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Articles

The conceptual and methodological framework of drought risk and its components: Hazard, exposure and vulnerability

Marco conceptual y metodológico del riesgo por sequía y sus componentes: amenaza, exposición y vulnerabilidad

Heidy Viviana Castellano-Bahena[1], ORCID: https://orcid.org/0000-0002-1387-516X

David Ortega-Gaucin[2], ORCID: https://orcid.org/0000-0002-5336-7442

[1]Instituto Mexicano de Tecnología del Agua, Jiutepec, Morelos, México, heidyviv78@gmail.com

[2]Instituto Mexicano de Tecnología del Agua, Jiutepec, Morelos, México, dortega@tlaloc.imta.mx

Corresponding author: David Ortega-Gaucin, dortega@tlaloc.imta.mx

Abstract

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Drought risk reduction and its direct and indirect impacts have gained worldwide relevance during the last decades. This paper presents a review of the basic conceptual and methodological tools to analyze the drought risk in a given system. The fundamental components of risk are described, conceived primarily as a function of hazard (or specific danger, which in this case is the drought phenomenon); exposure (people, property, livelihoods, and systems that are subject to potential damage and loss due to hazard), and vulnerability (represented by the socio-economic and environmental conditions of the system that make it susceptible to suffering damage). The concepts and definitions associated with these components are explained and the most usual mathematical methods and models for calculating them are presented. It is concluded that, given the great diversity of approaches, concepts, and methods to determine drought risk, it is at the discretion of the researcher or evaluator the selection of the most appropriate depending on the approach adopted, the information available, and the objective or investigation context.

Keywords: Risk management, extreme phenomena, drought, climate change, vulnerability, adaptive capacity.

Resumen

La reducción del riesgo de sequía y sus impactos directos e indirectos ha cobrado relevancia mundial durante las últimas décadas. En este trabajo se presenta una revisión de las herramientas conceptuales y metodológicas básicas para analizar el riesgo por sequía en un sistema determinado. Se describen los componentes fundamentales del riesgo,

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concebido principalmente como una función de la amenaza (o peligro específico, que en este caso es el fenómeno de la sequía); la exposición (personas, propiedades, medios de vida y sistemas que están sujetos a daños y pérdidas potenciales debido al peligro), y la vulnerabilidad (representada por las condiciones socioeconómicas y ambientales del sistema que lo hacen susceptible de sufrir daños). Se explican los conceptos y definiciones asociados con estos componentes, y se presentan los métodos y modelos matemáticos más usuales para calcularlos. Se concluye que, dada la gran diversidad de enfoques, conceptos y métodos para determinar el riesgo por sequía, queda a criterio del investigador o evaluador la selección del más apropiado en función del enfoque adoptado, la información disponible, y el contexto u objetivo de la investigación.

Palabras clave: gestión del riesgo, fenómenos extremos, sequía, cambio climático, vulnerabilidad, capacidad de adaptación.

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Introduction

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In recent decades, disasters caused by natural phenomena have increased globally, mainly due to an increase in the population's vulnerability and partly due to changes in the hazard's characteristics (IPCC, 2012). Increased exposure of the population to extreme climatic and hydrometeorological events has resulted in more disasters. Therefore, the impact of disasters on human activities has been addressed in several publications over the past years, which have been developed by different disciplines conceptualizing risk components in different forms, although in most cases in a similar manner (for example, UNDRO, 1979; Cardona, 1985; Cardona, 2001; Schneiderbauer & Ehrlich, 2004; Davis, 2004; Jordaan, 2006; Burg, 2008). In general terms, most conceptual proposals indicate that disaster risk is reduced by linking the threat or hazard, i.e., the probability of occurrence of a specific event, the vulnerability of the exposed elements, or the internal selectivity factor of the effects' severity on said elements (Figure 1a). Studies associated with this risk concept are, for example, those Yen (1971); Cardona (1985); Cardona (1993); Blaikie, Cannon, Davis, and Wisner (1994); Wisner, Blaikie, Cannon, and Davis (2003), and Tsakiris (2007). However, this concept of risk has changed; for instance, the fifth assessment report of the Intergovernmental Panel on Climate Change (IPCC, 2014) determined that the risks of climate change stem from an overlap between vulnerability (lack of preparation), exposure (people or assets at risk),

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and hazard (which trigger phenomena or climatic trends), as shown in Figure 1b.

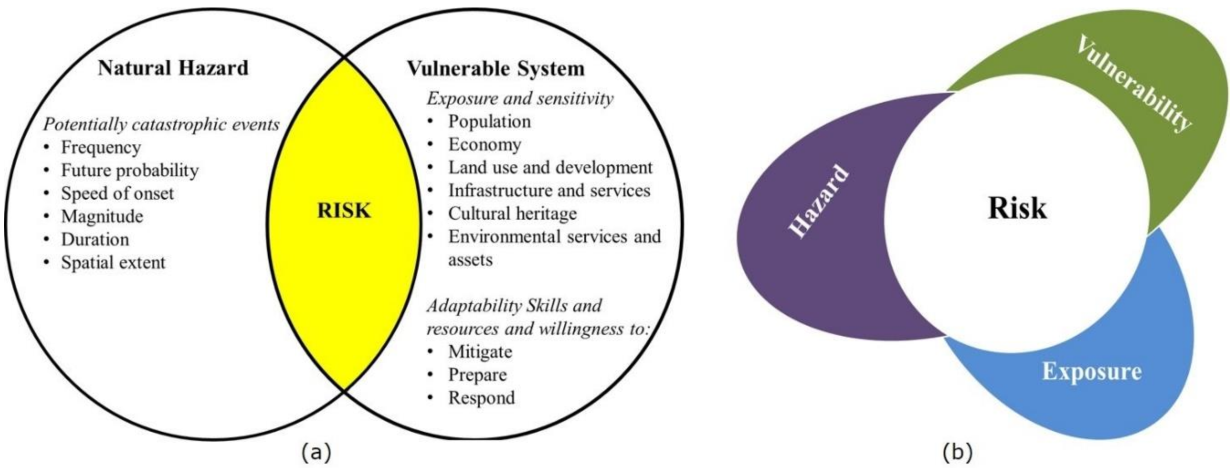

Figure 1. (a) Interaction of risk with hazard and vulnerability; (b) Interaction of risk with the threat (hazard), vulnerability, and exposure. Source: Adapted from Wood (2011) and IPCC (2014).

Each of the a forementioned components can be subject to selective measures to reduce risks (Ortega-Gaucin, López, & Arreguín, 2016). In addition, there are studies that conceptually and methodologically describe the interaction of risk components (without focusing on the analysis of a specific threat or hazard), such as those by Cardona (1993), Blaikie *et al.* (1994), Hoddinott and Quisumbing (2003), BID (2003), Schneiderbauer and Ehrlich (2004), Jordaan (2006), Tsakiris (2007), Birkmann (2007), and Welle and Birkmann (2015), among others.

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However, explicitly concerning drought risk, we found a limited review of the mathematical models used to calculate it since research focuses on analyzing one risk component, be it hazard or vulnerability, without a theoretical or methodologically approach to the interaction between both variables. Such as studies by Gibbs, Maher and John (1967); Bergaoui and Alouini (2001); Bhuiyan (2004); Boken (2005); Narasimhan and Srinivasan (2005); Velasco, Ochoa and Gutiérrez (2005); Chandrasekar, Sai, Roy, Jayaraman and Krishnamoorthy (2009), and Tsakiris *et al*. (2013). Thus, the present study seeks to conceptually and methodologically review and describe the most common ways to evaluate hazard, exposure, vulnerability, and drought risk. In this manner, this study's aim consists in concisely providing a broad panorama to be used as a basis to evaluate risk in the face of this natural hazard. The following sections describe each risk component in detail: starting with the hazard, presenting the main concepts associated with the drought phenomenon, such as the types of drought mentioned in literature and the most frequent methods used to characterize and evaluate the severity of the phenomenon; subsequently, exposure is analyzed describing the concept, its fundamental dimensions, and the indicators used to measure it; then, vulnerability is detailed, including the most common definitions, their components, characteristics, and methods to calculate vulnerability; after that, the different risk definitions and the mathematical models used to determine risk quantitatively are described; and finally, some considerations about the analyzed concepts and conclusions derived from the study are presented.

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Hydrometeorological threat or hazard

The hydrometeorological threat or hazard is a process or phenomenon of atmospheric, hydrological, or oceanographic origin that can result in death, injury, health impacts, loss of livelihoods and services, socioeconomic damages, or environmental damage (UNISDR, 2009). Generally, the hazard is estimated using historical meteorological or climatic information. It is represented by the probability of a particular meteorological or climatic phenomenon occurring (for example, tropical cyclone, torrential rain, drought). In this case, the relevant hazard is the phenomenon of drought understood in its broadest sense, that is, a severe and lasting decrease of precipitation capable of causing severe hydrological imbalances and affecting human activities and ecosystems (OMM & GWP, 2006). Thus, drought hazard refers to the probability of a drought event taking place in a specific spatial and temporal frame with enough intensity to cause damage. Hazard values vary from one region to another and depend on the specific characteristics of the studied phenomenon (Magaña, 2013). Definitions and types of drought, their

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parameters, and the main methods to determine their characteristics (duration, magnitude, severity, spatial extent, etc.) are described in the following sections.

Definition and types of drought

Drought is mainly initiated by deficient precipitation and is considered a natural phenomenon related to climatic variability in a region (Tsakiris *et al*., 2013). There are various drought definitions, adapted to specific economic sectors, climatic regions, and regional conditions (Wilhite & Glantz, 1985; Correia, Santos, & Rodrigues, 1991; Tate & Gustard, 2000), but none is universally accepted because drought is a relative phenomenon whose characteristics vary from one place to another. Thirty-six years ago, Wilhite and Glantz (1985) found more than 150 definitions of drought published in the literature and classified them into four groups according to the scientific discipline used to analyze the phenomenon and its impacts: meteorological drought, agricultural drought, hydrological drought, and socioeconomic drought. Currently, this classification is still valid and is widely used in specialized scientific articles (for example, Bootsma, Boisvert, & Baier, 1996; Barakat & Handoufe,

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1998; Wilhite, 2000; Valiente, 2001; Bergaoui & Alouini, 2001; Boken, 2005; Mishra & Singh, 2010). The first three types of drought (meteorological, agricultural, and hydrological) address ways to measure drought as a physical phenomenon; the last approach (socioeconomic drought) addresses drought in terms of supply and demand by tracking the effects of water deficit spreading through socioeconomic systems. Meteorological drought is defined as a function of the degree of rain decrease compared to a "normal" or average amount of rain and the duration of the dry period. Agricultural drought links various characteristics of meteorological (or hydrological) drought with agricultural impacts, focusing on precipitation scarcity, differences between actual and potential evapotranspiration, and soil hydrological deficits. Hydrological drought is associated with the effects of deficit precipitation periods on surface or groundwater supply. Socioeconomic drought differs from the previously mentioned types of drought because its occurrence depends on water supply and demand processes at a given time and space. Figure 2 shows the evolution sequence of the different types of drought described.

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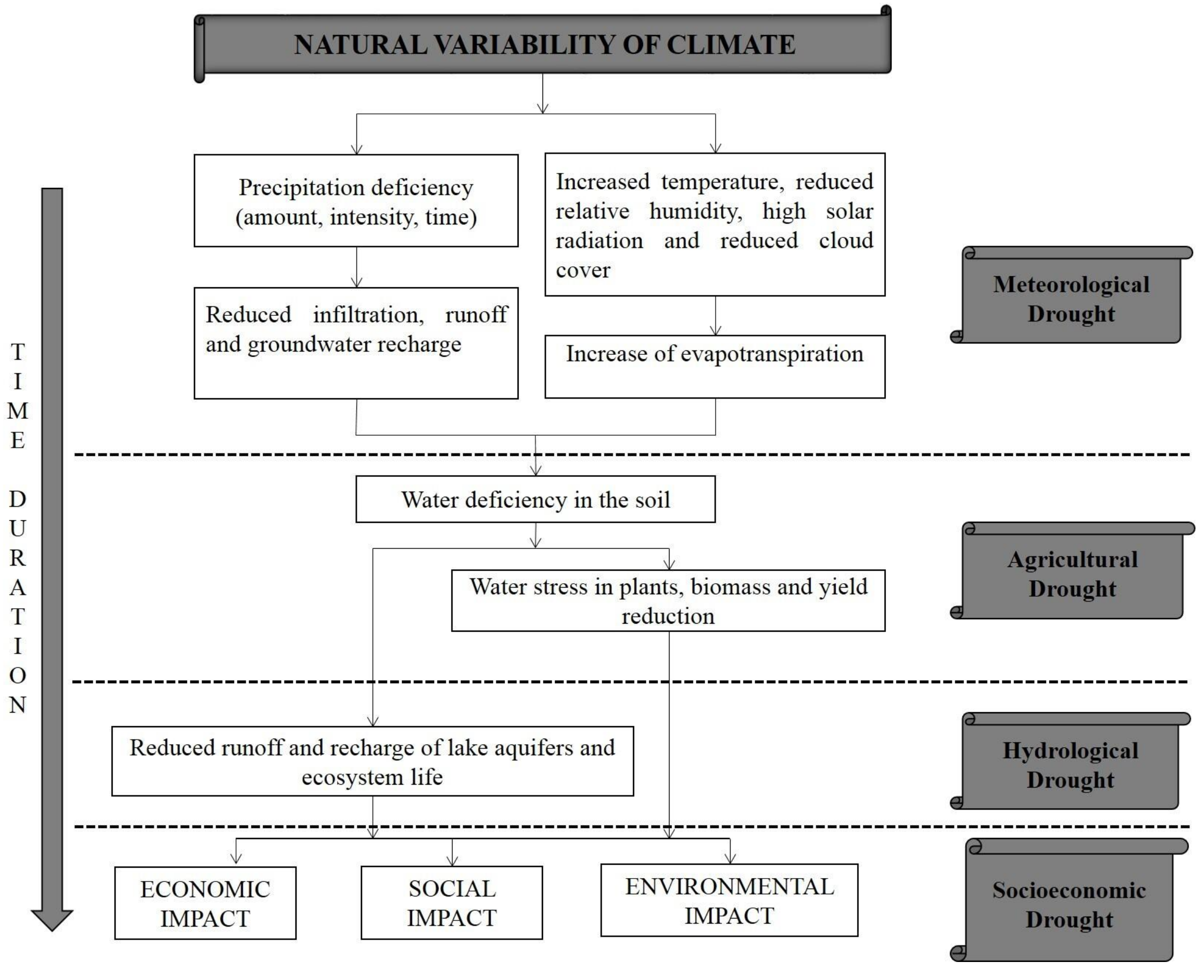

Figure 2. Evolution sequence of the different types of drought.

Source: Modified from NDMC (1995).

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Drought parameters

Operational definitions of the different types of drought need to be translated into a numerical format (parameters) to specify dry events' characteristics (Valiente, 2001). From the meteorological and hydrological points of view, the basic drought parameters are (Burton, Kates, & White, 1978; Dracup, Lee, & Paulson, 1980): magnitude, which is the mean precipitation or flow deficit during the dry period; severity, which is the cumulative flow or precipitation deficit for the duration of the dry period; the duration, which is the time (total number of days, months, or consecutive years) during which the total precipitation or flow is lower than the mean precipitation or flow for the same period. In addition, the above parameters are a function, among other factors, of the truncation level (X_o); at this reference point, lower values represent a deficiency and probably a drought, as measured by the amount of rain or runoff (Velasco *et al*., 2005), as shown in Figure 3.

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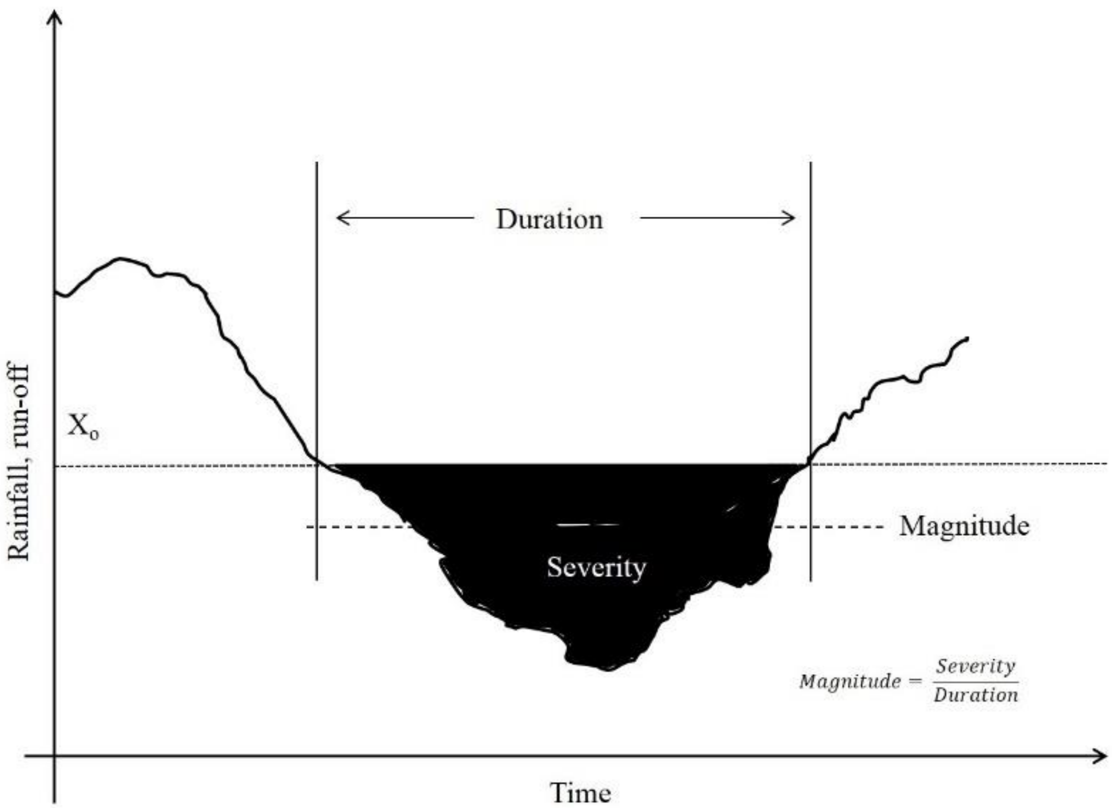

Figure 3. Basic parameters to characterize drought from the meteorological and hydrological perspectives. Source: Adapted from Velasco *et al*. (2005).

When analyzing drought from agricultural and socioeconomic points of view, it is difficult to determine its characteristics based on the parameters described above. Therefore, a great diversity of assessment methods and models based on indices and indicators have been created and used for each type of drought, as described in the next section.

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Drought assessment methods

Currently, a wide variety of indicators and indices are available to characterize drought, mainly from the meteorological, agricultural, and hydrological perspectives, each with advantages and disadvantages that limit or favor its application in a given setting (Byun & Wilhite, 1999; Heim, 2002; Hayes, Svoboda, Wall, & Widhalm, 2011). *Indicators* are variables or parameters used to describe drought conditions, for example, precipitation, temperature, streamflow, groundwater and reservoir water levels, soil moisture, among others. *Indices* are usually computerized numerical representations of drought severity, determined by climatic or hydrometeorological data, which include the mentioned indicators intended to analyze the drought's qualitative state in a given period. However, similarly to there being no single definition of drought, no index or indicator can be attributed to and applied to all types of drought, climate regimes, and drought-affected sectors (OMM & GWP, 2016).

Meteorologically, drought indicators are associated with climatic variables such as precipitation, temperature, and evapotranspiration (Wilhite, 2005). Common indices to characterize meteorological drought include the Deciles; the Rainfall Anomaly Index (RAI); the Standardized Precipitation Index (SPI); the Effective Drought Index (EDI); and the

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Standardized Precipitation Evapotranspiration Index (SPEI). From the agricultural perspective, drought indicators consider soil moisture data to detect crop drought situations and focus on anomalies in soil moisture values concerning season and location (Wanders, Van-Lanen, & Van-Loon, 2010), for instance, the Palmer Drought Severity Index (PDSI); the Soil Moisture Anomaly (SMA); the Evapotranspiration Deficit Index (ETDI); and the Soil Moisture Deficit Index (SMDI). Additionally, satellite remote sensing indices identify vegetation health status and help identify and characterize drought in agriculture; some of these indices include the Normalized Difference Vegetation Index (NDVI) and the Vegetation Health Index (VHI). Lastly, hydrological drought indicators refer to hydrological system variables, mainly groundwater levels, streamflow, and reservoir storage (Wanders *et al*., 2010). Indices derived from these indicators include the Palmer Hydrological Drought Index (PHDI); the Surface Water Supply Index (SWSI); the Standardized Water-Level Index (SWI); the Standardized Streamflow Index (SSFI); the Streamflow Drought Index (SDI); and the Standardized Reservoir Supply Index (SRSI). Table 1 presents the origins, applications, advantages, and disadvantages of each of the indices mentioned above. For a more detailed description of each of them and specific recommendations on their use, review the Handbook of Drought Indicators and Indices (OMM & GWP, 2016). For instance, the handbook mentions that in 2009 the WMO recommended the use by countries of SPI as the primary index to monitor and track meteorological drought conditions.

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Table 1. Characteristics of commonly used drought indices.

Type of drought	**Index**	**Input variables***	**Origin and applications**	**Advantages**	**Disadvantages**
Meteorological	Deciles	P	Created by Gibbs and Maher (1967) at the Australian Bureau of Meteorology. It can be used where the complete precipitation records for a period (preferably more than 30 years) and a place is available, which is used to classify the frequency and distribution of rainfall	Given that it analyzes only one variable, it is a flexible and useful method in situations of humidity and drought	The effects of temperature and other variables during the development of drought are not taken into account
	RAI	P	Developed by Van-Rooy (1965). It uses standardized values of precipitation based on the station's record in a particular place. The comparison with the current period is used to analyze the product from a historical point of view	It can be analyzed in monthly, seasonal, and annual scales	It requires complete serial data, and inter-annual variations should be minor compared to temporal variations
	SPI	P	Created by McKee, Doesken, and Kleist (1993) at Colorado State University (United States). It is a	It only requires monthly precipitation data, and it can be calculated at different time scales,	It does not consider the temperature component, which is important for the

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Type of drought	Index	Input variables *	Origin and applications	Advantages	Disadvantages
			standardized index that can be applied to all climate regimes and for different time scales	which makes it possible to monitor the effects of meteorological drought on agriculture and hydrology	general water balance and the water use in a region. This issue can make it challenging to compare episodes with similar SPI values but different thermal conditions
	EDI	P	Developed by Byun & Wilhite (1999) at the National Drought Mitigation Center in the United States. It is used to detect the beginning and end of hydrological deficit periods. It can be calculated anywhere in the world where daily precipitation records are available	It applies to all climate regimes, and results are comparable because they are standardized	Daily rainfall data can make it difficult to use the index in operational contexts since it may not be possible to update the input data daily

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Type of drought	Index	Input variables *	Origin and applications	Advantages	Disadvantages
	SPEI	P, T	Created by Vicente-Serrano, Beguería and López-Moreno (2010) at the Pyrenean Institute of Ecology (Spain). It uses SPI as a basis but takes into account the effect of temperature on droughts. It is applied anywhere in the world with records of complete series of monthly precipitation and temperature data	Given that it uses temperature data, it is ideal for observing climate change's effect on model results under different future assumptions	It is necessary to have sufficient monthly precipitation and temperature data. As it is a monthly index, rapidly developing drought situations may not be detected immediately
Agricultural	PDSI	P, T, AWC	It was developed by Palmer (1968) at the U.S. Weather Bureau to evaluate droughts affecting agriculture in the country's agricultural regions. It was the only operational drought indicator for many years and has been applied and is popular in different parts of the world	It is very reliable in detecting droughts due to using soil data and a total water balance methodology	The need to have complete serial data can be problematic. It has a time scale of approximately nine months, which results in a lag when detecting drought conditions based on the soil moisture component in the calculations
	SMA	P, T, AWC	Created by Bergman, Sabol, and Miskus (1988) at the	It considers the effects of temperature and	It is challenging to calculate due to the

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Type of drought	**Index**	**Input variables***	**Origin and applications**	**Advantages**	**Disadvantages**
			U.S. National Weather Service, as a method to evaluate global drought conditions. It can be used where weekly or monthly data on temperature, precipitation, and soil moisture retention capacity values are available	precipitation on soil moisture, which are the fundamental aspects of water balance	need for data from different soil layers. Estimates of potential evapotranspiration can vary considerably depending on the region
	ETDI	Mod	Created by Narasimhan and Sriniviasan (2005) at the Texas Agricultural Experiment Station (United States). It is a useful weekly result to determine water stress in crops. Applicable for modeled data obtained from a hydrological model using the SWAT model	Analyzes both actual and potential evapotranspiration and allows for the detection of wet and dry periods	The spatial variability of the index increased during the summer months during the period of highest evapotranspiration and highly variable precipitation
	SMDI	Mod	Created by Narasimhan and Sriniviasan (2005) at the Texas Agricultural Experiment Station. It is a weekly soil moisture product calculated at	It considers the complete soil profile and depths, which makes it suitable for different types of crops	The information needed to calculate the index is based on the result of the SWAT (Soil & Water Assessment Tool) model. There are

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Type of drought	Index	Input variables *	Origin and applications	Advantages	Disadvantages
			different depths. Applicable for modeled data obtained from a hydrological model using the SWAT model		autocorrelation problems when all depths are used
	NDVI	Sat	Developed Tarpley, Schneider, and Money (1984), and Kogan (1995) in the National Oceanic and Atmospheric Administration (NOAA). It uses data obtained from NOAA's AVHRR satellite. For monitoring agricultural droughts around the world	Innovative since it uses satellite data to monitor the health of vegetation concerning drought events. Very high resolution and excellent spatial coverage	Data processing is essential for the index, a phase in which a robust system is necessary. Satellite data historical record is not very extensive
	VHI	Sat	Created by Kogan (1990) at NOAA. It is derived from the NDVI. It is used to detect and monitor droughts affecting agriculture around the world	It has worldwide coverage and high resolution	A short period of satellite data records
Hydrological	PHDI	P, T, AWC	Part of the set of indices created by Palmer (1965) in the U.S. Weather Bureau. It is based on the original PDSI and modified to consider	Its water balance method allows for the analysis of the entire water system	Human impact, such as management decisions and irrigation, are not taken into account in the calculations

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Type of drought	Index	Input variables *	Origin and applications	Advantages	Disadvantages
			long-term drought that influences hydrological components		
	SWSI	P, SF, RD, S	Created by Shafer and Dezman (1982) to solve several of the limitations detected in the PDSI. It includes data on water supply (snowmelt, runoff, reservoirs) and is calculated for a watershed	By taking into account all water resources in a watershed, it provides a good indication of the overall hydrological health of a specific watershed or region	When the data sources change, the complete index must be recalculated, making it challenging to produce a homogeneous chronological series. In addition, calculations can vary between watersheds, complicating comparisons between watersheds or homogeneous regions
	SWI	GW	Created by Bhuiyan (2004) at the Indian Institute of Technology to evaluate groundwater recharge deficits. It is used where well-level data are available	Analyzes drought effect on groundwater, an essential water supply component for agricultural and municipal usage	Given that surface water is not accounted for, interpolation between points (data from groundwater wells) may not represent the region or the climate regime

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Type of drought	Index	Input variables *	Origin and applications	Advantages	Disadvantages
	SSFI	SF	Created by Modarres (2007). It uses monthly values of streamflow and standardized methods associated with SPI. It can be applied where there are daily or monthly records of streamflows	It examines the effect of drought on streamflows, an essential component for water supply to reservoirs and other uses	It only presents streamflows in the context of drought monitoring without analyzing other factors
	SDI	SF	Developed by Nalbantis and Tsakiris (2008) in Greece, based on SPI methodology and calculations. It allows for the analysis of wet and dry periods, similar to SPI but based on monthly streamflow data. A historical series of flow and water level data is required	It allows for the analysis of the effect of drought on streamflows at different time scales	It does not take into account surface water management decisions, and periods of no flow can distort results
	SRSI	SF, RD	Created by Gusyev, Hasegawa, Magome, Kuribayashi, and Lee (2015 in Japan as a systematic method to analyze reservoir data under drought conditions. It is used where	It takes into account the total inflow and storage associated with any specific reservoir system, and it provides useful information to those responsible for	It does not consider the changes caused by reservoir management and the losses caused by evaporation

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Type of drought	**Index**	**Input variables ***	**Origin and applications**	**Advantages**	**Disadvantages**
			there are monthly records of reservoirs inflow and average reservoir storage volumes	water supply and irrigation suppliers	

*Key to variables: GW = Groundwater; AWC = Available Water Content; SF = Streamflows; RD = Reservoir; S = Snowpack; Mod = Modeled; P = Precipitation; Sat = Satellite information; T = Temperature. Source: Adapted from OMM and GWP (2016).

In recent years, due to the high relevance and contribution of artificial intelligence-based methods to the modeling and prediction of hydrological and climatic processes (Ardabili, Mosavi, Dehghani, & Varkonyi-Koczy, 2019), *learning machine* techniques have been used in combination with drought indices for drought assessment, monitoring, and forecasting. For example, Rhee and Im (2017) developed a high-resolution drought forecasting model in South Korea using the technique of the extremely randomized tree and the SPI and SPEI indices; conversely, Deo and Sahin (2015) used the extreme learning machine algorithm to predict the EDI index in Australia; Park, Im, Jang and Rhee (2015) used three machine learning approaches (random forest, decision trees) in conjunction with the SPI and NDVI indices to evaluate and monitor meteorological and agricultural drought in the United States; Feng, Wang, Liu and Yu (2019) adopted three advanced machine learning methods (random forest with bias correction, support vector machines,

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and neural networks) in combination with the SPEI to improve predictions of agricultural drought in southeastern Australia; and Zhang, Chen, Xu and Ou (2019) used the artificial neural network method and the SPEI to predict meteorological droughts in the province of Shaanxi, China; among other studies.

However, despite the utility of drought indices to monitor, evaluate, and forecast drought (meteorological, agricultural, and hydrological), none evaluate the socioeconomic impact of drought. Therefore, this impact's evaluation is considered an unresolved problem and, to a certain extent, an impossible mission (Marcos, 2001); this is because the drought phenomenon causes a complex and intricate network of economic, social, and environmental effects that accumulate gradually and can persist even years after the end of the event (Ortega-Gaucin, 2012a). Moreover, the information generated around the phenomenon is usually scarce and scattered, making it difficult to calculate its effects and severity accurately, reliably, and timely, and, in the end, prevents or significantly limits the formulation of contingency plans by most of the governments in the affected countries (Wilhite, 2000). Therefore, due to the very nature of the phenomenon, there is no single definitive answer to the question: What is drought's socioeconomic impact? Total and sectoral impacts will depend on the duration and territorial extension of the phenomenon; the amount of water availability reduction (Ortega-Gaucin, 2012b), along structural and relevant economic conditions, including the development stage and affected crop prices (Sisto, Guajardo-Quiroga, & Aguilar-Barajas, 2011), among other variables. The water shortage

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impacts translate into lower production and income since the volumes available during the drought period are insufficient to meet the water demand under normal conditions. Thus, economic drought assessment is based on concepts such as productivity, income, efficiency, and unemployment (Sisto *et al*., 2012). For the agricultural and livestock sector, economic analyzes based on harvested and lost crops, production volume, production value, lost livestock, etc., provide indicators of drought impact and reflect, perhaps better than other sectors, the severe adverse effects hydrological deficit has on a resource-dependent field (Velasco, 2002; Ortega-Gaucin, 2012a; Ortega-Gaucin, 2012b).

However, to manage drought risk effectively, it is vital to understand the possible impacts, albeit in relative terms, and to identify who will be at risk and why. Therefore, assessing hazard, exposure, vulnerability, and risk entails, in a certain sense, the prediction of the seriousness and extent of the hazard, and its possible effects on the economy and society, while simultaneously allowing decision-makers to design measures to prevent and mitigate the impact (Ortega-Gaucin & Velasco, 2015). Hence the importance of analyzing and evaluating these variables.

Drought exposure

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The IPCC (2014) defines exposure as the presence of people, properties, livelihoods, and systems that are prone to potential damage and losses. In recent years, increased population exposure to extreme meteorological events has resulted in more disasters. Exposure is a factor that generates vulnerability; if there is no exposure to a specific phenomenon, then there is no risk (Magaña, 2013). About meteorological and agricultural drought, for instance, exposure includes rainfed crops, the farmers and ranchers who are at risk of losing their jobs, food, and income (Ortega-Gaucin, De-la-Cruz-Bartolón, & Castellano-Bahena, 2018a); for hydrological drought, it includes all users of surface and groundwater, such as irrigation districts and units, hydroelectric plants, urban and industrial public users, and all people from rural areas lacking sufficient water to carry out their daily activities.

Characteristics that influence exposure assessment

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According to a study conducted by the Inter-American Development Bank (Cardona, 2005), the indicators most suited for measuring physical susceptibility or exposure to any kind of disaster are those reflecting the susceptibility of populations, assets, investments, production, sustenance means, essential patrimony, and human activities; indicators of this kind are also those reflecting the growth and population density rates. According to Füssel (2005), climate-related exposure assessments must consider the characteristics or factors of the exposed system, the type and number of stress factors and their main causes, their effects on the system, and the time horizon of the evaluation, as shown in Table 2.

Table 2. Fundamental dimensions describing the exposure situation.

Dimension or Characteristic	**Question**	**Possible options**
System/Method	Who or what is exposed?	A community, a geographical region, an economic sector, a natural system
Hazard (or threats or stress factors)	Exposed to what?	Anthropogenic climate change, natural climate variability, atmospheric composition, other non-climatic factors

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Dimension or Characteristic	Question	Possible options
Consequences (or effects or valued attributes or variables of interest)	What is at risk?	Ecosystem's viability, food security, human health, economic goods, other valued goods, and services
Temporal and spatial scale	What time frame?	Months, years, decades, centuries
	Which region?	State, municipality, watershed, hydrological region, country, continent

Source: Prepared by the authors based on Füssel (2005).

Exposure to drought increases poverty (Carter, Little, Mogues, & Negatu, 2007; Dercon, 2004). The impact of disaster risk on poverty is visible (losses in the event of a disaster), and less obvious: households exposed to meteorological risk reduce their investment in productive assets and select low risk and low yield activities (Cole *et al*., 2013; Elbers, Gunning, & Kinsey, 2007). This link of exposure to poverty in the presence of natural hazards can create a feedback loop in which poor households have no choice but to settle in risk zones and, therefore, face greater challenges to escape poverty (Winsemius *et al*., 2018).

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Methods to calculate exposure

The most widely used methods to evaluate exposure are based on socioeconomic and environmental indicators; these indicators are often combined to produce composite indices that represent the different components of vulnerability, exposure, and risk (Hagenlocher *et al*., 2019). This methodological approach contributes to better understanding the multidimensional nature of this variable—this is especially useful in decision-making processes aimed at reducing vulnerability.

Mathematical models

Some studies consider exposure a component of vulnerability (Burg, 2008; Ortega-Gaucin *et al*., 2018a; Ortega-Gaucin, De-la-Cruz-Bartolón, & Castellano-Bahena, 2018b; Fontaine & Steinemann, 2009), based on

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the IPCC (2001) definition for vulnerability. However, other studies consider drought exposure a component of risk independent of vulnerability (Carrao, Naumann, & Barbosa, 2016; Frischen, Meza, Rupp, Wietler, & Hagenlocher, 2020; Ortega-Gaucin, Ceballos-Tavares, Ordoñez, & Castellano-Bahena, 2021), based on the IPCC (2014) risk concept. Nevertheless, regardless of the adopted conceptual framework, several mathematical models have been proposed to calculate exposure. Peduzzi, Dao, Herold, and Mouton (2009) presented a model of the factors affecting human losses from natural hazards at a global scale for the 1980-2000 period, the purpose was to monitor risk evolution. The combination of average annual hazard frequency and the exposed populations provides the physical exposure. Welle and Birkmann (2015) provided a new approach to assessing risk from natural hazards at the country level. Carrao *et al*. (2016) proposed a non-compensatory model of drought exposure to estimate the potential losses of different types of drought-related disasters. Winsemius *et al*. (2018) investigated the global exposure of poor people to floods and droughts in 52 countries. Ahmadalipour, Moradkhani, Castelletti, and Magliocca (2019) evaluated the national risk of drought in Africa. Ortega-Gaucin *et al*. (2021) determine the agricultural drought risk in Zacatecas, Mexico. Table 3 displays the mathematical models used by the aforementioned authors to calculate exposure.

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Table 3. Most common mathematical models to calculate exposure.

Author	Formula	Description
Peduzzi *et al.* (2009)	$PhExp = \sum_{i}^{n} F\ Pop_i$	Where: *PhExp* = Average annual physical exposure for the spatial unit (exposed population/year); *F* = Annual frequency of an event of given magnitude (event/year); Pop_i = Total population living in the spatial unit for each event "*i*" (exposed population/event); *n* = Number of events considered
	$PhExp = \sum \frac{Pop_i}{Y_n}$	Where: *PhExp* = Average annual physical exposure for the spatial unit (exposed population/year); Pop_i = Population living in the affected area for each event "*i*" (exposed population/event); Y_n = period (year)
Welle and Birkmann (2015)	$Exp = \frac{A + B + C + (0.5 * D + E)}{N}$	Where: *Exp* = Exposure; *A* = People exposed to earthquakes; *B* = People exposed to storms; *C* = People exposed to floods; *D* = People exposed to drought; *E* = People exposed to sea level rise; N = Population number
Carrao *et al.* (2016)	$de_i = \overline{OR}_i / \overline{OR'}_{i'}$	Where: de_i = Exposure to drought; $\overline{OR}_i$ is the multivariate distance between the origin and the indicators real values observed for region *i;* and $\overline{OR'}_{i'}$ is the distance between the origin and the projected regional values at the maximum exposure limit
Winsemius *et al.* (2018)	$I_p = \frac{f_p}{f} - 1,$	Where: I_P is the poverty exposure bias (PEB), f*p* and *f* are the fraction of people exposed to floods/droughts in the country, respectively
Ahmadalipour *et al.* (2019)	$Exp = \frac{Esposición_{fut;\,p}}{Exposición_{hist}}$	Where: *Exp* = Exposure; *hist and fut* indicate historical and future periods; and *p* population scenarios (low, medium, and high)

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Ortega-Gaucin *et al.* (2021)	$$DEI = \sum_{i=1}^{n} X_i W_i$$	Where: *DEI* = Drought Exposure Index; X_i is the normalized value of indicator *i*; W_i is the weight of normalized indicator *i*; *n* is the number of drought exposure indicators

Source: Developed by the authors.

For a drought exposure index to be easy to use and process, its formulation should rest on a small number of indicators reflecting relevant and guiding aspects of the type of action to be carried out by decision-makers. This set of indicators by themselves, and especially when disaggregated at the local level, could facilitate the identification and orientation of actions to be promoted, strengthened, or prioritized to achieve a higher level of safety from hazards. Consequently, a small number of all possible indicators must be selected based on data availability, personal judgment, or previous research (Ortega-Gaucin *et al*., 2018b; Ortega-Gaucin *et al*., 2021).

Vulnerability to drought

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Assessments of vulnerability to drought are the first step in identifying the underlying causes of its impacts (González, Urquijo, Blauhut, Villarroya, & De-Stefano, 2016). Vulnerability to drought is a complex phenomenon; therefore, it is essential to fully understand the phenomenon to design effective preparation and mitigation strategies and support policies and programs (Patrick, 2003). The concepts and methodological aspects most frequently used to evaluate vulnerability to drought are described below (Figure 4).

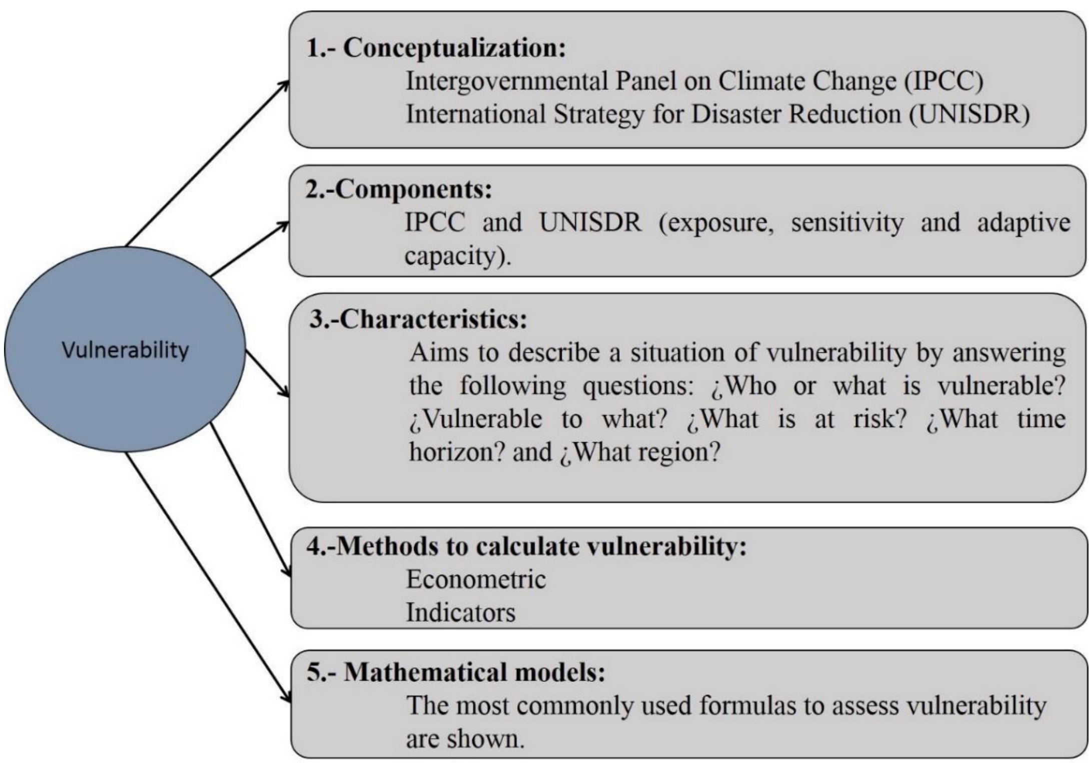

Figure 4. The methodological diagram to evaluate vulnerability to drought. Source: Developed by the authors.

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Conceptualization of vulnerability

The concepts and definitions of vulnerability have been analyzed by authors such as Timmerman (1981); Kates (1985); Chambers (1989); Downing (1991); Anderson (1994); Blaikie *et al.* (1994); Bohle, Downing, and Watts (1994); Downing and Bakker (2000), and Birkmann (2007), among others. Based on the concepts used by these authors, in general, vulnerability is a condition of frailty or weakness of an individual or system to a hazard (be it of physical origins such as drought, earthquakes, floods, or anthropogenic such as accidents, devaluations, economic crises); it has a multifaceted and multidimensional nature; it is dynamic both spatially and temporally, and it is linked to a specific hazard. In this case, the hazard we are interested in is the drought phenomenon. Concerning this, González *et al.* (2016) state that most definitions of vulnerability applied to drought and other climatic phenomena are based on the definitions of the IPCC (IPCC, 2001; IPCC, 2014) and the United Nations Office for Disaster Risk Reduction (UNISDR, 2009), shown in Table 4.

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Table 4. Vulnerability definitions are based on the IPCC and UNISDR.

Concept	Concept origin		
	IPCC		UNISDR (2009)
	IPCC (2001)	IPCC (2014)	
Definition of vulnerability	The degree to which a system is susceptible to or incapable of withstanding the adverse effects of climate change, including climate variability and extreme events	Propensity or predisposition to be negatively affected	The characteristics and circumstances of a community, system, or property make it susceptible to the harmful effects of a hazard
Objective	Considers the assessment of vulnerability as the expected result of the analysis	Emphasizes how to reduce and manage climate change risks	Its purpose is to highlight the means to reduce disaster risk. Considers vulnerability as a step in the risk assessment process

Source: Adapted from IPCC (IPCC, 2001; IPCC, 2014), González *et al.* (2016) and Brooks (2003).

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Based on these concepts, vulnerability to drought can be understood as the degree to which a system is susceptible to and unable to cope with the adverse effects or damage caused by this natural phenomenon. Thus, vulnerability is associated with the potential impacts of drought events and has been used to evaluate socio-economic and environmental systems' susceptibility to this hazard. Examples, where the IPCC (2001) definition is applied, are the studies by Chandrasekar *et al.* (2009); Deems (2010); Flörke, Wimmer, and Laaser (2011); Antwi-Agyei, Fraser, Dougill, Stringer, and Simelton, (2012), and De-Stefano, González, Ballesteros, Urquijo, and Blauhut (2015). The IPCC (2014) definition is used by Bouroncle *et al.* (2016), Guo *et al*. (2019), Meza *et al*. (2020), and Frischen *et al*. (2020). Finally, about the UNISDR (2009) definition, examples of its use can be found in the studies by Iglesias, Moneo, and Quiroga, (2007); Adepetu and Berthe (2007); Cheng y Tao (2010); Zarafshani *et al*. (2012); Naumann, Barbosa, Garrote, Iglesias, and Vogt (2013), and Safavi, Esfahani, and Zamani (2014).

Components of vulnerability

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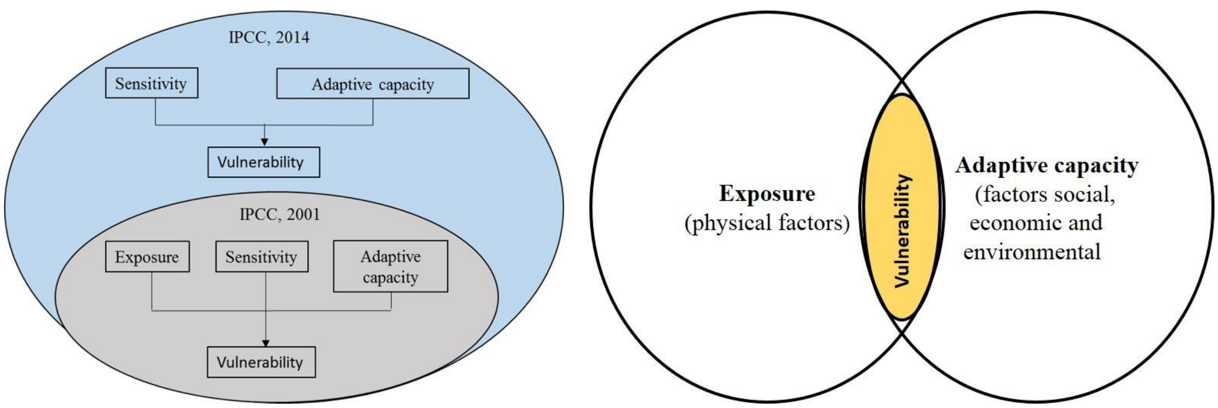
Initially, the IPCC (2001) proposed the vulnerability concept as a function of a system's exposure to climate variation, sensitivity, and adaptive capacity. However, in its fifth assessment report, the IPCC (2014) modified the understanding of these terms, leaving vulnerability only as a function of a system's sensitivity and adaptive capacity (Figure 5a). The exposure component became part of the risk concept, as will be later described. For its part, UNISDR (2009) states that the components of vulnerability are exposure and adaptive capacity (Figure 5b). Table 5 describes each of the mentioned components based on the concept's origin.



(a) (b)

Figure 5. Components of vulnerability according to the IPCC (a) and UNISDR (b) approaches. Source: Adapted from IPCC (IPCC, 2001; IPCC, 2014) and UNISDR (2009).

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Table 5. Components of vulnerability according to the IPCC and UNISDR approaches.

Concept origin	Components		
	Exposure	**Sensitivity**	**Adaptive capacity**
IPCC (2001)	The degree to which a system is exposed to important climatic variations	The extent to which a system is affected, in a detrimental or beneficial sense, by climate-related stimuli	The ability of a system to adjust itself to climate change (including climate variability and its extremes) to mitigate possible harm, take advantage of opportunities, or face the consequences
IPCC (2014)	The presence of people; means of subsistence; species or ecosystems; environmental functions, services, and resources; infrastructure; or	The extent to which a system is affected, whether adversely or beneficially, by climate change stimuli	It is the adjustment process to the actual or projected climate and its effects. In human systems, adaptation seeks to moderate or avoid damages or take advantage of beneficial opportunities. In some natural systems,

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Concept origin	Components		
	Exposure	Sensitivity	Adaptive capacity
	economic, social, or cultural assets in places and environments that could be adversely affected		human intervention can facilitate adjustment to the projected climate and its effects
UNISDR (2009)	Refers to population, properties, systems, or other elements present in areas where hazards exist and are therefore exposed to experience potential losses. Measurements of the degree of exposure can include the number of people		The ability of the population, organizations, and systems to face and manage adverse conditions, emergencies, or disasters by using available resources and skills

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Concept origin	Components		
	Exposure	Sensitivity	Adaptive capacity
	or types of assets in an area		

Source: Adapted from IPCC (IPCC, 2001; IPCC, 2014) and UNISDR (2009).

The most accepted and used of the previous conceptual approaches by the scientific community in recent years is the one proposed by the IPCC (2014), which defines vulnerability as a function of the sensitivity and adaptive capacity of the analyzed systems, as observed in the increasing number of studies using it (Bouroncle *et al*., 2016; Guo *et al*., 2019; Frischen *et al*., 2020; Meza *et al*., 2020, among others).

Characteristics that influence vulnerability assessment

According to Füssel (2005), climate-related vulnerability assessments must consider the characteristics or factors of the vulnerable system, the

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type and number of stress factors and their main causes, their effects on the system, and the assessment time frame, as shown in Table 6.

Table 6. Fundamental characteristics describe a situation of vulnerability.

Characteristic	Question	Possible options
System/Method	Who or what is vulnerable?	A community, a geographical region, an economic sector, a natural system.
Hazard (or threats or stress factors)	Vulnerable to what?	Anthropogenic climate change, natural climate variability, atmospheric composition, other non-climatic factors.
Consequences (or effects or valued attributes or variables of interest)	What is at risk?	Ecosystem's variability, food security, human health, economic goods, other valued goods, and services.
Scale:	Time: What time frame?	Years, decades, centuries.
	Spatial: Which region?	State, municipality, watershed, hydrological region, country, continent.

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Source: Adapted from Füssel (2004).

Methods to calculate vulnerability

The most commonly used methods in the literature related to climate change are the econometric method and indicator-based methods (Table 7). The econometric method, rooted in the literature on poverty and development, uses socioeconomic survey data at the household level to analyze the level of vulnerability of different social groups (Hoddinott & Quisumbing, 2003). Indicator-based methods are based on selecting some variables from the entire set of potential indicators and then systematically combining them to evaluate vulnerability levels (Cutter, Boruff, & Shirley, 2003; Kaly & Pratt, 2000).

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Table 7. Methods to calculate vulnerability.

Concept	Econometric method	Indicator-based methods
Description	The method is divided into three categories: vulnerability as expected poverty (VEP), vulnerability as a low expected utility (VEU), and vulnerability as uninsured exposure to risk (VER) (Hoddinott & Quisumbing, 2003). These categories are used to construct a measure of the loss of welfare attributed to disasters (Deressa, Hassan, & Ringler, 2008)	They are based on selecting some indicators from the entire set of potential indicators and then combining them systematically to determine levels of vulnerability (Deressa *et al.*, 2008)
Advantages	The method is easy to estimate; the calculation of VEP can be used to identify non-poverty at-risk households, the VEU calculation provides a breakdown of vulnerability to poverty and vulnerability to uninsured risk, and finally, the calculation of VER can indicate whether covariates or idiosyncratic risk are the main cause of welfare losses (Hoddinott & Quisumbing, 2003)	This method is valuable for monitoring trends and exploring conceptual frameworks (Deressa *et al.*, 2008). Integrates and summarizes different dimensions of a topic, is easy to interpret, and facilitates the evaluation of policy effectiveness and accountability by

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Concept	**Econometric method**	**Indicator-based methods**
		government representatives (Schuschny & Soto, 2009)
Disadvantages	If estimates are made using a single cross-section, it assumes that cross-sectional variability is a proxy of temporal variability (Hoddinott & Quisumbing, 2003), and it is also difficult to explain an individual's type of risk since individuals are not well informed about them (Kanbur, 1987); and in the absence of datasets, impact estimates are often partial and, therefore, are not conclusive indicators (Deressa *et al*., 2008)	This leads to a lack of connection between the conceptual definition of vulnerability and the metrics (Deressa *et al*., 2008)

Source: Developed by the authors.

Similar to drought exposure, methods based on socioeconomic and environmental indicators are the most commonly used methods to evaluate vulnerability; these indicators combine to produce composite indices representing the different degrees of vulnerability (Hagenlocher *et*

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al., 2019). This approach makes it possible to understand this variable's different facets better and to guide actions aimed at reducing it by implementing drought prevention and mitigation measures.

Mathematical models

Given that vulnerability manifests itself at specific times and places (Adger, 2006), there are different mathematical models to calculate it. The models presented in this section share similarities; for instance, both Webb and Harinarayan (1999, and the IPCC (IPCC, 2001; IPCC, 2014) models identify adaptive capacity as an essential element mitigating hazard's impact; Fontaine and Steinemann (2009) model, modified the IPCC (2001) model, where exposure and sensitivity are added together and then divided by adaptive capacity; ; Luers, Lobell, Sklar, Addams and Matson (2003) measures vulnerability as a function of the state of the interest variables to a damage threshold, the sensitivity of the variables to stress factors, and the magnitude and frequency of the stress factors to which the system is exposed; Me-Bar and Valdez (2005) see vulnerability as the threshold level for a disaster; Burg (2008) defines vulnerability as the probability of an acute decrease or chronic deficit of access to food or consumption below a critical value; Ortega-Gaucin *et al*.

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(2018a and 2018b) developed an overall drought vulnerability index, which includes the economic, social, and environmental vulnerability of the analyzed systems; and Ortega-Gaucin *et al*. (2021) propose to assess the vulnerability of agricultural systems to drought based on indices of sensitivity and adaptive capacity. Table 8 presents the most common mathematical models to calculate vulnerability.

Table 8. Most common mathematical models to calculate vulnerability.

Author	Description	Formula
Webb & Harinarayan (1999)	They used the formula to study the relationship between vulnerability and malnutrition	$V = H - CA$ Where: *H*= Hazard or threat, *CA*= Adaptive capacity
IPCC (2001)	Provides an operational definition of vulnerability	$V = CA - (S + E)$ Where: *CA*= Adaptive capacity, *S*= Sensitivity, *E*= exposure
Luers *et al.* (2003)	It examines the vulnerability of socio-ecological systems	$V = \frac{SE}{ERA\ x\ POE}$ Where: *V*= Vulnerability, *SE*= Sensitivity to stress, *ERA*= State relative to the threshold, *POE*= Probability of stress occurrence

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Author	Description	Formula
Me-Bar and Valdez (2005)	They provided a model used by Zarafshani *et al.* (2012) to evaluate the vulnerability of wheat producers to drought	$V_{i=\frac{1}{C_i}*}\sum_{j=1}^{k_i}(P_j * W_j)$ Where: *P* in this formula is a parameter value, *W* is the weight assigned to each parameter. *C* is derived from *Ci = 1/2 (W max ki*) to the sum of all weights, where W max is the maximum value on the weight scale
Burg (2008)	Proposes the chronic vulnerability index (CVI) measure levels of vulnerability to food insecurity	$V = E + I$ Where: *E*= Risk exposure, *I*= Inability to cope
Fontaine and Steinemann (2009)	They developed a conceptual model modifying the IPCC (2001) proposed model to evaluate vulnerability to drought.	$V = \frac{E + S}{CA}$ Where: *E*= Exposure, *S*= Sensitivity, *CA*= Adaptive capacity

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Author	Description	Formula
IPCC (2014)	Modifies the operational definition of vulnerability that was defined in 2001	$$V = S - CA$$ Where: *S*= Sensitivity, *CA*= Adaptive capacity
Ortega-Gaucin *et al*. (2018a and 2018b)	They propose an overall drought vulnerability index, including economic, social, and environmental vulnerability	$$IVG = \frac{IVE}{3} + \frac{IVS}{3} + \frac{IVA}{3}$$ Where: IVG = Overall drought vulnerability index; IVE = Economic vulnerability index; IVS = Social vulnerability index; and IVA = Environmental vulnerability index. The IVG is calculated assuming a 1/3 weight P_i for each of its components
Ortega-Gaucin *et al.* (2021)	They develop an index of vulnerability to agricultural drought assessed based on sensitivity and adaptive capacity indices	$$DVI = \frac{SI + (1 - ACI)}{2}$$ Where: *DVI* = Agricultural drought vulnerability index; *SI* = Sensitivity index; and *ACI* = Adaptive capacity index

Source: Developed by the authors.

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The international academic community's most accepted and used of the previous mathematical models is the IPCC (2014); it modifies the operational definition of vulnerability developed by the same organization in 2001, expressing vulnerability as a function of sensitivity and adaptive capacity (leaving out the exposure component, which became part of the risk concept).

Therefore, based on the risk concepts described below, the system's level of drought risk can be determined based on the combination of exposure, vulnerability, and hazard analysis in a specific system.

Risk

The concept of risk, associated with the idea of an uncertain future, has always been present in human societies (Cardona, 2001). This section describes the different risk definitions and the mathematical models used to calculate risk.

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Risk definitions

The extinct United Nations Disaster Relief Organization (UNDRO, 1979) presents two definitions of risk that are considered the basis of current concepts; the first is a specific risk, and the second is total risk: a) *Specific risk-Rs*: Degree of expected losses due to the occurrence of a particular event and as a function of hazard and vulnerability; b) *Total risk-Rt*: Number of human losses, injuries, damage to properties, and effects on economic activity due to the occurrence of a disastrous event, in other words, the product of the specific risk (*Rs*) and the elements at risk (*E*). For its part, UNISDR (2009) defines risk as to the possible losses a disaster could cause in terms of lives, health conditions, means of livelihood, goods, and services, which could occur in a particular community or society at a specific time in the future. Finally, the IPCC (2014) defines risk as a potential consequence in which something of value is endangered with an uncertain outcome, recognizing the diversity of values. Risk is often represented as the probability of occurrence of hazardous events or trends multiplied by the impact of such events or trends. Risks result from the interaction of vulnerability, exposure, and hazard. The term risk is used mainly about the risks associated with climate change.

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Mathematical models to calculate risk

There are different frameworks and equations to evaluate risk; this section explains some model examples: Yen (1971) calculated risk as the probability of an adverse event; UNDRO (1979) determines risk as a function of exposure, hazard, and vulnerability; Cardona (1985), and Schneiderbauer and Ehrlich (2004) took UNDRO (1979) proposed model and modified it, firstly eliminating the exposure variable and secondly by appending the temporal aspect; Cardona (2001) did a holistic assessment of risk by taking into account the socioeconomic fragility and the context's lack of resilience; Davis (2004) incorporates adaptive capacity in his model since capacity development can play a fundamental role in minimizing the scale of disasters; Jordaan (2006) proposed a model to evaluate the risk of agricultural drought considering the hazard's characteristics (probability, severity, and intensity) and three types of vulnerability (economic, social, and environmental); Ortega-Gaucin *et al*. (2018b) developed a methodology to determine municipal indices of hazard, vulnerability, and risk due to drought, by evaluating the hazard based on historical meteorological records from Mexico's National

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Meteorological Service (SMN) and considering four types of vulnerability (economic, social, environmental, and overall); and Ortega-Gaucin *et al.* (2021) proposed a method to calculate agricultural drought risk by considering its three essential components: hazard, exposure and vulnerability to drought. Table 9 presents the formulas of the mentioned mathematical models.

Table 9. Most common mathematical models are used to calculate risk.

Author	Formula	Description
Yen (1971)	$R = 1 - P(X \leq x)^n$	Where: *P (X ≤ x)* is the cumulative probability, and n is the number of years, assuming stationary and independent extreme events
UNDRO (1979)	$Rt = E\ x\ RS = E\ x(A\ x\ V)$	Where: *Rt* = Total risk, *E*= Exposure, *Rs*= Specific risk, *A*= hazard, *V*= Vulnerability
Cardona (1985)	$Rie = f(Ai, Ve)$	Where: *Rie* = Risk, A_i= hazard, V_e= Vulnerability
Schneiderbauer and Ehrlich (2004)	$R_{ahd} = H_{ahd} x\ E_{ad}\ x\ V_{ahd}$	Where: R_{ahd}= Risk, *E*= Exposure, *V*= Vulnerability, *"h"* = type of hazard, and *"a"*= geographical region affected by hazard *"h"*, *"d"*= a given

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Author	Formula	Description
		day within the period during which the disaster occurs
Cardona (2001)	$R_T = R_F(1 + F)$	Where: R_T is the total risk, R_F is the physical risk, and F is a coefficient of aggravation —or impact— that depends on socioeconomic fragility *FS*, and the context's lack of resilience *FR*
Davis (2004)	$R = \frac{V\ x\ H}{CA}$	Where: *R*= Risk, Vulnerability, *H*= Hazard or threat, *CA*= Adaptive capacity
Jordaan (2006)	$R = (H / C_H)\ x \left[\frac{\sum(V_{econ} V_{env}\ V_{soc}}{\sum(C_{econ}\ C_{env}\ C_{soc}}\right.$	Where: = *()*, with*:* = Probability of occurrence of a drought of certain magnitude (severity), H_s = Severity of drought *H*, = *( ),* = Drought intensity and H_d = Duration of Drought *H*, = *1*, V_{econ}= Economic vulnerability, V_{env}= Environmental vulnerability, V_{soc}= Social vulnerability, C_{econ}= Capacity to deal with economic vulnerability, C_{env}= Capacity to deal with environmental

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Author	Formula	Description
		vulnerability and C_{soc}= Capacity to deal with social vulnerability
Burg (2008)	$Riesgo(R) = V + H$	Where: *V*= Vulnerability and *H*= Hazard or threat
Ortega-Gaucin *et al.* (2018b)	$IR = Px\ IVG$	Where: *IR* is the drought risk index; *P* is the drought occurrence probability (drought hazard), and IVG is the overall drought vulnerability index (described in Table 8)
Ortega-Gaucin *et al.* (2021)	$DRI = \frac{DHI + DEI + DVI}{3}$	Where: *DRI* is the agricultural drought risk index; *DHI* is the drought hazard index; *DEI* is the drought exposure index; y *DVI* is the drought vulnerability index

Source: Developed by the authors.

In general, all the mathematical models described above use the hazard or threat and vulnerability variables as essential components of drought risk, including exposure as an independent variable in some cases. In recent years, the most accepted and used mathematical formula considers risk as a product of hazard (represented by the probability of

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occurrence of a drought of certain severity), exposure, and vulnerability (measured by socioeconomic and environmental indicators), as can be observed in the studies by Carrao *et al*. (2016), Frischen *et al*. (2020) and Meza *et al*. (2020), among others. This is in line with the concept of risk proposed by the IPCC (2014), which is widely accepted and disseminated in the current scientific community.

Considerations

As we have seen in this study, a wide range of approaches, methods, and tools exist to determine the components of drought risk. The results of an extensive literature review produced in different parts of the world have been summarized here. Systematically reviewing and compiling the different methods can help adapt and improve the assessments' effectiveness. Although there are many methodological approaches and options, the truth is that there are no universally applicable methods to conduct these assessments since the drought phenomenon depends on many contextual factors whose effects are different in each case.

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According to the United Nations Convention to Combat Desertification (UNCCD), the United Nations Food and Agriculture Organization (FAO), the Global Water Partnership (GWP), and the World Meteorological Organization (WMO), in order to improve assessments of vulnerability and drought risk, decision-makers and public policymakers could take into account the following aspects (UNCCD/FAO/GWP/WMO, 2019):

- Adopt a proactive approach to conducting assessments before the drought crisis happens.
- Recognize that drought is often a recurrent phenomenon that interacts with other hazards and can be exacerbated by water and terrestrial resource management patterns.
- Use available assessment methods to promote inclusive, cross-sectoral, and multi-scale vulnerability and risk assessment approaches at the community and watershed levels.
- To learn by trial and error and to review based on the experiences of others, which methods are the most adequate to encourage participation in vulnerability assessments of different social groups.
- Analyze where and how scattered data should be collected, analyzed, and protected.
- Document assessment successes and failures, including cases in which drought impacts were more or less severe than anticipated by prevailing climate conditions.

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- Learning from the experiences of others by participating in coordinated international knowledge exchange and advocating for the use of these processes, including review, validation, documentation, and dissemination.

Anticipating the results of an event that has not yet happened can be difficult, but its effects are well known in the various drought-affected regions. In these areas, vulnerability and risk estimations are informal and continuous processes that are part of the popular culture. Integrating and coordinating these informal estimates with formal and well-documented collective assessment processes involving civil society organizations, local and federal governments, and other institutions can create a more extensive shared understanding and provide a promising basis to share and manage risk at all levels.

Conclusions

Reducing drought risk and its direct and indirect impacts have become a global priority, shown by the increasing number of approaches, methods,

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and assessment tools published over the past decades. Efforts to reduce drought impact should be based on a solid understanding and a reliable characterization of the phenomenon leading to accurate assessments for decision-making and public policy implementation aimed at achieving that goal. Although progress has been made over the past years to develop better methods and tools to characterize individual risk components, much remains to be done in this regard. The present study has shown the great diversity of concepts and methods for this purpose, none of which applies to all circumstances. Each specific context requires determining the most appropriate approach depending on the adopted focus, available information, and purpose of the assessment. With the information provided here, researchers and evaluators have an overview that can be used to carefully examine these points and choose the theoretical framework and method that best fits the context of their study or, failing that, develop or adapt their own conceptual and methodological proposal.

However, regardless of the concepts or mathematical models used to evaluate drought risk and its components, attention to the effects of the phenomenon should be based on a proactive approach to risk management, the continuous planning and design of strategies (structural and non-structural measures) to be implemented before the occurrence of drought to prevent and mitigate the level of risk exposure and, consequently, the vulnerability to its impacts.

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