Research Article

Municipal level water security indices in Mexico

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Abstract

As tends to be the case in other large, developing countries, Mexico is a nation of strong meteorological, hydrographic and social contrasts throughout its territory, which impact the various strata of the population in different ways. The current paper seeks to show how these contrasts create different water-security scenarios using pertinent indices. While some of the impact factors, such as precipitation, drought and floods, are of intrinsically probabilistic nature, others are related to population vulnerability. There have been a small number of studies on water security at global or regional scale that include Mexico, or at local level in Mexico, but none of them consider probabilistic aspects and population vulnerability, neither extend to municipal level. A probabilistic methodology was defined in this paper, and applied at municipal scale in Mexico, to obtain a water security index, which considers the concepts of risk, hazard and social vulnerability. Hazard comes in the form of water supply and drainage shortage, flooding, pollution, water quality, groundwater depletion and drought indicators. Vulnerability considers factors such as the educational level of the population, access to health services, illiteracy, housing conditions, unemployment and the proportion of indigenous language population. All these indicators are very heterogeneous throughout the Mexican territory. The proposed probabilistic methodology was applied in a geographic information system environment, and it was used to obtain water security indices for all municipalities in Mexico (2456 municipalities).

1 Introduction

Several definitions have been proposed for the concept of water security by different authors [4, 15, 16, 22–25, 31]. As a common denominator, the proposed definitions and their related methodologies consider the availability and access to an adequate quantity and quality of water for the population and industry, along with an acceptable level of risk from the impacts of hydro-meteorological extremes and environmental deterioration. This is particularly relevant for large countries like Mexico, with about two two-thirds of its territory in arid or semi-arid areas, which face natural water scarcity, and only one-third with very high relative water abundance. Such is its importance for Mexico that it was incorporated into the National Water Program 2019–2024 (still in discussion at the time of writing this

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paper), considering this concept as a strategic objective, through prevention, resilience and climate change adaptation actions, promoting green infrastructure for population center protection and addressing emergencies caused by extreme and anthropogenic natural phenomena [7].

Proper water management must be established in order to face the uncertainty of climate change and future socioeconomic conditions [10, 30]. Therefore, a tolerability of the risk associated with water needs to be established [17], which is linked to the social and economic environment in addition to considering the hazards to which the society is exposed. Varis et al. [32] proposed to divide water security into two groups: direct water security (which deals only with water) and indirect water security (which includes other aspects related to water).

A wide range of water-related risks undermine human well-being and can contribute to instability, violent conflicts, human displacement, migration and acute food insecurity; which in turn can undermine municipal, state, and even national security [14].

Jensen and Wu [20] divide water security in cities into four groups: resources, access, risk and governance. Other researchers [21] describe 4 fundamental issues that must be addressed: droughts, floods, governance and health; without leaving aside the need to recover, reuse and recycle water [3]. Therefore, water security is a multifaceted problem [3, 18].

Regarding water security, the United Nations Organization set out 17 Global Sustainable Development Goals (SDGs), with the goal 6 "Ensure availability and sustainable management of water and sanitation for all. It includes eight global targets, one at 2020 and seven at 2030, that cover the entire water cycle. The United Nations Statistical Commission approved the official list of global SDG indicators in March 2017, including indicators for monitoring progress in SDG 6 targets, which may be complemented by additional national, regional and thematic indicators [29]. Gain et al. [13] proposed a global water security index (GWSI), based on SDG 6, which integrates physical and socioeconomic criteria of: availability, accessibility to services, safety and quality, and management. The results of its global application include maps for each of the four criteria and for the resulting GWSI, in which the performance of each country can be identified using a scale of "0–1" values representing "low to high" condition.

Public administration in Mexico is divided into federal (nationwide), state and municipal levels. In this sense, it is desirable to have water security metrics for the states and municipalities. Several studies have been devoted to water security in Mexico. [22] analyzed the trends of demographic growth, urbanization, demand for energy and food, climate change and water management in Mexico, making recommendations with a particular focus on water security

centered on the urgency of achieving good water management. Oswald Spring [26] discussed water security in Mexico, based on social, political and economic aspects, with a focus on a national water law that favors participation in developing an integrated management model that compares the current use of water among the different social and productive sectors. Arreguín-Cortes et al. [1] pointed out that Mexico faces various water security challenges, such as pollution, climate change impact, water scarcity, management, and a need to strengthen water-related science and technology in the country. None of these authors defines and quantifies specific water security indices, however.

Water security is highly related to events that are of intrinsically probabilistic nature, such as floods, droughts and others, that affect differently the different population strata depending of their vulnerability. These, in turn, generally are heterogeneous within the Mexican territory. In the current work, a methodology is proposed and applied to derive water-security indices at the municipal level, using risk and social vulnerability indicators.

2 Methodology

2.1 Methodological framework

There is no methodology in the literature that allows to generate an indicator on water security based on a probabilistic analysis that integrates both social vulnerability as well as different hazards integrated into a single map, including drought, overexploitation of aquifers, water availability and extreme weather events. In this sense, the present work proposes for the first time such a methodology, aimed at determining geographically the municipalities that are exposed to significant number of water-related hazards, in addition to including social vulnerability, in order to stimulate social and political actions.

The proposed method is based on the information generated by public agencies in the country that is freely accessible, which allows generating hazard, vulnerability and water security maps to be regularly updated at a minimum cost. It is sought that the results obtained serve as a reference to the decision makers for the development of the most vulnerable communities, as well as identifying the areas where it is most necessary to implement public policies [8] that allow a better use of the water resource, with the purpose of increasing water security.

2.2 Probabilistic methodology for determination of the water security index

Water security is closely related to the concept of risk [17]. Risk measures biophysical and social damage that can take place inside of ecosystems and populations. Water

security shows the capacity of a society to satisfy its basic water needs, to conserve and make sustainable use of its land and aquatic ecosystems, to produce food without threatening the quality and quantity of available water resources. It also demonstrates the social and regulatory mechanisms, related to the water resources, for reducing and handling conflicts or water disputes. To establish a water security index, it is necessary to consider that, in a probabilistic sense, the risk index is the complement of the water security index and thus:

Security = 1 − Risk   (1)

Risk is defined as the contingency or proximity to harm, and can also be understood as the possibility of having significant losses or adverse results. An alternate definition can be the probability that a determined event may occur (called hazard), with consideration for the characteristics and circumstances of a town that make it susceptible to the effects that it would suffer in terms of human health, the environment, and economic activities (vulnerability).

An identical level of hazard affects the different strata of the country's population in different ways, especially municipalities, thus, in order to define the risk index for each municipality, a vulnerability index was added (in probabilistic terms) to the hazard index:

Risk = Hazard × Vulnerability   (2)

At the same time, vulnerability is expressed by a series of indicators explained below (see Table 1).

2.3 Hazard

The hazard index is quantified in terms of the probability of the occurrence of a phenomenon in a given, estimated time period, that is potentially damaging to exposed goods. To calculate the probability of the incidence and thus the hazard index, the parameters are considered according to their level of hazard. Once the index for the occurrence of each phenomenon is generated, they are summed up to obtain a hazard probability index. Using the previously mentioned criteria, the hazard calculation can be expressed in the following equation:

Hazard = (1 − GWSAI) + Flooding + Droughts + Aquifers
                                              (3)

Table 1 shows the four indicators used for hazard and the 13 used in water vulnerability. These correspond to information gathered from Mexican federal institutions which can be obtained free of charge.

2.3.1 Global basic water-service access index (GWSAI)

This index was proposed and is reported by the Mexican National Water Commission (CONAGUA). It has two components [access to drinking water (ADW) and access to sanitation (AS)] and nine variables (drinking water coverage, urban drinking water coverage, rural drinking water coverage, disinfected water, drainage coverage, urban drainage coverage, rural drainage coverage, wastewater collection efficiency, and municipal wastewater treatment coverage). This calculation was done for each municipality. To arrive at the GWSAI, first it is necessary to obtain the ADW and the AS. To calculate the first, the following was used:

- The number of inhabitants according to municipality
- The number of inhabitants with public drinking water service
- The second was divided from the first to get the ADW. The values range from 0 to 1.

The AS is made up of two parameters, one has to do with the drainage network and the other is the treatment of the generated wastewater. For the first, the following information was given:

- The number of inhabitants
- The number of inhabitants with access to the public sanitation network
- The generated wastewater (L/s)
- Installed capacity for wastewater treatment

To calculate the generation of wastewater per municipality, the first is multiplied by the second and by 0.75 (which represents the portion of wastewater that makes it to drainage). This value is divided by the value given in point 4. The resulting values range from 0 to 1.

Once the ADW and the AS are obtained, each one is multiplied by 0.5 (consideration of the weight importance), and the result is that both are added to get the GWSAI. The resulting values range from 0 to 1.

2.3.2 Floods and other extreme meteorological events

Since 2000, the National Water Commission (CONAGUA) registers and publishes officially the number of states of emergency declared in every municipality, such as cyclones, intense rains, low temperatures, strong winds, snow–frost and tornadoes according to year. This number was divided by the number of days in a year to obtain an annual value of emergency declarations per municipality. This information was standardized with a normal distribution function for its normalization:

$$F(x) = \int_{-\infty}^{x} \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{(x-\mu)^2}{2\sigma}} dx \quad for \quad -\infty \leq x \leq \infty \quad (4)$$

Table 1 Indicators that make up hazard and vulnerability

| Water-security criteria	Indicators	Temporal and spatial scale	Definition and data source
Hazard	Global basic water service access index (GWSAI)	According to municipality and year	CONAGUA, Situation of the Subsector drinking water, drainage and treatment, 2015
	Flooding	Emergency announcements (cyclones, intense rains, flooding, low temperatures, hail, snow, frost and tornado)	CONAGUA, with information from 2000 to 2016
	Aquifers	Depletion of the water table according to municipality	Mexican Institute of Water Technology, information from 2003 to 2015 (considers municipal, industry and agricultural demand)
	Droughts	Abnormally dry Moderate drought Severe drought Extreme drought Exceptional drought	Mexican Institute of Water Technology, with information from 2003 to 2017
Vulnerability	Average education level (AEL)	Data at the municipal scale	INEGI. National Institute of Statistics and Geography, with information from the 2010 census
	Number of physicians for every 1000 inhabitants (NP)	Data at the municipal scale	
	Child mortality rate (CMR)	Data at the municipal scale	
	Population without health care coverage (PWHC)	Data at the municipal scale	
	Illiteracy (I)	Data at the municipal scale	
	Homes without drinking water service (HWDWS)	Data at the municipal scale	
	Homes without drainage service (HWD)	Data at the municipal scale	
	Homes without electricity (HWE)	Data at the municipal scale	
	Homes with earthen floors (HWEF)	Data at the municipal scale	
	Economically active population (EAP)	Data at the municipal scale	
	Economically dependent population ratio (EDR)	Data at the municipal scale	
	Open unemployment rate (OUR)	Data at the municipal scale	
	Indigenous language population (ILP)	Data at the municipal scale	

where μ and σ^2 are, respectively the mean and the variance of the annual series of number of municipal emergency declarations.

2.3.3 Nationwide municipal drought hazard index

The hazard brought about by drought at the municipal scale was determined by calculating the probability of drought (relative frequency) using the Mexican Drought Monitor (SMN in Spanish) logs available on the SMN web page [28]. These probability values oscillate between a closed range of [0, 1]. With the objective of classifying these probabilities in percentiles with categories of equal size, these values were adjusted to a normal distribution.

2.3.4 Groundwater depletion

The depletion of groundwater was calculated using available data for the Mexican territory from the Gravity Recovery and Climate Experiment (GRACE) [5] which is geared towards the monthly monitoring of the temporal gravity variances that are associated with the movement of mass on the earth's surface. The results of the gravity field anomalies allow us to obtain a total value of water storage which represents the contribution of water contained in solid state (ice, snow), liquid surface (first two meters of depth on the earth's surface) and groundwater. For our study, the final product is a recovery–recharge map of water with a 1° (111.12 km) surface spatial resolution and an annual temporality. Municipal information was drawn from this using a weighted average of depletions per area
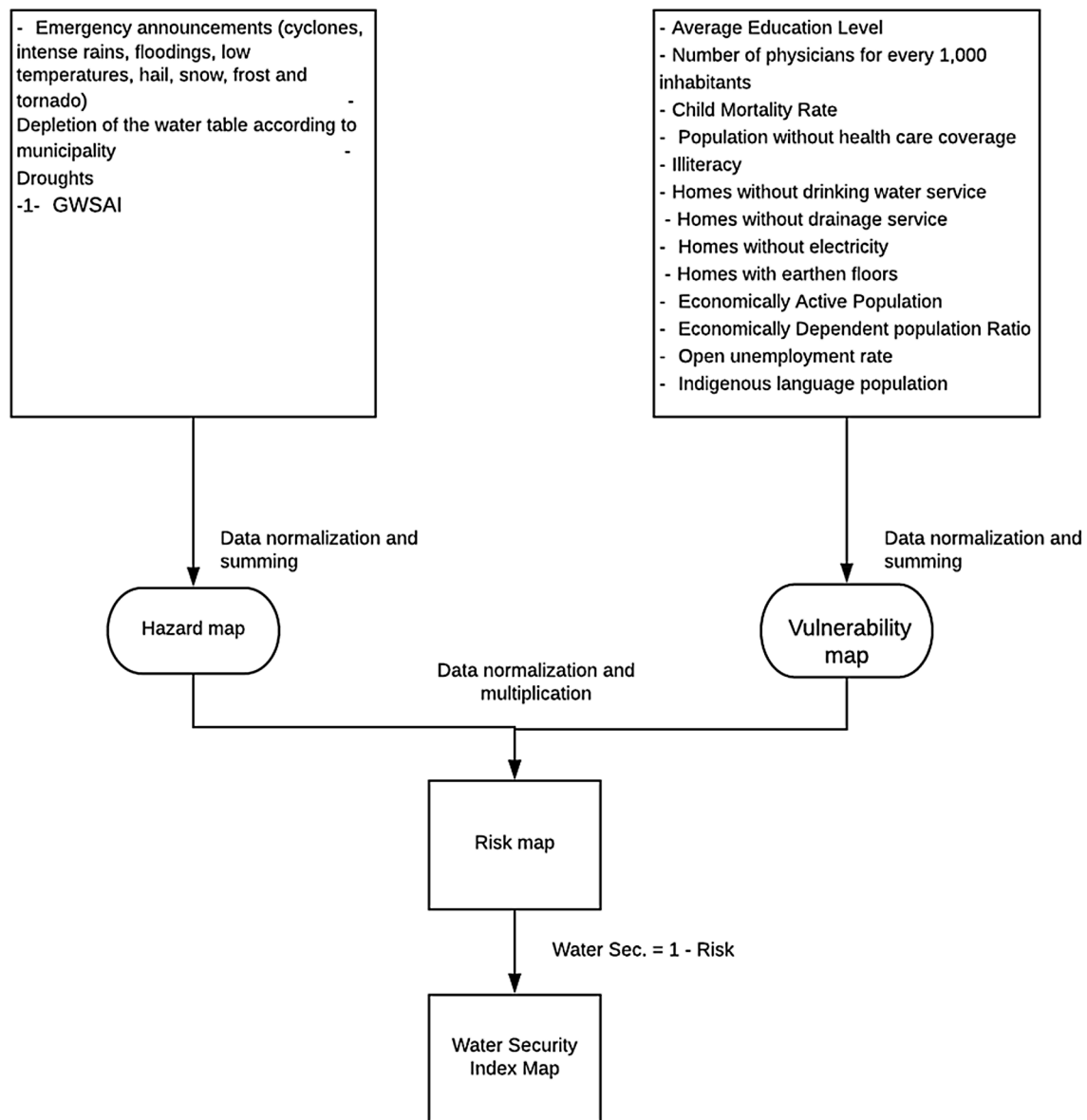
Fig. 1 Flowchart of the water security map creation

in a given basin. Following that, a normal distribution function was used to normalize data [12, 27]. With this spatial resolution, which is equivalent to an area of 12,347.65 km^2 per pixel, the surface of the country is covered by 159.78 pixels. Despite that this number of pixels is smaller than the number of the 653 aquifers existing in Mexico, the overexploitation areas identified with GRACE agree well with the 101 overexploited aquifers reported by Conagua [11]. It is of course desirable that the resolution thrown by GRACE cover a smaller area, for better detail.

Depletion data at municipal level were obtained by geographic information system processing tools,

interpolating the given raster depletion information over the municipality polygons, in order to establish an average value for each of them.

2.3.5 Integration of the hazard indicator

To create the hazard indicator, the normalized values of 1-GWSAI (the complement of GWSAI) were summed up with the flooding, aquifer depletion and drought indicators, the result of which was divided by the number of variables, which in this case is four.
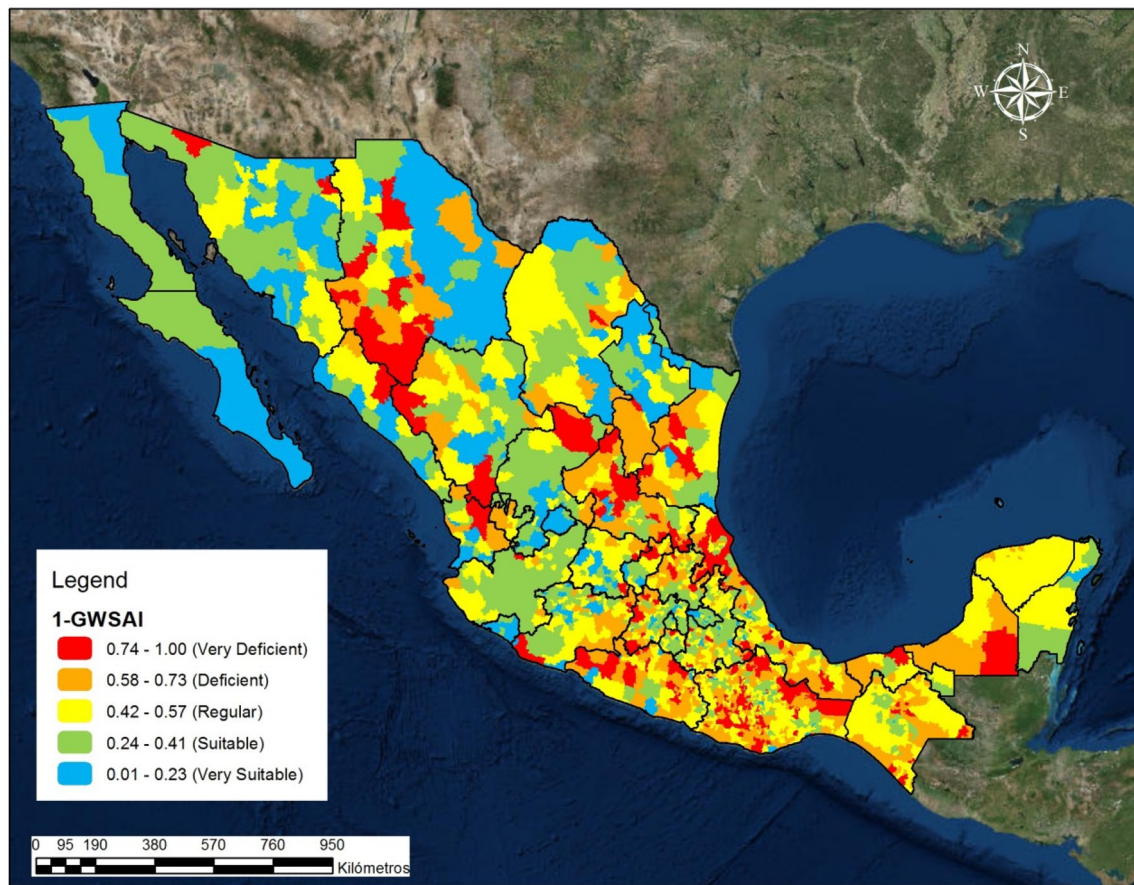
Fig. 2 1-GWSAI hazard map

2.4 Vulnerability

2.4.1 Concept of water vulnerability

The concept of water vulnerability has been well evaluated and documented by the Mexican Institute of Water Technology. The institute published an atlas titled "Atlas of Water Vulnerability in Mexico 2015 in light of climate change" [2], among other documents which go as far as the municipal level. Nevertheless, an analysis of the methodology for the generation of the related social vulnerability was carried out. The following lays out the selected method which has as a principal objective, namely, the identification of the characteristics of the population susceptible to harm either to their person or to their material goods as a consequence to some natural phenomenon. The previous is linked to the possibility of measuring the prevention and response capacity of each municipality, in other words, the degree of organization and resources set aside for emergency response. To achieve this, some indicators were chosen that allow for the identification of the primary characteristics of the population, its organizational capacity, and indispensable elements for attending to an emergency. These characteristics contribute elements for quantifying the social vulnerability associated with disasters.

The National Center for Disaster Prevention (abbreviated as CENAPRED in Spanish) defines social vulnerability as "The group of social and economic characteristics of the population that limit a society's developmental capacity; as well as its prevention and response capacity in the face of a phenomenon and the population's local perception of risk". Table 1 shows the indicators proposed by CENAPRED [6] that make up the vulnerability index. Using data available from the National Institute of Statistics and Geography (INEGI) a global social vulnerability index was calculated, based on the methodology proposed by CENAPRED [6], taking into account all the values present in the ranges of the methodology which span from very low vulnerability to very high vulnerability.
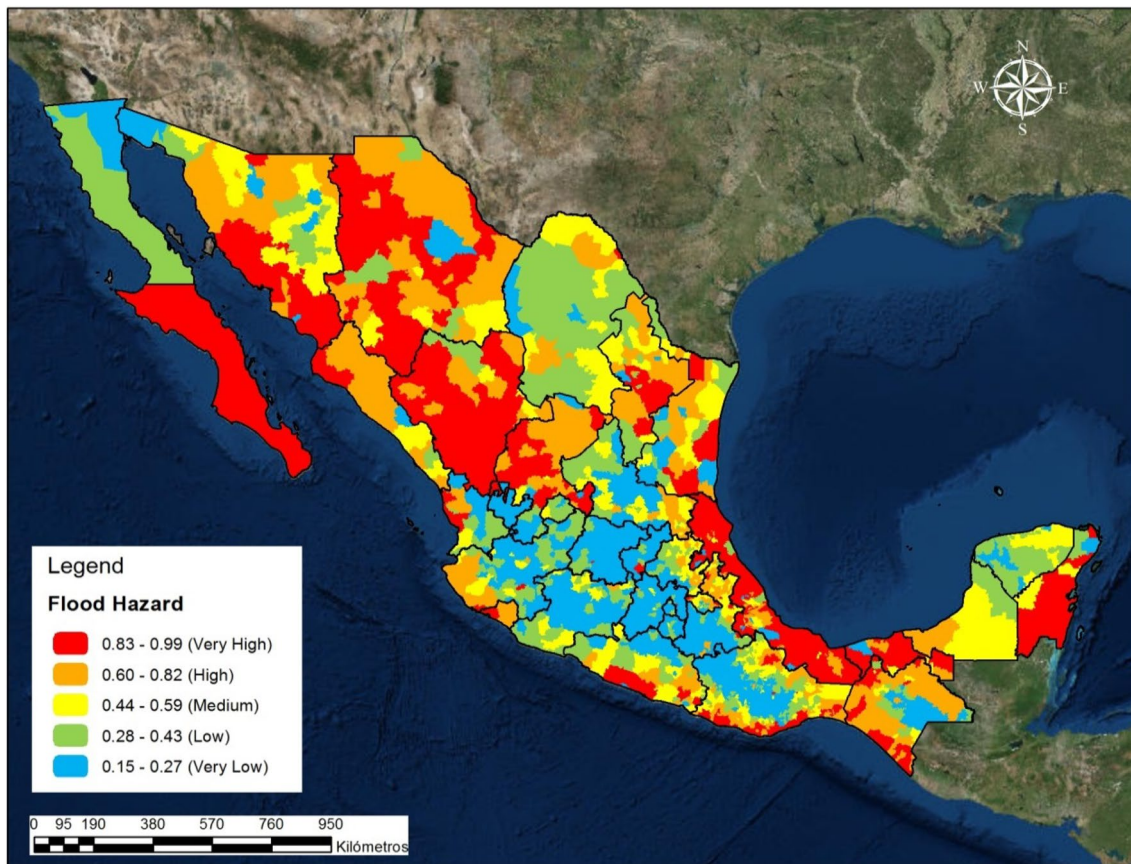
Fig. 3 Flood hazard map

2.4.2 Integration of vulnerability indicator at a municipal level

To generate a general vulnerability indicator, data was normalized and each one of the parameters was added up to obtain a global index for each municipality in the following manner:

$$Vulnerability = AEL + NP + PWHC + CMR + I + HWDWS$$
$$+ HWD + HW + HWEF + EAP + EDR$$
$$+ OUR + ILP \quad\quad (5)$$

The results from Eq. 5 for each municipality were classified to create a vulnerability indicator map.

2.5 Handling and integration of the information in a GIS

In light of the amount of data that has to be processed for the creation of the mapping of the indices, it is necessary to use a geographical information system (GIS) that permits the capture, analysis, storage, consultation and presentation of data in reference to each municipality. The process was carried out using the open QGIS platform. A multiplication of hazard and vulnerability was done for the generation of risk and lastly, the risk values were subtracted from one to obtain the water security index for each municipality (see Fig. 1).

3 Results

Figures 2, 3, 4 and 5 demonstrate the maps for each of the four hazard indicators and Fig. 6 shows the hazard index drawn for the Mexican republic.

Being a state with a high percentage of rural settlements and indigenous people, the state of Oaxaca presents a low GWSAI in 83.5% of its municipalities (476 municipalities in regular, deficient or very poor conditions in terms of access to potable water and sewerage coverage). By relative state extension, it is the state of Chihuahua, located in the north of the country, which has a greater portion with very poor GWSAI. Chihuahua is the largest Mexican state, with dry climate conditions, high population concentration in only two large cities, where
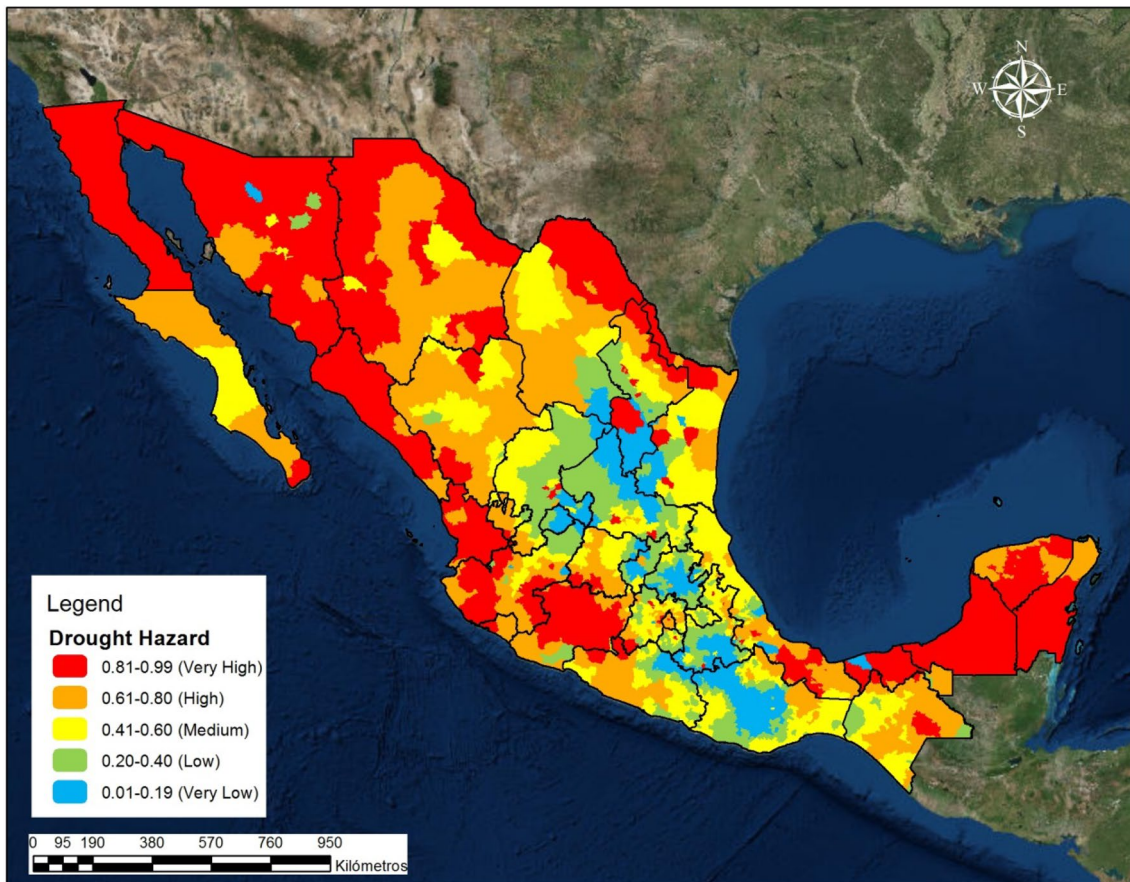
Fig. 4 Drought hazard map

GWSAI is high, and a large extension of low populated areas.

In contrast, it is the industrialized and densely populated State of Mexico, located in the center of the country, that has the best coverage of the services, followed by the states of Sonora and Sinaloa. At country level, 30% of the total has very poor and deficient GWSAI and 39.5% adequate and very adequate GWSAI (Fig. 2).

The state with the highest recurrence of extreme hydro meteorological events in its municipalities is Veracruz, with 70% of its total municipalities. With respect to their municipal extension, the states that present more extreme weather events are the state of Chihuahua (104,996.26 km^2), Durango (87,672.19 km^2) and Baja California Sur (73,277 km^2) (Fig. 3).

The affected population is 22.67 million people, located in an area of 524,923.79 km^2 and 330 municipalities.

With respect to drought, the state with the largest number of affected municipalities is Michoacán (70% of the total), followed by the northern states Baja California, Sonora, Coahuila, and the southeast peninsula that is made up of the states of Campeche, Quintana Roo and Yucatan (Fig. 4).

The largest affected municipal areas are in the states of Sonora (153,051.17 km^2), Chihuahua (131,997.46 km^2) and Baja California (71,195.53 km^2). A total of 440 municipalities have a very high degree of drought, where 25.05 million people live, in an area of 756,617.08 km^2.

By number of municipalities, the state with the highest aquifer depletion is Veracruz, with 102 municipalities, and the state with the lowest depletion is Jalisco, located in the west of the country. With regard to the area of the municipalities, the low industrialized state of Guerrero presents the lowest problems of aquifer depletion, followed by the state of Hidalgo, in contrast with the arid, but with large areas under irrigation, state of Sonora which has the highest aquifer depletion (Fig. 5).

Although the state of Oaxaca has 230 municipalities in low and medium conditions of aquifer depletion, which suggests that they have aquifer recharge, this state also has 200 municipalities that are in high depletion conditions.
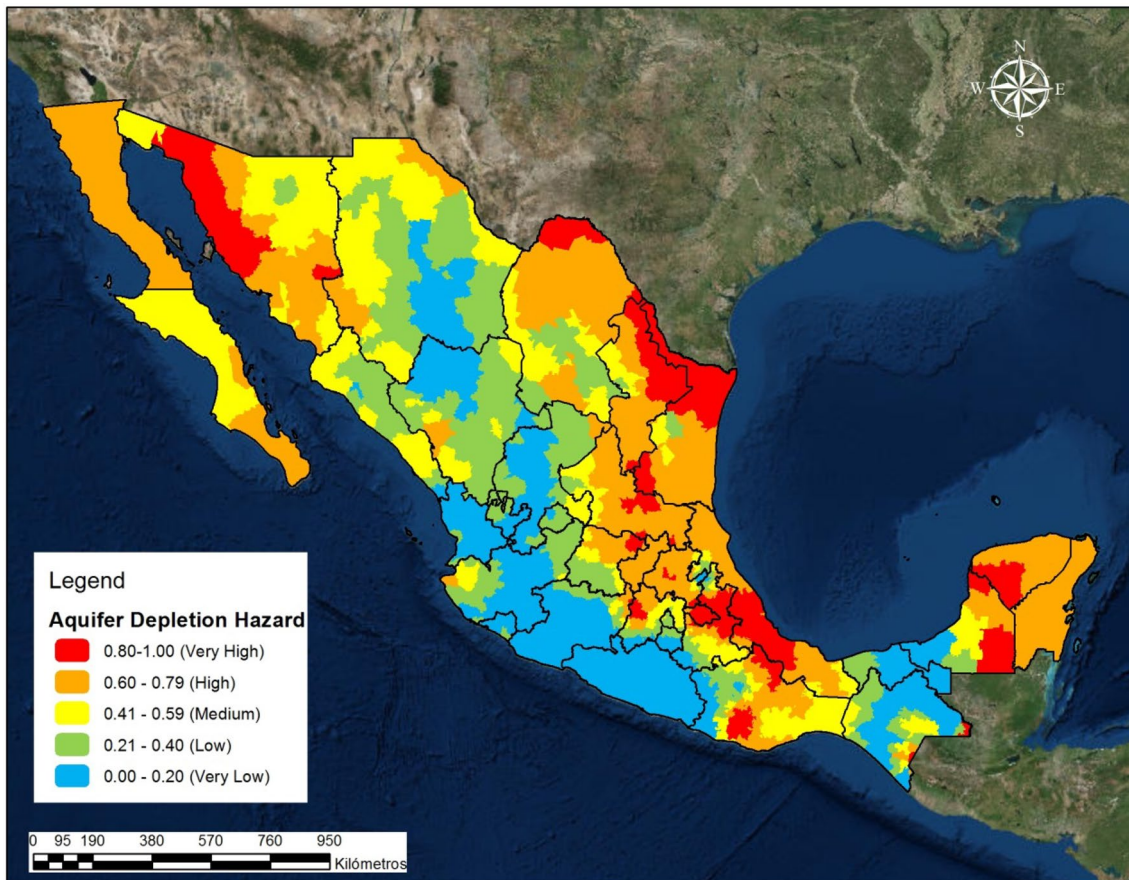
Fig. 5 Aquifer depletion hazard map

The combination of the hazard sub-indices in Figs. 2, 3, 4 and 5, with equal weights for each, provided the hazard index map for the country shown in Fig. 6. The resulting greatest hazard index state, by area, is Chihuahua (130,127 km²), followed by Durango (69,589.98 km²) and Chiapas (34,445.59 km²). A total of 205 municipalities in the country are subject to a very high hazard level, corresponding to 9.42 million people living in an area of 408,632.10 km². A total of 437 municipalities have low hazard level, located in an area of 97,526.96 km², with a population of 13.57 million people.

Figure 7 shows vulnerability in a global manner separated into municipal areas. The municipalities with the highest vulnerability index are located in the states of Oaxaca, Guerrero, Chiapas, Campeche, Nayarit, Durango, Chihuahua, and San Luis Potosi. It is known that these areas of the country present problems of access to drinking water (HWDWS), sewerage (HWD) and electricity (HWE), along with low educational level (AEL) and poor health care coverage (PWHC). All this, in addition to their low portion of economically active population (EAP), makes them the highest vulnerability municipalities in the country.

The maximum and minimum values in the maps shown above, and that of the water security index, were obtained through first by multiplying hazard by social vulnerability, then the Jenks natural breaks classification algorithm [19] was applied to obtain the best arrangement of values into different homogeneous classes. The homogenization was established in five classes for each of the maps (very high, high, medium, low and very low) in order to facilitate its visualization and interpretation.

Figure 8 demonstrates the level of risk obtained from the hazard index (Fig. 5) and the vulnerability index shown in Fig. 7. Finally, Fig. 9 shows a map of the water security index obtained for all of the municipalities of the Mexican republic. In the GIS that was created, several results were extracted, including the water security index for the 0.35 to 0.66 range that corresponds to an area of 273,480.90 km² and 240 municipalities (in red). For the range of 0.67 to 0.74 there is an area of 311,081.61 km², the area for the 0.75–0.81 range is 764,131.30 km², for 0.82–0.88 the area is 434,924.18 km², and for the final range of 0.89–0.94 there is an area of 30,268.54 km², see Table 2.
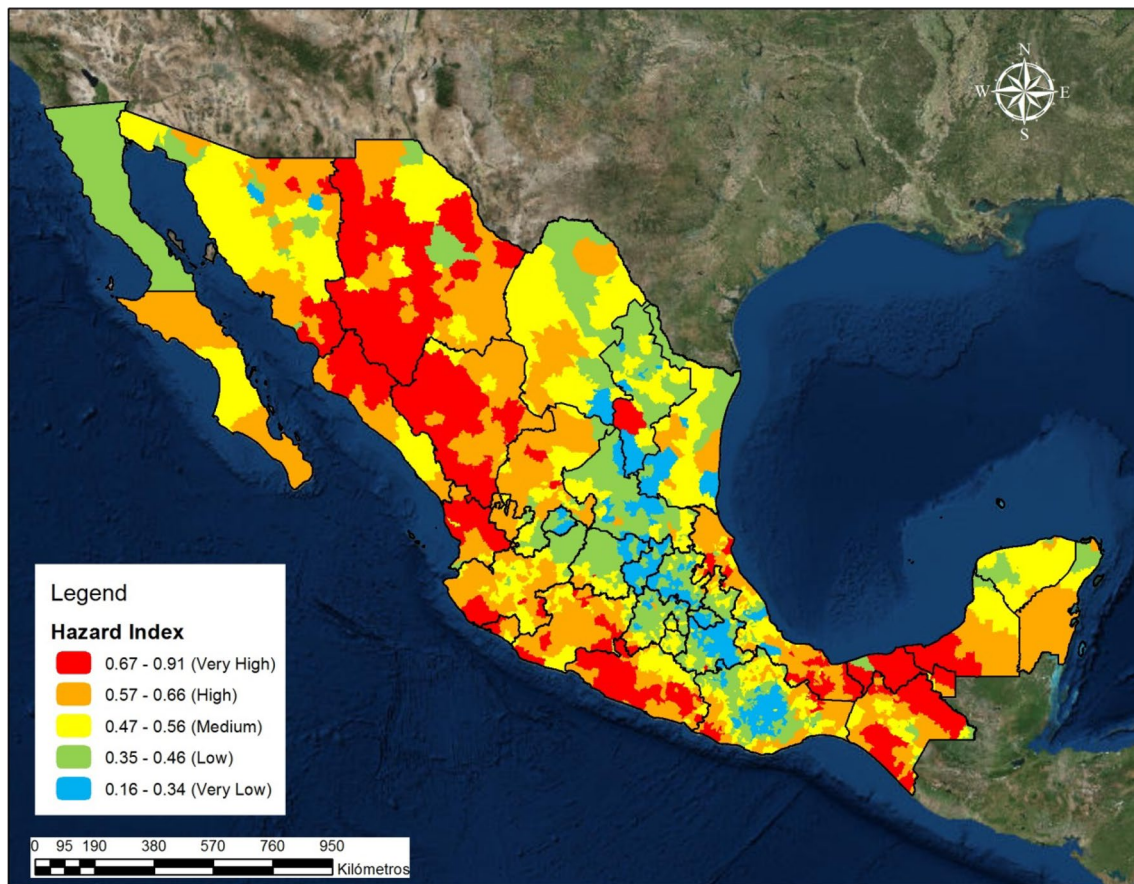
Fig. 6 Hazard index map at municipal level

Of the 468 municipalities with a water security range between 0.35 and 0.66 (shown in red in Fig. 11), those with the lowest GWSI are as follows, from least to most: Mezquital, State of Durango; Balleza, State of Chihuahua; Malinaltepec, State of Guerrero; Tlacoapa, State of Guerrero; San Miguel Totolapa, State of Guerrero; Acatepec, State of Guerrero; Del Nayar, State of Nayarit; Guachochi, State of Chihuahua; Tehuipango, State of Veracruz; Carichi, State of Chihuahua; Cochoapa el Grande, State of Guerrero; Iliatenco, State of Guerrero; Urique, State of Chihuahua; Aquila, State of Michoacan; San Luis Acatlan, State of Guerrero; Metlatonoc, State of Guerrero; Ilamatlán, State of Veracruz; Guadalupe y Calvo, State of Chihuahua; Batopilas, State of Chihhuahua; and Copanatoyac, State of Guerrero.

The municipalities with the lowest water security have the highest risk, thus this map coincides with the previous figure. Lastly, Table 2 lays out the number of municipalities, area and population according to water security ranges. As an example, there are 6,373,349 inhabitants that are in the worst situation (shown in red), which corresponds to 6.02% of the total population, and spanning an area of 273,480.90 km^2, which is 15.08% of the national territory.

4 Discussion

The states of the Mexican republic that have a higher probability of being affected by drought are those found in the northwest of the country (Baja California, Baja California Sur, Sonora, Sinaloa), in the central north (Chihuahua, Coahuila, Durango, northern part of Nuevo León and Tamaulipas), central west (Nayarit, Jalisco, Michoacán, Guanajuato), and the southeast (Tabasco, Chiapas, Yucatán, Campeche and Quintana Roo). These results coincide with historical drought logs since states in the national territory that have historically been more affected by droughts are in the Mexican highlands. These states have the aggravation of being located in zones that are characterized by being eminently arid, which is why their population and distinct economic activities are highly vulnerable amid water scarcity provoked by drought, given that in the majority of them extreme dry and semi-dry climates predominate. Although the vast majority of the most vulnerable states and municipalities that have the highest risk of drought are found in the north of the country in the Mexican highlands, even
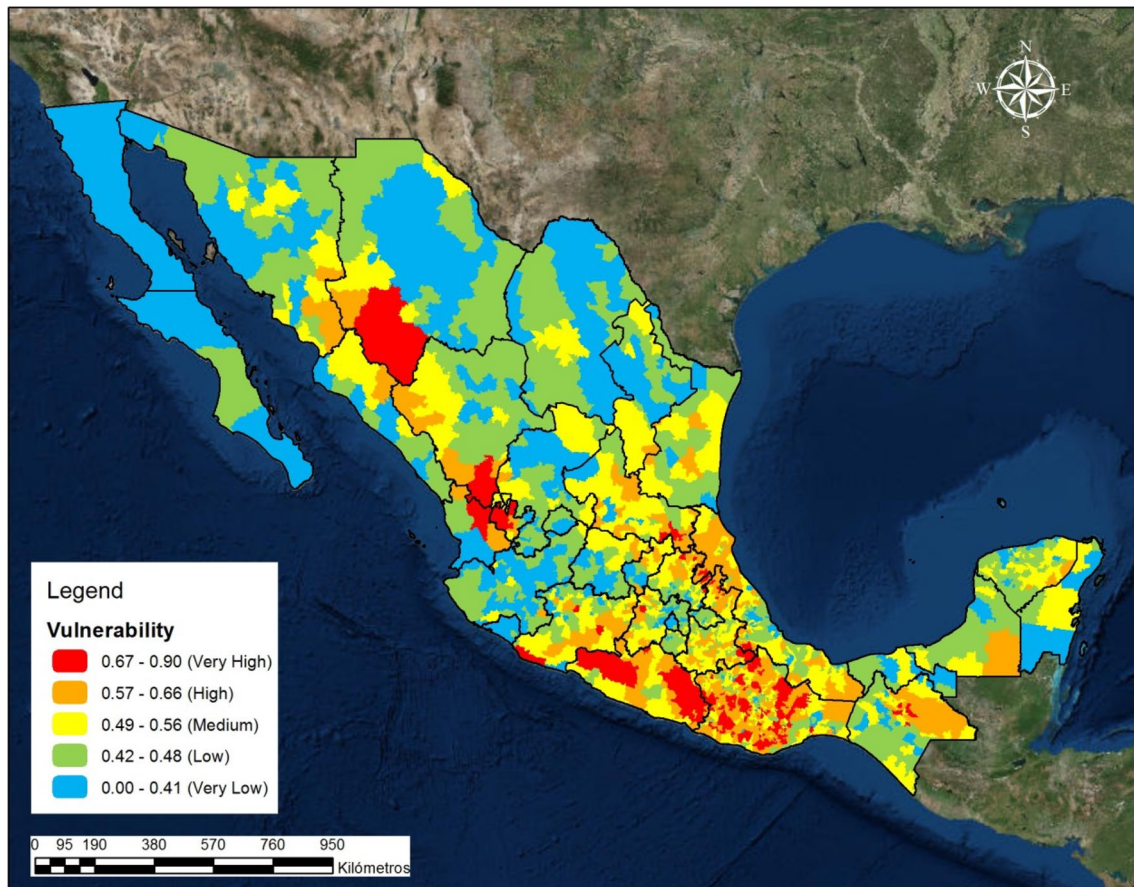
**Fig. 7** Vulnerability index at the municipal level

southern states such as Guerrero, Oaxaca, Chiapas, and Tabasco (which are characterized for being typically rainy) have municipalities that have a high degree of drought vulnerability and are also severely affected by this phenomenon, especially in those years in which El Niño manifests itself, as was the case in 2015. That year, many municipalities in Chiapas Guerrero, Oaxaca and Tabasco, mainly, were declared in a state of emergency on account of drought, and the agriculture and livestock sectors were hit with significant losses.

For result validation, the computed social vulnerability was first compared to official information from the Mexican National Council for the Evaluation of Social Development Policy [9] where four ranges of poverty in the municipalities are presented, based on the economic and social dimensions indicated in the Mexican General Law of Social Development: income, educational lag, access to health services, access to social security, quality and space of housing, basic services in housing, access to food, and degree of social cohesion. The corresponding map, presented in Fig. 10, is practically coincident with our results in the areas of greatest poverty, being the differences

between that map and the map in Fig. 7 explained by the different data sources and processing methods.

For further validation, the water security results were compared to the map presented in Fig. 11, published by the Mexican National Water Commission [7]. That map presents the most disadvantaged areas of the country, where government investment for year 2019 is essential and prioritary. The agreement is good, with some differences that probably are due to the different data fed for both maps.

In a more general way, the results were also compared to the global water security index (GWSI), based on SDG 6., obtained for Mexico by [13]. In the global world map of the availability index, integrated in turn by the water scarcity index, the drought index, and by the depletion of aquifers, the average value observed for Mexico is ≈ 0.50. The accessibility index varies between ≈ 0.69 and ≈ 0.81; the quality and protection index ≈ 0.44 in some areas and ≈ 0.25–0.31 in the rest; the management index between ≈ 0.56 and 0.63, except at the borders, and the GWSI ≈ 0.5. When comparing the map of the proposed municipal water security index (Fig. 9), with the map of the global water security index presented by Gain et al. [13], a clear
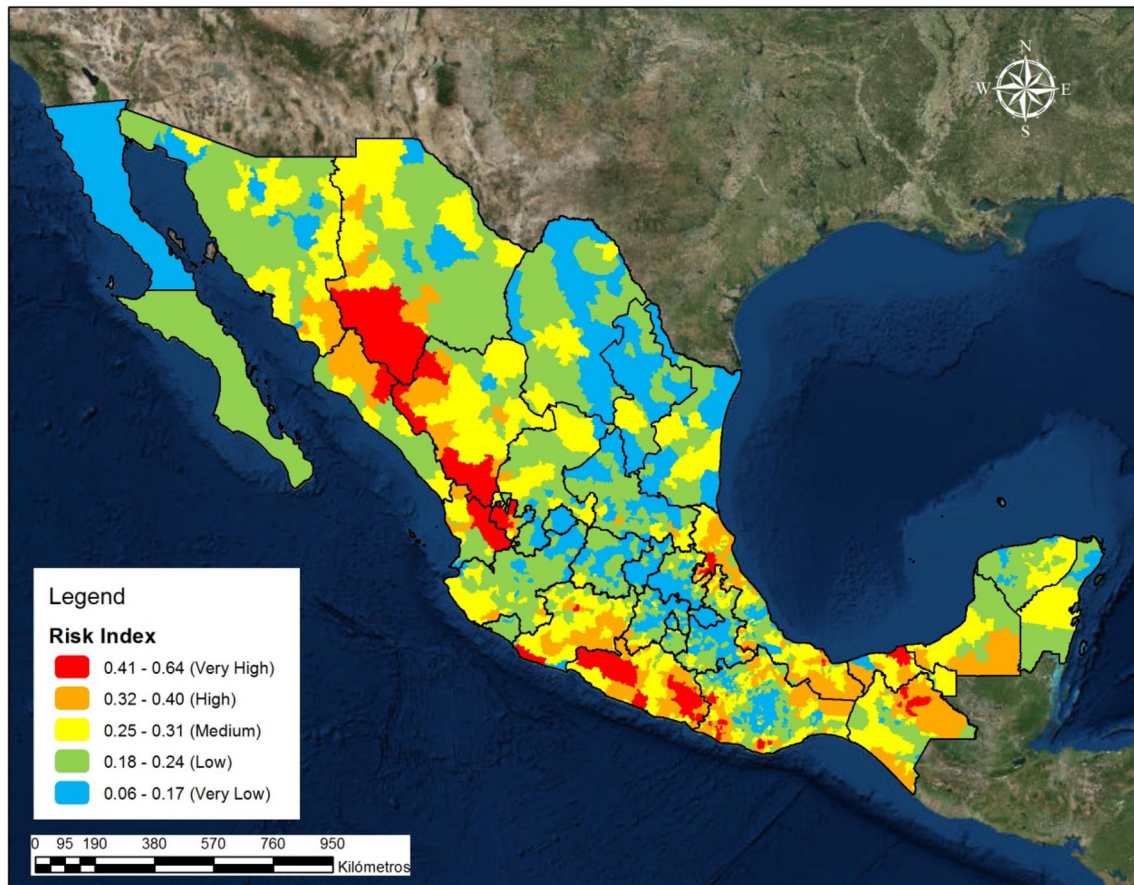
Fig. 8 Risk index at the municipal level

coincidence of low water security can be observed in the states of Guerrero, Oaxaca, Chiapas and Veracruz, as well as in a part of Sonora.

5 Conclusions

The task of reaching improved water security implies responding not only to the risks that are observed in the present but also in giving adequate responses to new challenges that are present in the sector. Known challenges to overcome in reaching water security are water scarcity, water pollution, the adverse effects of hydrometeorological events, growing water conflicts and environmental deterioration of basins and aquifers [1, 4, 15, 22–26, 31]. The methodology proposed in this paper, and applied at municipal level in Mexico, presents an option for including other topics of high concern, such as risk, hazard, and population vulnerability. These sub-assessments contribute to understanding the implications of water security, and have high potential to track changes over time to

inform integrated water resources management practice and define public policies.

The use of the proposed methodology can change the perception of which regions in a country are less or more water secure than others. As an example, the drought hazard map in Fig. 4 shows that all municipalities in the state of Baja California have a very high drought index (from 0.61 to the maximum 0.99) combined with a high aquifer depletion index (from 0.61 to 0.80, Fig. 5). This may lead to the conclusion that they are characterized by low water security. However, they also have a suitable GWSAI (Fig. 2) and a very low flood hazard index (Fig. 3), resulting in a low overall hazard index for most of the municipalities (Fig. 6). On another hand, their vulnerability index is among the lowest in the country (from 0.00 to 0.41, Fig. 7). The final result is that they are among the highest water security municipalities in Mexico (Fig. 7). In contrast, the very rainy and very low aquifer depletion Tabasco and the north of Chiapas turn out to be among the lowest water security areas of the country (Fig. 9).

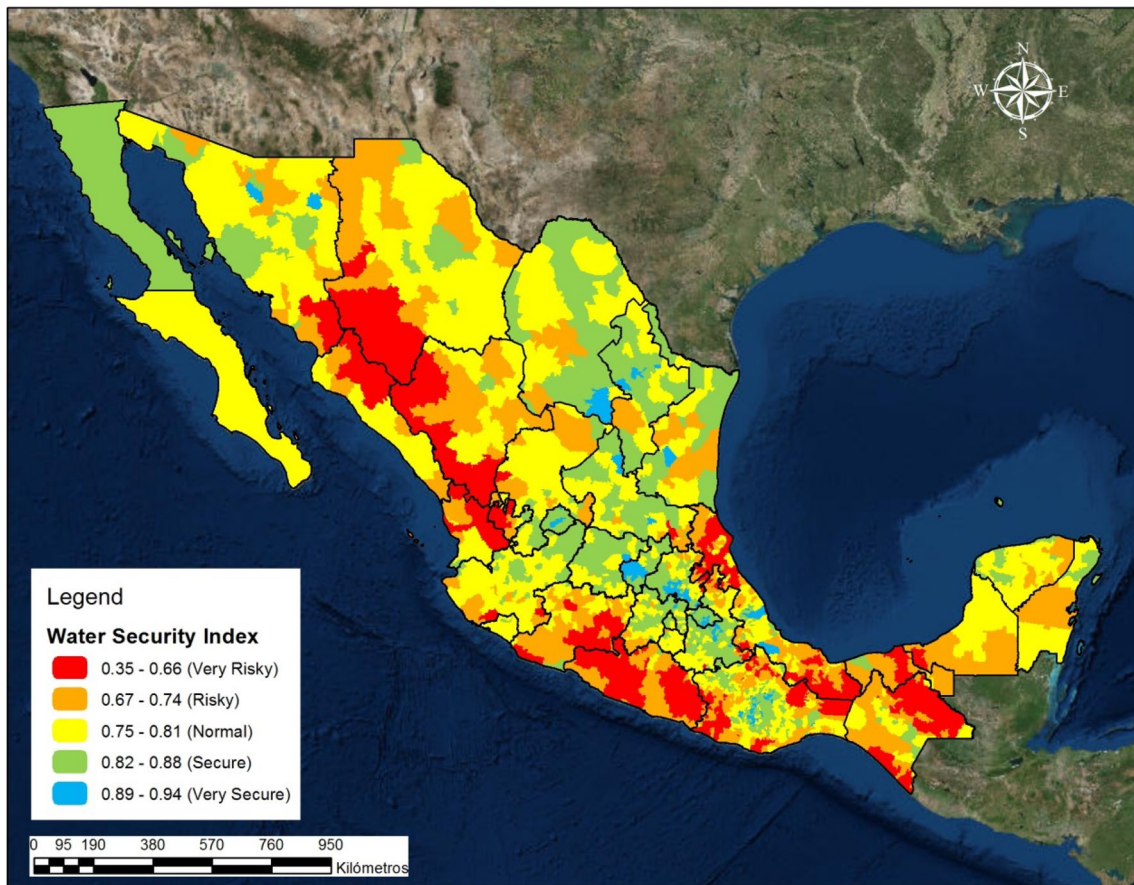Last but not the least, the introduction of population vulnerability and its components, as a component in the

Fig. 9 Water security index at the municipal level

concept and calculation of the water security index, adds a new dimension to the problem of water security, especially important for countries like Mexico where social stratification is high.
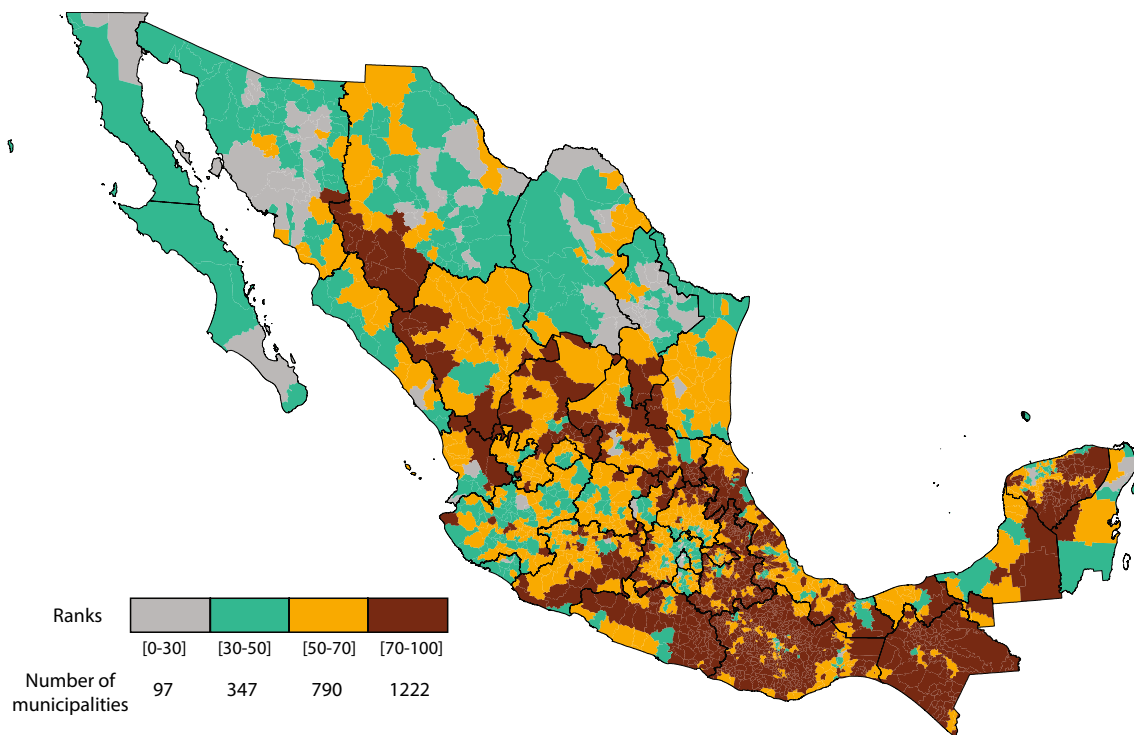
The main limitation for the construction of an index that adheres to the reality of Mexico and clearly reflects the situation in the country is the lack of information. In this area there is an absence of measurement, follow-up and data processing, asymmetrical information at different aggregate levels (state and municipal), and the discretional handling of existing information. On the other hand, a complication present upon carrying out integration of

Table 2 Water security index in Mexico in regards to area and population

Ranges	Municipalities	Population	Area (km²)
0.35 - 0.66 (Very risky)	240	6,373,349	273,480.90
0.67 - 0.74 (Risky)	488	13,301,075	311,081.61
0.75 - 0.81 (Normal)	847	27,704,496	764,131.30
0.82 - 0.88 (Secure)	723	58,451,328	434,924.18
0.89 - 0.94 (Very secure)	158	41,179	30,268.54

the information is determining the degree of benefit that water security contributes given the complexity of the problem. In the future, it is recommended to incorporate information relative to the authorized budgets and their effective employment in the municipalities related to flood control, droughts, water treatment, improved drinking water services, etc.—actions that directly strengthen water security in the country.

Upon applying a geographic information system at the municipal level, based on the proposed probabilistic methodology, it was found that for the water security index below 0.78 there is a corresponding area of 989,279.53 km²; for the 0.35 to 0.66 range there is an area of 273,480.90 km²; for the values between 0.67 and 0.74 there is an area of 311,081.61 km²; from 0.75 to 0.81 the area is 764,131.30 km²; from 0.82 to 0.88 the area is 434,924.18 km²; and, lastly, from 0.89 to 0.94 there is an area of 30,268.54 km². The municipalities with the lowest water security index are Mezquital, State of Durango; Balleza, State of Chihuahua; Malinaltepec, State of

Fig. 10 Map of poverty estimation in Mexico, according to the Mexican National Council for the Evaluation of Social Development Policy, year 2010 [9]
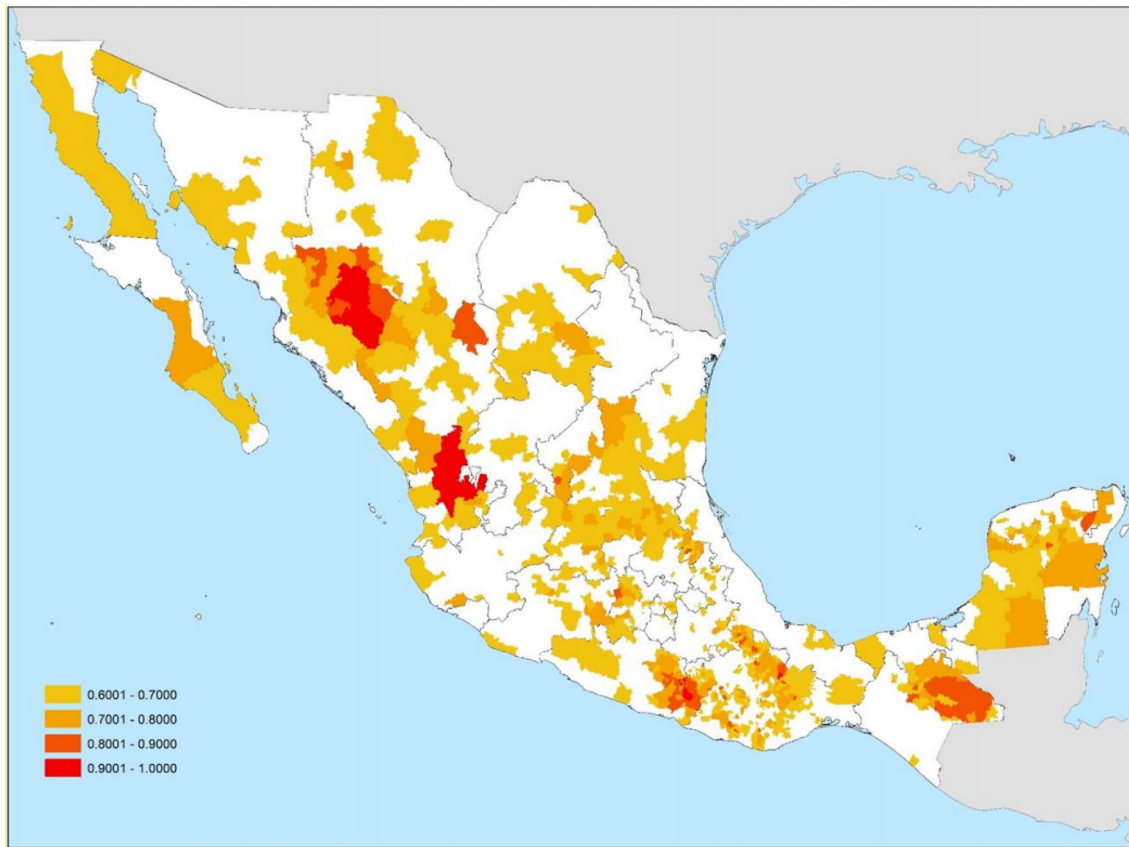
Guerrero; Tlacoapa, State of Guerrero; San Miguel Totolopa, State of Guerrero; and Acatepec, State of Guerrero.

Aspects like water governance, institutional (effectiveness) coordination and environmental water requirements at this moment are not considered in the municipal level water security assessment methodology. The main difficulty in integrating these aspects lies in the lack of information and monitoring of variables which normally are not measured in Mexico. It would be desirable to determine such indicators for each of the municipalities. The future challenges are to have relevant real and documented information for the different levels of government, as well as an authority responsible for the monitoring and recording of institutional coordination and effectiveness, a role that river basin councils could play. Finally, the methodologies proposed in this paper may serve as an example of how to assess water security at municipal level, at least

as a first approximation, using mainly free and officially published information.

Sensitivity analysis was not considered at this stage of the work, given the high geographic, climatic, social, cultural and economic parameter heterogeneity present in Mexico and in the indicators, but may be considered in future work, Other limitations, to be addressed in future work, include:

- Water availability is not considered at municipal level, since the relevant information is now accessible only at basin level.
- Water quality
- Climate change impact, and its medium and long-term effects.

Fig. 11 Priority attention zones generated by CONAGUA [7]

Compliance with ethical standards

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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