Estimation of Vulnerability and Risk to Meteorological Drought in Mexico

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ABSTRACT

Prolonged droughts severely affect the economic, social, and environmental sectors in Mexico. The interest in reducing the costs of drought is now focused on prevention by means of vulnerability reduction. The present study proposes a methodology to estimate vulnerability and risk to drought, considering the physical, economical, and social factors that make regions of Mexico prone to experiencing hydrological and agricultural droughts. Recognizing that there is no universally accepted way to describe vulnerability, the proposed method defines the object under study, the natural hazard, and vulnerability factors by means of indicators. The vulnerability factors are related to water infrastructure, the condition of aquifers or water reservoirs, the levels of wastewater treatment, water productivity in agriculture, hydraulic infrastructure, and water tariffs. A drought vulnerability model for each Hydrological Administrative Region (RHA) in Mexico is obtained by combining the vulnerability indicators. The product of vulnerability and hazard results in risk estimates that are compared with impact data to validate the approach. Information on agricultural or hydrological drought is used as impact data. The validation process is an important step in the methodology, since it allows examination of the causes of disasters by the vulnerability factors and leads to risk management strategies. It is found that although vulnerability to meteorological drought in the agricultural and hydrological sectors in Mexico has decreased in recent years, the drought risk is still high and results in severe economic losses, such as those registered in central and northern Mexico during the 2011–12 prolonged drought.

1. Introduction

Droughts are one of the major climatic hazards around the world. Their impacts range from reductions in water supply to famine and even death. Frequently, responses to drought are oriented to optimize the use of water in households, agriculture, livestock, and industry, or to increase water storage capacity and distribution infrastructure (UNISDR 2011). Public policies have been developed to reduce the magnitude of drought impacts in countries like the United States, Australia, and South Africa (Wilhite and Rhodes 2005; Howden et al. 2014; Wilhite et al. 2014). Most of them focus on the postimpact interventions mainly by means of economic assistance to those affected by severe water deficit. There are also programs intended to reduce vulnerability by means of prevention, using early warning systems with improved seasonal forecasts and drought risk awareness and education (Wilhite et al. 2014; Steinemann 2014). But even with recent advances in the understanding and prediction capacity of climate variability (CLIVAR 2011), risk to drought appears to be reaching critical levels more frequently (UNISDR 2013). This appears to be related to increased vulnerability rather than signals of climate change (Liverman 1990; Burton et al. 2002; ISDR 2003; IPCC 2012). Therefore, international programs like the National Drought Management Policy initiative (WMO and GWP 2014) promote the creation of public policies and strategies to face droughts based on vulnerability analysis and risk management.

Meteorological droughts in arid and semiarid regions have resulted in significant losses in the agriculture and livestock sectors. The impacts of drought may even lead to migration and abandonment of subsistence activities (Feng et al. 2010), as in central-northern Mexico (García 1993; Magaña and Neri 2012). The 1998–2002 hydrological drought, for instance, resulted in difficulties for
Mexico in complying with the 1944 Mexico–U.S. Water Rights Treaty (Sánchez 2006). Even short-term (seasonal) droughts associated with El Niño–Southern Oscillation have had negative consequences, mainly in rain-fed agriculture and for control of forest fires (Delgadillo et al. 1999).

During the 2011–12 prolonged drought, one of the most severe and damaging in recent decades, 86% of Mexican territory experienced a severe water crisis (SMN 2011). Reports indicate that the drought affected around 310,000 people in the agricultural and cattle ranching sectors, 800,000 agricultural hectares, and 1.3 million head of livestock (CENAPRED 2013). Economic losses exceeded $1.2 billion (U.S. dollars) in the agriculture sector alone (Langner 2012). Additionally, insufficient municipal water supplies resulted in substantial reductions in the water provision service for more than 2000 communities, approximately 2 million people (DOF 2012). Some states were more severely affected than others, which had to do with the level of preparedness and vulnerability to drought. Most governmental actions against drought focused on providing financial assistance to those affected in the agricultural and cattle ranching sectors. The severe impacts of the recent drought event led the Mexican authorities to launch the National Program Against Drought (Programa Nacional contra la Sequía, also known as PRONACOSE; Korenfeld Federman et al. 2014). This program requires identifying effective actions aimed at managing drought risk by reducing vulnerability factors.

An adequate characterization and quantification of vulnerability may serve to reduce the hazard-oriented perspective of disaster risk management and may help to better understand the causes of disasters (Hewitt 1983; Maskrey 1993; Lavell 1996). However, there are no universally accepted methodologies to characterize and quantify vulnerability (Birkmann 2006; Eakin and Luers 2006; Cardona et al. 2012). By looking at various approaches aimed at quantifying vulnerability, one can construct a methodology based on the use of indicators that can be combined into a single index to represent the dynamical and multifactorial essence of vulnerability. The drought vulnerability index may also serve to guide the definition of measures aimed at reducing vulnerability and managing risk and, consequently, to reduce the socioeconomic and environmental costs of drought (Dessai et al. 2003; Birkmann 2006).

The main goal of the present study is to propose a methodology to evaluate vulnerability and risk to meteorological drought in a quantitative manner that can explain the spatial and temporal contrasts in the hydrological and agricultural droughts in Mexico. The paper is outlined as follows: the conceptual framework to quantify vulnerability and risk to drought is presented in section 2. The methodology proposal is described in the section 3. The application of the methodology to determine vulnerability and risk to drought at a regional level in Mexico is presented in section 4. Conclusions are given in section 5.

2. Conceptual framework

a. Vulnerability and risk assessment

Various methodologies have been proposed to characterize and evaluate vulnerability in the disaster risk and climate change fields (Downing 1990; Cutter 1996; Turner et al. 2003; UNDP 2004; Luers 2005; Eakin and Luers 2006; Cardona et al. 2012). Most approaches are based on the description of the socioeconomic factors that make a sector vulnerable (Blaikie et al. 1994; Cutter et al. 2000; Kelly and Adger 2000). Others propose to estimate vulnerability as a function of exposure, adaptive capacity, and sensitivity (Luers et al. 2003; IPCC 2007; O’Brien et al. 2008). The United Nations International Strategy for Disaster Reduction (UNISDR 2004) defines vulnerability as “the conditions determined by physical, social, economic and environmental factors or process, which increase the susceptibility of a system or community to the impact of hazards.” This is the approach we follow in the present study, since it allows for examination of a broader spectrum of vulnerability factors, which in turn can be represented as indicators and, later on, as indices (Carreño et al. 2004; Birkmann 2006; Cardona 2006; UNISDR 2009; USAID 2014).

A vulnerability assessment is adequate as long as it serves to estimate risk that, in turn, explains disasters in their spatial or temporal context. Therefore, it is necessary to analyze whether the vulnerability description serves to obtain risk assessments that compare well with recent impacts. Risk may be defined as the interaction between a potentially damaging event (hazard) and the vulnerable conditions of a society or element exposed (UNISDR 2004; Grossi and Kunreuther 2005; IPCC 2007; Cardona et al. 2008; UNISDR 2011). We consider that risk is actually the element that serves to estimate the chances of a disaster, and consequently, it may be compared with impact data. If risk and recent impact data are coherent, the vulnerability estimates (i.e., the vulnerability model) capture the contexts in which the hazard (e.g., meteorological drought) results in disasters. The validation of the risk estimates is crucial to determine if the vulnerability model modulates the magnitude of the impacts. Only a few studies validate their vulnerability models by comparing risk and impact data. The present methodological proposal considers the evaluation of risk to be a crucial step.
b. The concepts of hazard and hazard event (meteorological droughts)

Weather and climate events outside of their normal range of variability are natural hazards whose magnitude or frequency may result in disasters in vulnerable regions. Meteorological or climatic hazards are usually given in terms of probability, calculated from historical data. Hazard probability changes with climate change; for instance, extreme weather phenomena have become more frequent in recent decades (Aguilar et al. 2005). However, it is not clear if this is the case for meteorological drought (Méndez and Magaña 2010; Sheffield et al. 2012). The chances of a meteorological drought (i.e., the hazard) as a recurrent condition that results in agricultural or hydrological droughts (i.e., the impacts) may be characterized in terms of probabilities. Hazard (probability) times the vulnerability (index) results in risk (probability of a disaster). In the present case, disaster corresponds to a hydrological or an agricultural drought. Risk among regions may be compared to determine if higher (lower) risk matches the observation of higher (lower) frequencies of disasters.

On the other hand, historical events of drought are actual manifestations of a hazard. They had a magnitude and duration that was measured as a precipitation deficit for particular years. When the magnitude or duration of a drought is described for a specific time, it is an actual manifestation of the hazard, and it can be called a hazard event. When vulnerability and hazard event information are combined, risk is given as an actual (deterministic) value that should be proportional to the impact. The use of a hazard event concept allows evaluation of risk to be compared with actual information about impacts and examined to see if there is coherence between the two signals. A similar type of drought in two different time periods may have different impacts depending on the vulnerability context, which modulates the magnitude of the impact. We will refer to the actual manifestations or specific events of drought (on a yearly basis for instance) as a hazard event.

c. Hydrological and agricultural droughts

Hydrological or agricultural droughts correspond to the impacts of a meteorological drought in a context of vulnerability. Their magnitudes may be the result of a severe precipitation deficit or large vulnerability conditions. For example, at La Boquilla Dam in Chihuahua in northern Mexico, water levels vary, slightly lagging annual precipitation (Fig. 1). Years with negative (positive) precipitation anomalies in the region result in low (high) dam levels in the following season or year. In this case, meteorological droughts are the main driver of hydrological droughts as in the 1950s or 1990s. However, hydrological droughts may also be the result of a high vulnerability context, particularly related to inadequate water management practices (Ortega-Gaucin 2012). In the San Fernando River in Tamaulipas in northeastern Mexico, hydrological droughts—determined, for instance, by low streamflow—may occur even when precipitation remains within its normal range of variability, as in the late 1980s (Fig. 2). Here, vulnerability related to inadequate water management practices is the key element in explaining hydrological droughts.

3. Proposed methodology to quantify vulnerability and risk

To examine the risk of hydrological or agricultural droughts in Mexico, a methodological framework to quantify vulnerability is proposed. It includes a characterization of the elements of the study, the quantification of the vulnerability factors, the development of risk...
estimates (model), and a validation of the risk model (Fig. 3).

a. First phase: Vulnerability characterization

In the first phase, it is necessary to define what is vulnerable. It may be a region, a social group, or a socioeconomic sector. In each case, one should have in mind what aspect of the object under study may be affected by the hazard. This is related to recent impact measures used as reference. Therefore, it is necessary to determine the natural phenomenon defined as the hazard and characterize it. The characterization depends on the probability of occurrence (hazard) or its magnitude, or its occurrence in specific times (hazard event) that leads to impacts at a particular time in recent years. For instance, drought as a hazard may correspond to the chances of net precipitation less than 140 mm yr\(^{-1}\) in the Baja peninsula (around 25% in the 1900–2010 period). This threshold of precipitation is estimated as the minimum required for having enough water for various sectors in the region. The hazard event corresponds to the times in recent years when this condition (<140 mm yr\(^{-1}\) of precipitation) has been met.

In the latter part of this phase, it is necessary to determine some of the main factors that make the object under study vulnerable. They correspond to physical, social, or economic conditions that show high- and low-frequency variations and vary from one region to another. This implies that in the risk management process, a measure aimed at reducing a vulnerable factor with dominant low-frequency variations may take time to show, but it may be more robust than targeting a factor with high-frequency variations (i.e., that is “flexible”) since it may easily change from one year to another.

b. Second phase: Vulnerability estimation

The second phase of the process characterizes vulnerability factors by means of data or indicators. The Organization for Economic Cooperation and Development (OECD 2003) defines an indicator as a “parameter, or a value derived from parameters, which points to, provides information about, describes the state of a phenomenon/environment/area, with a significance extending beyond that directly associated with a parameter value.” The combination of various indicators represents the multifactorial characteristic of vulnerability. There are no generally agreed upon rules for the construction of vulnerability indicators (Tate 2012). Thus, a vulnerability index may simply be the result of averaging indicators. It is advisable to select clear, robust, representative, and easily understandable indicators to make them meaningful to public policy makers (Carreño et al. 2007; OECD 2008; USAID 2014). Indicators may describe aspects of the population (e.g., population density), economy (e.g., poverty levels), or physical conditions (e.g., land use changes). It is advisable that indicators, constructed from data,
express a condition of the object of study for a period to observe how they change in time.

Once the indicators are identified, they are normalized so they can be compared with each other and aggregated into an empirical–quantitative expression of vulnerability. The normalized indicators for each region (\( Vr \)) are constructed with the following equation:

\[
Vr(t) = \frac{a_i(t) - \min(\alpha)}{\max(\alpha) - \min(\alpha)},
\]

where \( a_i(t) \) is a vulnerability factor (indicator), as a function of time \( t \), and \( \max(\alpha) \) and \( \min(\alpha) \) are its maximum and minimum values. Therefore, \( 0 \leq Vr \leq 1 \) where the lowest (highest) vulnerability values are 0 (1).

A weighted average of normalized vulnerability indicators results in an average or compound vulnerability index (\( VI \)):

\[
VI(t) = \frac{\sum_{i=1}^{n} wiVr(t)}{n},
\]

where \( n \) is the number of indicators and \( wi \) is the weighting factor that represents the importance of vulnerability factor \( i \) in the average or compound vulnerability index. The weights for every indicator may be adjusted until an adequate fit between risk and impact data is reached. For instance, a hydrological drought may require giving more weight to the condition of the aquifers and pollution levels than those factors related to agricultural drought.

c. Third phase: Risk quantification

The third phase corresponds to risk determination by combining vulnerability and hazard information. This relationship is described as

\[
\text{Risk} = \text{Hazard} \times \text{Vulnerability}.
\]

If hazard (probability) information is used, a risk value (probability) for the entire period of time and a given region or sector is obtained. Risk estimates between regions may be compared to determine if the higher risk regions or sectors correspond to regions where disasters are more frequent or with higher magnitude.

d. Fourth phase: Risk model validation

The fourth phase corresponds to the comparison of risk and impact data. Risk estimates obtained with event hazard information may be compared with time series of impact activity or magnitude to determine if vulnerability actually modulates impacts (frequency or magnitude). This is an indirect form of validating vulnerability

4. Risk and vulnerability to meteorological drought in Mexico

a. First phase: Vulnerability characterization

Meteorological droughts (hazard) may be described in terms of negative values of the so-called standardized precipitation index (SPI; McKee et al. 1993; Keyantash and Dracup 2002). Méndez and Magaña (2010) have found that prolonged meteorological droughts extend to spatial scales of thousands of square kilometers and are adequately represented with SPI-12. The Hydrological Administrative Regions (RHAs) of Mexico (Fig. 4) approximately correspond to large basins. For each RHA, a group of water stakeholders defines water management policies. The Climate Assessment for the Southwest (CLIMAS) group has worked with some of these stakeholders on binational water activities (Wilder et al. 2010). There are subdivisions of the RHAs into subbasins, but information to document the impacts of drought or the vulnerability factors is not always available at these finer scales.

Several factors make RHAs vulnerable to meteorological drought (e.g., Breña 2004; Jiménez Cisneros et al. 2010), including increasing demands for water that frequently exceed water availability; overexploited aquifers and salinity intrusion in coastal aquifers; low wastewater treatment levels; low water prices relative to its actual economic value; low agricultural water productivity; and insufficient, obsolete, or inoperative water
infrastructure. Various water managers in the RHAs consider these factors as the important ones that make regions vulnerable to drought. Data representing these factors for a selected period of time were obtained from official sources, such as the Mexican Water Agency (CONAGUA), for the 2002–12 period. The drought vulnerability indicators are defined as follows.

1) PRESSURE ON WATER RESOURCES (PW)

The PW indicator shows the water consumed with respect to water availability. The economic and demographic growth in recent decades has increased the demands for water. The available water is used for agricultural activities (76.6%), for the urban water supply (14.5%), for industry (4%), and for hydro-power generation (4.9%; CONAGUA 2013). In recent years government actions have been aimed at reducing water supply and water demands. However, during periods of drought, water deficits are exacerbated, and the lack of appropriate policies frequently results in crisis in the agricultural and hydrological sectors.

2) CONDITION OF AQUIFERS (CA)

Aquifer overexploitation is one of the major problems in several regions of Mexico. According to CONAGUA (2013), 106 of 653 aquifers are overexploited. In coastal regions, seawater intrusion in aquifers is becoming a problem, mainly because of sea level rise (Moreno Vázquez et al. 2010). The recovery of an overexploited aquifer may take several years or even decades.

3) WASTEWATER TREATMENT (WT)

According to CONAGUA (2013), 47.5% of water used in the cities during 2012 was treated. This is relatively low compared to wastewater treatment levels in developed countries; in Canada this value is around 87%, in Denmark it is 90%, and in Germany it is 97% (OECD 2013). This water is not necessarily potable, but it may be used for irrigation.

4) WATER TARIFFS IN URBAN AREAS (WTU)

Only 76% of water in urban areas is charged, at an average cost of $0.30 per m³ (Sandoval Minero 2010). The total revenue for the water services is insufficient to maintain a high level of efficiency in the sector; consequently, the federal government finances most urban water services and projects (Pineda Pablos 2011). At the city level, water leakage is a common problem because of limited financial capacity. The WTU indicator makes reference to the financial deficit in the RHAs, considering that the average international price of water in urban areas is around $2.5 per m³ (OECD 2009). In Mexican metropolitan areas, the cost of water varies from around $0.14 to $2 per m³ (CONAGUA 2013).

![FIG. 4. Hydrological-Administrative Regions (RHAs) in Mexico.](image-url)
5) WATER PRODUCTIVITY IN IRRIGATION DISTRICTS (WP)

Irrigated agriculture is the largest water user. The efficiency in irrigation districts has been around 37% (Arreguin et al. 2011). However, WP is increasing in recent years thanks to the introduction of new irrigation technologies (Palerm Viqueira et al. 2010). The situation for the (rain-fed and irrigation) agricultural sector becomes critical under prolonged meteorological droughts. Rising water productivity in agriculture, instead of allowing overpumping, constitutes one of the major challenges to guarantee food security and reduce pressure on water resources at a low environmental cost (Rijsberman 2006; FAO 2013).

6) INFRASTRUCTURE AND WATER STORAGE (WS)

The 2011–12 drought in northern Mexico showed that regions with adequate water levels in dams and reservoirs managed to mitigate the impacts of precipitation deficit. Since the 1940s, the development of hydraulic infrastructure has increased. The volume of water stored annually in 172 major dams corresponds to almost 80% of the total water storage capacity of the country, which is around 150 hm³ (CONAGUA 2013). The WS indicator is calculated only for RHAs where large dams exist and takes into account the annual mean water level in the dam, since there may be several half empty dams that make a region vulnerable to meteorological drought.

In summary, six drought vulnerability factors have been considered (Table 1), represented by indicators constructed from data of CONAGUA for the 2002–12 period. Indicators for each RHA have been normalized and their temporal behavior analyzed.

b. Second phase: Vulnerability estimation

The vulnerability to drought factors continuously changes, which is apparent in the fluctuations and trends of each indicator (Fig. 5). The higher the value of the indicator, the more vulnerable an RHA is because of this factor. Regions where pressure on water resources is high usually correspond to arid regions, as in the northern part of Mexico or in regions where demands are high, as in the Mexico City region. The pressure on water resources vulnerability indicator has been increasing mainly because of higher water consumption and population increases. In some cases, the pressure on water resources remains almost constant in spite of increased demands, thanks to creation of water programs (Fig. 5a).

Most RHAs are moderately vulnerable to drought based on the condition of their aquifers. However, in several parts of northern and central Mexico, aquifers are critically overexploited and polluted. This indicator may be considered “rigid” since it takes several years for an aquifer to recover. Public policies to reduce aquifer overexploitation have been put forward but are still insufficient. Aquifer overpumping increases during drought periods, as during 2010–12 in northern Mexico (Fig. 5b).

The water deficit for irrigation may be relieved by the use of treated water (Hamdy 1992). This is not a
common practice in Mexico, as the wastewater treatment indicator shows high levels of vulnerability for most of the RHAs. The percentage of wastewater treatment and reuse is less than 20% on average. However, most regions show a slow but constant improvement (vulnerability reduction) in terms of wastewater treatment. For instance, RHA I has invested in wastewater treatment plants since the beginning of the twenty-first century, and it shows a corresponding reduction in the wastewater treatment vulnerability indicator (Fig. 5c). This indicator may also show negative changes when water treatment plans are out of order for long periods of time.

The water tariffs in the urban areas indicator relates to the financial efficiency in the RHAs. Higher water tariffs in urban areas values lead to more consciousness by citizens of the actual cost of potable water or to additional resources to maintain water infrastructure. Insufficient revenue leads to inefficiencies in the water system and reduces the financial capacity to respond to crises during meteorological droughts (Fig. 5d).

Similar to most of the world, water in Mexico is used mainly for agricultural purposes. The efficiency in irrigation practices varies from place to place, depending on the technologies available, the type of crop, standard practices, etc. (FAO 2003). Most of the RHAs have improved water productivity by establishing regulations for groundwater extraction and by using pressurized irrigation systems in large areas. However, this has not necessarily resulted in water consumption reductions since data indicate water demands in the sector remain the same or even increase. This becomes a serious

Fig. 5. Dynamic vulnerability indicators for RHAs from 2002 to 2012: (a) PW resources, (b) CA, (c) WT, (d) WTU areas, (e) WP in irrigation districts, and (f) WS capacity in major reservoirs.
problem during drought periods as low levels in dams are compensated for by increased overpumping from aquifers. The water productivity in irrigation districts provides a measure of the efficiency of water use in the agricultural sector (Fig. 5e). In the northern part of Mexico water productivity is high, but the real cost of crop production is high as well, given the energy subsidies for water pumping (Quadri de la Torre 2011).

During the second half of the twentieth century, numerous dams were built in Mexico, mostly for irrigation projects (Aboites 2009). However, the dependency of this sector on this source of water makes it highly vulnerable to prolonged droughts. Below-average dam levels may lead to crises in agricultural and cattle-ranching activities. Therefore, it is not only the existence of water reservoirs or infrastructure that reduces vulnerability to drought, but also adequate management practices. The water storage capacity in the major reservoirs indicator refers to the ratio of the mean annual volume of water stored (with respect to maximum water storage capacity) and the amount of water consumed in the RHAs. Regions with the highest water storage capacity in major reservoirs vulnerability are RHA I, RHA III, RHA VII, RHA VIII, and RHA XIII (Fig. 5f). In the Baja California region, dams have not been a solution to water scarcity since precipitation is so low that the infrastructure, such as the Abelardo L. Rodríguez Dam in the Tijuana River, fills up approximately once every decade, typically during an intense El Niño winter (Magaña 1999). In the Mexico City metropolitan area, almost 30% of water is supplied by the Cutzamala system of water reservoirs. When the Cutzamala levels are below normal, even a minor precipitation deficit may result in a hydrological drought in the Mexico City metropolitan area.

There are certainly other vulnerability factors that may contribute to explaining drought impacts in Mexico, including poverty, which may limit access to water in the agricultural sector during drought periods. For the time being, the six previously defined factors are combined into a single vulnerability index with an equally weighted average (Fig. 6). However, it is possible to use different weights for each indicator, depending on what may be the most important water use, the sector under consideration, or the impact. The time evolution of the vulnerability index can be interpreted as the context in which precipitation deficit (meteorological drought) may occur and result in a hydrological and agricultural drought (impact).

In general, drought vulnerability is decreasing, but in some RHAs it is still high, as in northern Mexico (e.g., RHA VII) or in the Mexico City metropolitan area (RHA XIII), which may be the region most vulnerable to drought in the entire country ($\bar{V}I = 0.76$). However, it is risk that matters when estimating the impacts of drought. The adequacy of the vulnerability estimate in combination with hazard information should be evaluated to compare the risk values with agricultural or hydrological drought information.

c. Third phase: Risk quantification

Some indices of drought severity, such as the North American Drought Monitor, refer to negative anomalies of precipitation and to the potential impacts in regions or sectors. But at least for Mexico, they appear to estimate the risk of agricultural or hydrological drought without an actual quantification of vulnerability. To characterize the critical magnitude of a drought (or event hazard), it is necessary to estimate the amount of precipitation that would result in insufficient water for human activities and environmental requirements. Meteorological drought information, such as the SPI-12, only gives an idea of the magnitude of the precipitation deficit that could cause agricultural or hydrological droughts, but in some highly vulnerable regions, a slight reduction in precipitation (e.g., $0 > \text{SPI-12} > -1$) may result in hydrological or agricultural droughts.

When risk is evaluated using the hazard (probabilities of negative precipitation anomalies), the corresponding water deficit should be estimated. For example, RHA I has an average annual rainfall of around 165 mm. Considering the entire area of RHA I and that a high percentage of precipitation evaporates, this amount of rain results in an average water availability of approximately 4625 hm$^3$ yr$^{-1}$. Since the water concession volume (to 2010) is 3733 hm$^3$, a rain reduction of 19% or more would reduce water availability to a critical level. Thus, an accumulated annual rainfall of 133 mm or less is considered the critical level of drought or the event hazard that results in hydrological and/or agricultural droughts. The
probability that this condition occurs (the hazard) is about 36%, (approximately SPI-12 = 1.2). In RHA I, drought risk = hazard \times vulnerability = 36\% \times 0.55 = 19.8\%.

Drought indices are important and useful elements for monitoring and assessing since they simplify complex interrelationships between many climate and climate-related parameters (Tsakiris et al. 2009). The negative SPI-12 provides information of the intensity of droughts in terms of standard deviations of the negative precipitation anomalies. If a SPI-12 of less than -1 is considered a threshold for intense meteorological droughts, then there were two prolonged drought periods in northern Mexico during for the period of analysis: around 2002 and around 2011 (Fig. 7). SPI-12 data were obtained from the Data Library of the International Research Institute for Climate and Society (IRI).

A drought risk index obtained by multiplying an annual value of SPI-12 for each RHA times its annual vulnerability for the 2002–12 period may be compared between regions or with impact information for the entire period of analysis. Risk values are in the range between 0 and 1, with 1 corresponding to intense drought and vulnerability to drought conditions.

d. Fourth phase: Risk model validation

There are at least two methods to validate the vulnerability estimates (model):

(i) Comparing risk levels between regions with an equivalent hazard. If, for the same magnitude of hazard, two regions with different vulnerabilities exhibit a proportional level of impact, then vulnerability estimates may be considered adequate. For instance, regions in northern Mexico may all experience an intense drought (e.g., SPI-12 = -2), but hydrological or agricultural droughts may be different if their vulnerabilities are different.

(ii) Examining the temporal behavior of risk and impacts. If a region experiences similar meteorological droughts in different periods of time under changing vulnerability conditions, the risk and negative impacts should reflect this change. For instance, some RHAs of northern Mexico experienced similar meteorological droughts in 2002 and in 2011, but the magnitude of the hydrological and agricultural droughts varied since vulnerability to drought changed between these periods.

Information on hydrological droughts is available in the Mexican surface water database known as BANDAS (Banco Nacional de Datos de Aguas Superficiales), obtained from the Mexican Institute for Water Technology (IMTA-CONAGUA). Hydrological droughts may also be described in terms of water storage levels in dams. On the other hand, the agricultural sector in Mexico issues seasonal reports at the state level on productivity (tons of production per hectare) and on the percentage of area affected by natural phenomena for each crop. Negative impacts in agriculture may occur from meteorological (e.g., hail storms, freezing temperatures) or climatic hazards such as drought. Agricultural drought is documented with data from the Agricultural Data Archives [Sistema de Información Agroalimentaria de Consulta (SIACON)] of the Ministry of Agriculture, Livestock, Rural Development, Fisheries and Food (SAGARPA).

The high-frequency variations of risk are usually related to interannual climate variability, while its low-frequency component corresponds to vulnerability. In general, hydrological or agricultural drought activity is related to the hazard, while the magnitude of the impact is related to the vulnerability level. In 11 of the 13 regions, the percentage of area affected by drought in rain-fed or irrigated agriculture compares well with risk levels (positive correlation). For instance, when one considers the impact of similar droughts in the RHAs, as Río Bravo (RHA VI) and Cuencas Centrales del Norte (RHAVII), the risk to drought and the percentage of area affected by drought are larger in RHA VII than in RHA VI (validating the first criterion) since vulnerability and risk to drought are smaller in the former (Fig. 8). Vulnerability in RHA VI is lower since its water storage capacity (WS) and water productivity in irrigation districts (WP) are larger than in RHA VII.

In the Yucatán peninsula (RHA XII), the magnitude of agricultural drought shows a negative trend (validating the second criterion) in relation to decreasing vulnerability (Fig. 9). Here, the agricultural sector has managed water resources more efficiently even under
drought conditions, as in 2009, mainly through improved water productivity in irrigation districts (WP). A meteorological drought in 2008 had smaller negative impacts than a similar drought in 2002 because of the reduced drought vulnerability. In 2005 and in 2008 there were also losses in the agricultural sector of this region, but they were related to other meteorological phenomena (intense winds and precipitation). Figure A1 in the appendix shows the results of all other RHAs.

Hydrological droughts are related to reductions in dam water level (Fig. 10). Data on water storage in October correspond to maximum values of water storage after the summer rainy season. They serve to estimate the impact of a meteorological drought in four of the six regions (negative correlation). For instance, in RHA VI Río Bravo and RHA IX Golfo Norte, drought risk was high in 2005, 2009, and 2011, which resulted in negative water storage anomalies (Fig. 10). Risk of hydrological drought was particularly high in northern Mexico (RHA VI) during 2011 given the severe prolonged drought. But in RHA IX, the Gulf of Mexico states, the risk was lower since the vulnerability is less than in RHA VI. This resulted in weak or no hydrological droughts in RHA IX even during recent drought periods, as in 2009 or 2011. Figure A2 in the appendix shows the results of all other RHAs.

Drought risk estimates from six vulnerability indicators in conjunction with meteorological drought information characterized by SPI-12 show a correspondence with impacts for hydrological and agricultural drought over 76% of the regions in Mexico for the 2002–12 period. There are some discrepancies between the RHA VIII and RHA X regions that may be explained by insufficient vulnerability indicators, by the averaging method used to construct the vulnerability index, and at times because of insufficient impact data. In any event, vulnerability acts as a low-frequency modulator of the magnitude of the impact.

5. Conclusions

Quantifying vulnerability to drought at the RHA level using the proposed methodology has proved to be useful in explaining the spatial and temporal contrasts for hydrological and agricultural droughts in northern Mexico in recent years, that is, the semi-arid regions, where water deficit is a constant problem. In most regions in southern Mexico, the evaluation of the risk model was complicated since the water management conditions are contrasting to those in northern Mexico in the hydrological and agricultural sectors. Therefore, the proposed vulnerability indicators work better for central and northern Mexico.

FIG. 9. As in Fig. 8, but for RHA XII Frontera Sur. Data correspond to Yucatan state. Note that in 2005 areas were affected by Hurricane Emily, and in 2008 areas were affected by strong winds from tropical wave No. 8.
A risk analysis approach to identify solutions for dealing with meteorological drought should be based on an adequate identification of the vulnerability factors. The use of seasonal climate forecasts and drought outlooks may help to define contingent actions to reduce the risk of drought and its negative impacts. The analysis of drought risk should also be useful in defining structural measures to reduce vulnerability. The identification of vulnerability factors may help to identify adaptation to climate change measures, mainly to meteorological drought.

The proposed methodology tests vulnerability factors by comparing risk estimates with impact data. This methodology focuses on meteorological drought; however, it can be applied to other natural hazards. It is found that vulnerability tends to modulate the low-frequency component of risk and disaster activity. The hazard generally corresponds to high-frequency component since it is related to interannual (or higher frequency) climate variability.

The use of hazard information in the risk assessment may serve to define structural measures against meteorological drought. On the other hand, the use of hazard value in the risk evaluation may serve to implement nonstructural risk management measures such as drought early warning systems, for instance. This approach could also prove to be useful for estimating the impacts of drought in Mexico and can serve as a guide for drought monitoring efforts, such as those in the North American Drought Monitor.

A comparison of drought risk between regions and the analysis of how vulnerability has evolved in each one of them in recent decades may serve to influence public policies in Mexico aimed at preparing for prolonged meteorological droughts, changing the tradition of responding to the disaster rather than preventing it. A more proactive practice for risk management could be to change from climate forecasts only (e.g., Lyon et al. 2012; Quan et al. 2012) to risk scenarios that include mitigation actions.

The analysis of drought at the RHA spatial scale is useful since it combines the hydrologic basin structure and the administrative decision level for planning and public policy definition. The RHA is the spatial level at which CONAGUA intends to implement the PRO-NACOSE program to reduce the impacts of drought. The vulnerability index and consequently the risk model may be further adjusted and refined to make them more adequate at finer spatial scales if necessary.

Finally, communicating risk to stakeholders is an additional challenge to implement a disaster risk management scheme (Steinemann 2014). Some initiatives, such as the NOAA-funded Regional Integrated Sciences and Assessment (RISA) CLIMAS program in Arizona, have established a significant collaboration with stakeholders in northern Mexico, which may assist the PRONACOSE efforts. Better ways of communicating risk are necessary to transform risk management proposals into actions. Exploring new avenues to better understand and communicate the potential impacts of drought should also be considered as an adaptation to climate change in arid regions (Meadow et al. 2013). The construction of drought impact scenarios following a methodology such as the one presented here could also be implemented around the world if creative ways of representing the vulnerability factors are found. As some studies show, it would be more significant if participatory consultation and expert opinion become part of the process of defining actions (Brooks et al. 2005). This requires clarity of the risk associated with drought.

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FIG. A1. Drought hazard, vulnerability, risk index, and percentage of agricultural area affected in RHAs between 2002 and 2012.
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APPENDIX

Risk Model Validation in Other Regions

Figure A1 shows the analysis of the risk index validation in agriculture drought for all regions following the representative examples shown in Fig. 8. The results in hydrological drought for additional regions are presented in Fig. A2 following the same approach as in Fig. 10.

FIG. A2. Risk of hydrological drought (solid line) and water storage levels in dams in October (bars), used as a measure of hydrological drought impacts for RHAs where data was available between 2003 and 2011.

REFERENCES


