrological drought risk in urban areas. This work aimed to contribute to closing the mentioned gap.

According to the obtained results, it was demonstrated that the proposed methodology is feasible and useful in assessing drought risk in the areas under study (AHM and AMG). The main findings of this research align positively with those of previous studies, such as the works of Camacho (2012), Esparza (2014), Pineda-Pablos and Salazar-Adams (2016), and Ahmadalipour *et al*. (2019), and with the reports of major local and national newspapers on the drought impact in these two areas in recent years. For example, in the AMG, evidence of deficient institutional management, uncontrolled population growth, poor water quality, lack of drinking water coverage for some neighborhoods, water stress, and the socioeconomic impact on the population in purchasing water tanks is apparent (Meléndez, 2021; Manuela, 2021; Badillo, 2021; Ramírez, 2021; Martín, 2021).

In the case of the AHM, the degree of pressure on the water resource is evident, with physical efficiency not increasing and resulting in losses due to leaks. This result aligns with those reported by García *et al*. (2012), Aguilar-Barajas *et al*. (2015), and Aguilar and Monforte (2018), who mention that, despite the current management in the AHM being considered efficient when evaluated in terms of performance indicators and operational efficiency, this condition is not sufficient to be deemed sustainable.

The way vulnerability, exposure, and drought risk have evolved in the AHM and AMG facilitates understanding the risks, and appropriate adaptation and mitigation plans can be developed. This can also contribute to a shift from a reactive to a proactive paradigm in addressing drought.

Finally, it is recommended that for future studies, decision-makers such as managers and operational staff of water and sanitation agencies (OOAPAS) be involved in the assessment of various components of drought risk. Specifically, in terms of vulnerability assessment, it can be enhanced by incorporating the corruption index where available. Lastly, it is important to encourage OOAPAS to have reliable and high-quality indicator information to properly assess their institutional performance.

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