Involving Resilience In Assessment of The Water-Energy-Food Nexus For Arid And Semiarid Regions

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Abstract

The proper planning of the water-energy-food nexus is key for urban sustainability. However, the security of water, energy, and food is posed at risk due to uncertain events such as natural disasters. The quantification of resilience in water-energy-food systems has gained relevance in recent years and has served as a key tool to identify vulnerable areas. This work presents a systematic approach to assessing the resilience of the water-energy-food nexus in arid/semiarid regions that present low availability of resources. A methodology for assessing the resilience of the water-energy-food nexus of an arid region is presented, which allows evaluating the system under the disturbances of natural disasters such as hurricanes, low-temperature events, and droughts. The events in which failures in functional services may occur are analyzed using penalty costs. To apply the proposed approach, scenarios corresponding to past conditions and future projections were evaluated for two Mexican arid cities. The results show that it is possible to identify vulnerable areas related to the existence of natural disasters and thereby look for alternatives to maintain the security of the nexus. The proposed approach is general, and it can be applied to other regions with similar characteristics.

Introduction

Nowadays, satisfying the needs of basic resources for life, such as water, energy, and food, represents one of the biggest problems around the world (Deng et al. 2020; Jirapornvaree et al. 2021); this is mainly due to urbanization, resource constraints and inadequate management (Engstrom et al. 2017), governance structures, policies (Kaddoura and El Khatib 2017; Anser et al. 2020), and the impacts of climate change (Dargin et al. 2020). The water-energy-food nexus (WEF) approach emerges with the potential to study the interlinkages among water, energy, and food, reduce trade-offs and promote resource security and efficiency to ensure urban sustainability and facilitate greater climate change adaptation (Rasul and Sharma 2016).

The security of the water-energy-food nexus has become a remarkably high concern due to future uncertainties (Zhang et al. 2018), and tackling natural disasters is a key challenge for sustainable cities (Saad et al. 2021). Recently, the frequency in the occurrence of different natural disasters (such as freezing, droughts, and flood) has been increased (Botzen et al. 2019). These events have put the production and availability of resources at risk; therefore, resilience is a critical factor that must be included in the nexus assessment for urban sustainability. The use of the resilience concept has been gaining relevance in recent years. The term resilience has been employed in various areas, but in general, resilience aims to resist and adapt to a disturbance and recover its normal state (Ribeiro and Pena Jardim Gonçalves 2019). Núñez-López et al. (2021) defined resilience as the ability of the system to deliver its functional service(s) during and after an interruption process. There are different means to address resilience. In the first contributions, resilience was evaluated using qualitative methods (Hecht et al. 2019; Bruce et al. 2020; Pawar et al. 2021), but lately, special attention has been paid to the development of quantitative methods mainly in the process engineering area (Ren et al. 2017; Nezamoddini et al. 2017, Ahmadi et al. 2021). The quantification of resilience in optimization systems has brought great benefits, since it allows identifying the scenarios where some failures that decrease the performance of the system may occur, and thus be able to make decisions on how to address the problem before, during, or after the design of the system. This shows the importance of implementing resilient planning frameworks compared to conventional planning methods.

Addressing resilience is a key factor for a sustainable system. In the food sector, resilience has been incorporated to supply chain systems to improve food security (Melkonyan et al. 2017; Sharma et al. 2020; Martínez-Guido et al. 2021). In the water sector, studies have focused on water supply resilience to disasters (Balaei et al. 2020; Balaei et al. 2021), water management (Brown et al., 2020; Behboudian and Kerachian, 2021), and water quality (Imani et al. 2021). In the early studies, resilience in the energy sector has been addressed focusing on weather events, which is the cause for most of the energy supply disruptions (Jasiūnas et al. 2021; Tang et al. 2021), geopolitical conditions (Wilson 2019), and technical failures (Cadini et al. 2017). In this regard, resilience quantitative assessments (Moslehi and Reddy 2018; Pierre et al. 2018; Abdin et al. 2019), indicators or metrics for planning energy systems (Charani Shandiz et al. 2020; Gholami Rostam and Abbasi 2021), and simulation models (Senkel et al. 2021) have been proposed. The resilience of energy supply chains exposed to disturbances have been studied (Emenike and Falcone 2020), and recently particular attention has been paid to the study of building energy prediction (Sun et al. 2020) and energy distribution (Fontenot et al. 2021) considering the climate change, providing this way recommendations to reduce energy consumption (Ashouri et al. 2020). In the context of the water-energy-food nexus, there are reported models that facilitate the decision-making and proposed strategies to reduce trade-offs between the sectors; however, some of them are limited in the sense that do not consider uncertainties associated with unexpected events and risks. Hence, resilience methods are capable to improve decision-making, mitigate emerging risks, and motivate system planning. For instance, Govindan and Al-Ansari (2019) addressed the WEF resilience by developing a computational framework based on reinforcement learning to quantify the emerging risks and determine rewards or the best action policy for network and adaptation to face the risks. Nevertheless, a limitation of these frameworks is that require dense information to infer the transition probabilities and that resilience depends on the reward given in a particular state since the location of the reward in the system could take an environmental, economic, and social dimension. To mitigate these limitations and facilitate the quantification of resilience, other indexes have been proposed. In this context, Shu et al. (2021) developed indexes to quantify the resilience and security of the WEF in industrialized nations through the measure of the availability and accessibility of resources. However, although this methodology does not require much data or information to calculate the resilience indicator, in this approach sub-indicators must be weighted based on expert´s opinions and this could bring uncertainty in the resilience calculation.

Considering that there is vast research on resilience for water, energy, and food systems independently, but minor research to quantify the WEF resilience of systems involving uncertain unexpected events, the aim of this paper is the development of a systematic approach for evaluating the resilience in the security of the water-energy-food nexus at different periods. The main contributions of this research are discussed below:

- The proposed methodology can identify and solve the blind spots of the system through alternatives that help to improve the functioning of the same.
- This approach has wide applicability since it can analyze the functionality of macroscopic systems and can be used to evaluate the WEF resilience in any region.

- According to the discretization used, it is possible to estimate the system resilience in future years.
- One of the primary benefits of this approach is to evaluate the resilience and identify critical disturbances to prevent unwanted events, propose corrective actions, and/or carry out an adequate design of the system in an anticipated way.

On the other hand, the main limitations lie in modifying the scale at which the methodology was designed, as well as the difficulty in accessing parameters to make use of another discretization measure. This could modify the results of the predictions for future years.

The paper is organized into 6 sections. In Sect. 2, the problem statement is explained. Section 3 describes the methodology used for the quantification of the resilience index. Section 4 presents the applicability of the proposed approach to two case studies for two economically important areas of Mexico. In Sect. 5, the obtained results are presented and discussed. Finally, the conclusion of the study is summarized in Sect. 6.

Problem Statement

There are many regions with unfavorable climatic conditions in which satisfying the water, energy, and food needs of their population is a challenging task. In the last years, more frequent and extreme events have occurred causing disruptions in the management of water, energy, and food. Frequently, places are not prepared to overcome failures related to natural disasters. Furthermore, these places are not able to cope with the demanded growth by the mobilization of residents with economic and social aspirations, directly affecting the development of basic activities. Resilience analysis is an efficient tool to estimate the future conditions or failures that affect the security of the water-energy-food nexus. Therefore, this problem consists in determining the resilience of the water-energy-food nexus security in arid/semiarid regions that are exposed to natural disasters (Fig. 1). To address this problem, the methodology proposed by Núñez-López et al. (2021) to assess the resilience in process systems engineering, together with the methodology proposed by CENAPRED (Jiménez et al 2012) for risk assessment, were considered for the analysis of resilience in current conditions and future projections. One of the benefits of quantifying resilience in process systems engineering is estimating the costs of repairing system components in the event of a failure, as well as the costs associated with the loss of a functional system. The identification of certain risks allows overestimating the considered system and, based on that, adapting it to avoid the total or partial functional loss of any service.

Methodology

In this paper, a methodology for quantifying the resilience of the water-energy-food nexus security in arid/semiarid regions is presented. A mathematical model is proposed to analyze the resilience of different scenarios to identify those in which a significant risk may occur that compromises the satisfaction of functional services. The quantification of resilience consists in first defining the system, its characteristics, needs, types of failures that can occur, inputs, and outputs. Subsequently, functional services of concern or that would be affected and their respective costs should be established if failures occur by weather conditions. It continues to identify the three-dimensional matrix, which is composed of scenarios formed by the functional services that can be affected in a certain period due to some types of failure, specific periods, and possible failures that may occur (Fig. 2). These sequential steps are described as follows:

a. Identify a three-dimensional matrix (Fig. 3), by analyzing the scenarios obtained from the mathematical model.

b. Calculate a bidimensional matrix (Fig. 4) through the estimation of the costs imposed by the system considering the priorities of each of the scenarios according to **Eq. 1**.

The imposed cost related to each possible failure in each period is calculated as follows:

$$\mathrm{ImpCost}_{f,t} = \sum_{fs} \mathrm{PenalizationCost}_{fs} \, \mathrm{Unit}_{fs} \quad (1)$$

Here, the penalty cost of each ($\mathrm{PenalizationCost}_{fs}$) of the functional services (*fs*) in every analyzed year is multiplied by the amount of water (m^3), energy (kWh), or food (ton) that is represented as Unit_{fs}, which also corresponds to each value in the three-dimensional matrix. The is a parameter that represents the unitary cost of water (\$ / m^3), energy (\$ / kWh) or food (\$ / ton).

c. Quantify the risk indexes according to the CENAPRED methodology.

In this work, the CENAPRED methodology is used to analyze the risk indices for a hurricane, low temperature, and drought events which are described below.

- *For hurricane*

To calculate the hurricane risk index, the use of **Eq. 2** is required, and a count of the trajectory segment of tropical cyclones within a 1° to 1° geographic box, for this count the highest category that the tropical cyclone has reached, such count is done through the computer program “Cyclone count” (León-Aristizábal and Peréz-Betancourt, 2018).

$$IPCT = \sum_{i=1}^{7} v_i I \quad (2)$$

where:

IPCT = Risk index for hurricanes

v_i = Exceedance rate for intensity *I*

I = Intensity (**Table1**)

Table 1
Intensity associated with the category of tropical cyclones of the Saffir-Simpson scale.

Intensity (I)	Category
1	tropical depression
2	tropical storm
3	hurricane category 1
4	hurricane category 2
5	hurricane category 3
6	hurricane category 4
7	hurricane category 5

The risk index for a hurricane (*IPCT*) is calculated by **Eq. 2**, where the intensity (*I*) associated with the category of tropical cyclones Saffir-Simpson scale (presented in Table 1) is multiplied by the exceedance rate for intensity $I\,(v_i)$.

- *For low temperature*

The highest incidence of freezing in arid/semiarid regions generates severe health problems, as well as damage to the population’s vines. To determine the risks associated with this phenomenon, the low-temperature risk index (*IPBT*) is used (Eq. 3), which involves parameters related to days with freezing in a certain region (H_{hel}) (Table 2 and Table 3) and extreme minimum temperatures (H_{tmext}) (Table 4 and Table 5).

$IPBT = H_{tmext}\,(0.5) + H_{thel}\,(0.5)$

where:

IPBT = Risk index for low temperatures

H_{tmext} = Index for extreme low temperatures

H_{thel} = Index for low temperatures days

Table 2
Intervals of number of days with freezing

Days
> 120
61–120
1–60
zero

Table 3
Assignment of values for the number of days with freezing

Number of days with freezing	Value	H_{hel}	Category
> 120	3	0.5	High
61–120	2	0.375	Medium
1–60	1	0.25	Low
zero	0	0.125	Very low

Table 4
Intervals of extreme minimum temperature

Temperature (°C)
> 12
6 to 12
6 to 0
0 to -6
-6 to -12
-12 to -18
-18 to -24
< -24

Table 5
Construction of minimum temperature class intervals

Extreme minimum Temperature (°C)	Value	Index H_{tmext}	Category
> 12	1	0.1	Very low
6 to 12	2	0.2	Low
6 to 0			
0 to -6	3	0.3	Medium
-6 to -12			
-12 to -18	4	0.4	High
-18 to -24			
< -24	5	0.5	Very high

It is important to mention that the parameters presented from Table 1 to Table 5 were previously calculated and reported in the methodology proposed by CENAPRED (Jiménez et al., 2012).

- *For drought*

The drought phenomenon has been evaluated by government institutions in such a way that studies have been made for each of the country's municipalities, where the rainfall deficit and its duration have been considered. Escalante-Sandoval (2005) has proposed a classification on the risk index for droughts, which are shown in Table 6 and Table 7.

Table 6
Drought classification

Average rainfall deficit (%) with respect to its average annual rainfall	Average drought duration D (years)		
	1 < D < 2	2 < D < 3	3 < D < 4
0 < deficit (%) < 10	Normal	Moderate	Extraordinary
10 < deficit (%) < 20	Severe	Very severe	Extremely severe
20 < deficit (%) < 30	Vast	Very vast	Extremely vast
30 < deficit (%) < 40	Critical	Very critical	Catastrophic

Table 7
Risk indexes for droughts

Average rainfall deficit (%) concerning its average annual rainfall	Average drought duration D (years)		
	1 < D < 2	2 < D < 3	3 < D < 4
0 < deficit (%) < 10	0.075	0.125	0.175
10 < deficit (%) < 20	0.225	0.375	0.525
20 < deficit (%) < 30	0.375	0.625	0.875
30 < deficit (%) < 40	0.525	0.875	1.225

d. Evaluate the resilience indexes (Fig. 5) for different possible failures in different periods using **Eq. 2**.

The resilience index is calculated using the maximum and minimum imposed costs and the imposed cost for the current scenario:

$$Re_{f,t} = \frac{\text{ImpCost}^{Max} - \text{ImpCost}_{f,t}}{\text{ImpCost}^{\text{Max}} \text{-ImpCost}^{\text{Min}}} \quad (4)$$

The resilience index ranges between 0 and 1. $Re_{f,t}$ = 0 represents the scenarios that the system would not be able to deliver any of its functional services, and $Re_{f,t}$ = 1 is when the functionality of the system would not be interrupted at all.

e. Identify the critical components of the system based on the obtained resilience indexes and propose a strategy to improve them.

Case Study

To show the applicability of the proposed approach, two case studies were selected, which correspond to the city of Monterrey, Nuevo León, and the city of Hermosillo, Sonora, both located in Mexico. The selection of case studies was made based on the limited resource conditions that these cities faced, a consequence of the climate change impacts that have put the security of water, energy, and food at risk.

4.1 Monterrey

The Monterrey Metropolitan Area (AMM) is selected as a case study because of the economic importance that it represents to the national gross domestic product. Its main activity is the manufacturing industry, which allows having a strong economic relationship with the USA. It is located in the Northeast Region of Mexico, in the state of Nuevo León. The AMM has the second-highest human development index in the entire country, after Mexico City. Around 88% of the total population of the state is concentrated in the AMM due to the developed economic activities, making the city a point of migration for the population of neighboring states. However, the current situation suffered by natural resources puts at risk the ability to cope with accelerated growth and achieve sustainable development. In addition, there are severe weather conditions in the city, which are dry and extreme (SET-NL, 2019). Water is supplied to the population by surface and underground sources, which completely depend on the rainfall registered in the area and upstream, causing conflicts derived from the rights to use water. The agriculture and livestock sector is exploited to a lesser extent due to weather conditions. The main crops harvested are pastures and forage sorghums and some vegetables to a lesser extent. Livestock activities consist of carcass meat, milk, and egg production. The energy sector is supplied mainly from non-renewable sources, such as combined cycle power plants. The generation of energy by renewable sources used to a lesser extent are wind and solar; however, due to topographic characteristics, they could be exploited to a greater extent. According to the historical climate recorded (CONAGUA, 2021a), there are great probabilities of having long periods of drought and sometimes heavy rainfall that leads to flooding. These floods are a consequence of the location and local topography in the face of tropical storms and have, on several occasions, saved the population from being without water in their aquifers. The most devastating hurricanes in the AMM have been “Gilbert, 1988”, “Emily, 2005”, “Alex, 2010”, and “Hanna, 2020” the most recent (CONAGUA, 2021b). The damages recorded range from economic losses, interruption of basic services such as water and energy, to human losses. In 2013, there was a lasting drought considered one of the worst in the last 50 years, where Hurricane Ingrid saved the city from a real emergency due to water shortages (CONAGUA, 2021c). Figure 6 describes the case study, as well as the most important hurricanes and droughts that have affected the city.

4.2 Hermosillo

Hermosillo, the capital of the state of Sonora, is the city with the greatest water supply problem in the country, this is mainly due to its geographical location. Sonora is almost covered by the hottest desert in the country; therefore, Hermosillo is located in an arid region where the low availability of resources predominates. Given that Hermosillo is the most economically developed city in the Sonora state, satisfying the demands of energy, water and food is a challenging problem that in recent years has been aggravated by the impacts of climate change. Natural disasters have caused great economic losses due to damage to hydraulic infrastructure and the agricultural, livestock, fishing, and energy sectors. The natural disasters that have occurred in Sonora have generally been of hydrometeorological origin, which are generated by extraordinary rains and tropical storms (Fig. 7). Even though the city of Hermosillo is located in an arid region with low levels of precipitation, the presence of torrential and short-lived rains causes large floods that have social, economic, and environmental consequences. Likewise, another meteorological phenomenon that also causes damage to the population is the low-temperature environment. This phenomenon has caused great losses in agriculture; only in the 1983–2004 period, more than 17,000 hectares of crops were lost with a production value of more than 3 MMUSD. The regions most affected by low-temperature events in Sonora are those of the north, northeast, and east, with occasional effects on the coastal regions. In the case of Hermosillo, the presence of low temperature is scarce, covering the months of December to February, with an incidence of 0 to 20 days per year. In addition to the problems caused by excess precipitation and low temperatures, droughts have a direct impact on all sectors, producing large losses, since according to the information provided by the National Water Commission (CONAGUA, 2021d) and the National Institute of Statistics, Geography, and Informatics (INEGI, 2020), there are approximately 70,093 km^2 of permanent drought, which comprises 38% of the total surface of the State. According to the drought severity calculation, the Sonora State is located between severe and very strong drought zones, while the Municipality of Hermosillo has an index of very strong. One of the main consequences of droughts is that capacity of the dams located in Hermosillo are at their minimum levels; thus, water has been transported from other regions to provide the water required in the city. However, these regions are the areas with the highest agricultural production in the state and therefore the agricultural users of these regions demand that their irrigation rights be respected. It is estimated that water scarcity events have caused a decrease in the sowing area, by more than 160,000 hectares.

The cities of Monterrey and Hermosillo have faced the impacts of climate change and unexpected events during the past few decades, because of this, strategies for better management of resources are needed to improve the security of the water-energy-food nexus.

Results And Discussion

A resilience methodology was implemented to assess the considered case studies. In Figs. 8 and 9, the tridimensional matrices for Hermosillo and Monterrey are shown, respectively. The functional services for water (m^3), energy (MW), and food (Ton) for the case studies are presented in the corresponding matrices. Moreover, five different years were evaluated, which correspond to previous and future years. Because of the frequency of natural disasters in the case studies, the possible failures modes considered are hurricanes, freezing, and drought.

Then, each of the functional services was multiplied for the respective penalization cost (Table 8) for constructing the dimensional matrices (Table 9 and Table 10). For both cases, it can be observed that functional services vary through the years; however, these are the same for each of the possible failure modes. This way, a risk index associated with each of the possible failure modes was used. The indices were calculated based on the methodology established by CENAPRED (Jiménez et al., 2012). According to Tables 9 and 10, an increase in the projection of imposed costs of 41.52% and 43.10% can be observed, for the City of Hermosillo and Monterrey respectively, from 2019 to 2030. Although a decrease in energy costs is expected in the coming years due to the increase in the use of renewable energy (38.28% for both cities), the trend shows an increase in water and food costs, as well as in the number of functional services required due to population growth. The increase in the cost of water for Hermosillo is 22.33% and 20.40% for Monterrey, while the cost of food will increase around 15% for both cities.

Table 8
Penalization costs for Water-Energy-Food Nexus in different years

Year	City	Cost ($US/unit)		
		Water (m^3)	**Energy (MW)**	**Food (Ton)**
2013	Hermosillo	1.378	47.0	289.0
	Monterrey	0.643	47.0	278.0
2015	Hermosillo	1.464	48.8	312.0
	Monterrey	0.724	48.8	289.5
2019	Hermosillo	1.836	47.8	340.5
	Monterrey	0.809	47.8	335.0
2025	Hermosillo	2.017	34.1	365.3
	Monterrey	0.891	34.1	357.8
2030	Hermosillo	2.246	29.5	391.1
	Monterrey	0.974	29.5	386.3

Table 9
Bidimensional matrix for Hermosillo

2013	**2015**	**2019**	**2025**	**2030**	
201,220,890	230,369,099	280,107,749	343,405,393	396,424,044	Drought
201,220,890	230,369,099	280,107,749	343,405,393	396,424,044	Low temp.
201,220,890	230,369,099	280,107,749	343,405,393	396,424,044	Hurricane

Table 10
Bidimensional matrix for Monterrey

2013	**2015**	**2019**	**2025**	**2030**	
340,133,705	377,761,763	480,403,602	572,902,791	687,474,157	Drought
340,133,705	377,761,763	480,403,602	572,902,791	687,474,157	Low temp.
340,133,705	377,761,763	480,403,602	572,902,791	687,474,157	Hurricane

According to the methodology with which the indices were calculated, the risk levels do not vary significantly in the proposed years, even for the projections for future years. Therefore, the risk index for each of the case studies regarding each possible failure is the same throughout all the years. These indices are shown in Figs. 10 and 11, where VL is an exceptionally low risk, L is a low risk, M is a medium risk, H is a high risk, and VH is an extremely high risk.

Subsequently, the resilience indices were calculated for each of the case studies. As the risk indices do not vary through the selected years, only one resilience matrix for each case was calculated. For both cases, only medium to very high-level risks are considered. Table 11 presents the resilience indices obtained from the case study of Hermosillo, it can be observed that some of the resilience indices are equal to 1, which represents a scenario that can be completely replaced if any possible failure appears. However, in the event of a drought, there is a value of 0.85 of resilience index for a medium risk index (with a probability of 15% according to Fig. 10), which indicates that this natural phenomenon could have important consequences for the interrelation of the water-energy-food nexus. This implies an imposed cost of $US 42,016,162 for the year 2019 and a cost of $US 59,463,607 for 2030, to obtain the necessary nexus resources to satisfy the needs of the population. Similarly, lower values can be observed in the failure modes for low and very low-risk indices, but because they are low risks they are not considered.

Table 11
Resilience indices for Hermosillo

	VL	L	M	H	VH
Hurricane	0.88	0.24	0.92	0.96	1.00
Low temp.	0.49	0.70	0.90	0.91	1.00
Drought	0.62	0.53	0.85	1.00	1.00

Table 12 presents the results of the case study of Monterrey, in this case, high resilience values for the case of hurricanes are presented, which indicates that this city will not present a major problem if any occurs (probability of 92% for very low risk). However, the occurrence of low temperatures or drought presents resilience values below 0.50, which indicates that these phenomena can drastically alter food and/or energy production, as well as the availability of water in this area. Besides, Monterrey presents a probability of 55% in medium-risk in case of scenarios with low temperature, and a probability of 56% in high risk in case of drought (Fig. 11). The imposed costs for Monterrey in 2019 in case of low temperature and drought are $US 264,221,981 and $US 269,026,017, respectively. While for the projection for the year 2030 are $US 378,110,787 in case of a low temperature, and $US 384,985,528 for a drought.

Table 12
Resilience indices for Monterrey

	VL	L	M	H	VH
Hurricane	0.08	0.92	1.00	1.00	1.00
Low temp.	0.94	0.85	0.45	0.76	1.00
Drought	0.93	0.96	0.67	0.44	1.00

Both case studies present similar conditions concerning climate and resource scarcity, for both cities the main issue is related to the availability of water. Therefore, the more threatening factor for the security of the water-energy-food nexus is the intensification of droughts, a result of climatic changes due to global warming. The analyzed cities are of national importance; however, their current distribution and management systems of basic resources are not resilient to climate change disturbances, nor to the growth demanded by society, limiting sustainable development. The resilience index indicates that in future years the nexus will be vulnerable to extreme events if conditions do not change; then, actions to improve the integration of resources are essential. To overcome the low availability of water, water reuse is an effective way to reduce freshwater consumption and increase its accessibility, consequently, this information can be used to enhance the security of the nexus and its resilience. Furthermore, the optimization of water management in the agricultural sector is key to decrease water consumption. In this sense, different types of irrigation could help significantly, in addition, new forms of cultivation can contribute to the change in land use and the production of food that under normal conditions would not be achieved. Likewise, a balance in food production and consumption must be found to reduce food waste. On the other hand, renewable energy must be included in the energy sector, the incorporation of flexible energy systems to enhance the security and the resilience of the nexus is urgent. Therefore, the resources and climatic conditions of these cities must take advantage of to create an environment of a circular economy.

Addressing resilience is a key factor for a sustainable system, it has many contributions in the ecological, economic and social sectors, and it has been used in many practical and social applications. Practical applications of the assessment of resilience in the water-energy-food nexus are to design systems that could recover quickly from disturbances by performing corrective actions. In addition, through the study of the systems and the probability of disruptive events that may occur, preventing actions can be implemented to build resilience optimally and effectively as well as maximizing the security of resources at those conditions. The water-energy-food nexus has important societal applications, but even more, if the nexus thinking involves a resilience approach. For instance, the study of these concepts together is essential for the development of long-term policies that help to regulate the unsustainable consumption of resources and this way reduce the impacts of climate change. Furthermore, planning resilient systems could ensure access to sufficient resources, reduce the poverty percentage, improve living conditions and create job opportunities. All this implicates to improve human well-being.

The main limitation of the proposed approach is that it requires accurate data for the studied resources in the considered region; therefore, the seasonal analysis would enhance the accuracy but in cases where predictions of future years are made, there is linked a range of uncertainty in the results. In addition, the proposed model is designed for its application at a regional level, and its application to large scales could bring more uncertainty in the results. On the other hand, it is important to mention that the main uncertainties related to the model are in the hydrometeorological variables for the calculation of the risk indexes. Data available related to natural disasters usually corresponds to monthly average parameters, but this type of data is constantly changing; therefore, this implies that the uncertainty is linked to the model.

Conclusions

In this work, a systematic approach for analyzing resilience in the security of water-energy-food nexus in areas that present significant climatic variations throughout the year has been presented. The interruption of functional services such as water, energy, and food due to weather conditions (droughts, floods, and droughts) is analyzed, where penalty costs are associated with total or partial failures in the systems. Two case studies from Mexico that have characteristic severe weather conditions have been presented to show the applicability of the proposed approach. Through the results of the resilience indices, it is possible to identify that among the failure modes considered (hurricane, drought, and low-temperature events), droughts are the phenomenon that puts the security of the water-energy-food nexus at risk. The imposed cost by drought for Hermosillo in 2019 is $US 42,016,62, while for the same event in Monterrey the imposed cost is 6.5 times more than for Hermosillo ($US 269,026,017). It is estimated that by 2030, the imposed costs of the case studies evaluated will increase due to the growing resource demand; $US 59,463,607 for Hermosillo and $US 384,985,528 for Monterrey. Projections for future years do not present significant variations regarding the resilience of the nexus; nevertheless, improvements can be made to enhance the availability and sustainability of resources.

The assessment of the resilience of integrated systems has the advantage to identify vulnerable sectors and make predictions about the trend on the availability of resources such as water, energy, and food and look for alternatives to improve their sustainability. Furthermore, it offers the possibility to estimate the economic losses associated with the existence of certain natural disasters due to climate change, making it an efficient decision-making tool. The interruption of each functional service can be reduced to a greater extent with the help of security policies by optimally building resilience. This type of study makes it possible to design strategies to deal with events in advance and to determine the costs of damage repair, overestimating the analyzed system. This way, the proposed approach allows maximizing the security of the resources that make up the water-energy-food nexus.

Declarations

7. Acknowledgments

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8. Conflict of Interest

The authors declare that they have no conflict of interest.

9. Author contributions

All authors contributed to the study's conception and design. Material preparation, data collection and analysis were performed by: Núñez-López Jesús Manuel, Cansino-Loeza Brenda, and Sánchez-Zarco Xate Geraldine; Methodology was performed by: Núñez-López Jesús Manuel. Writing, editing, and supervision were performed by: Ponce-Ortega, José María. The first draft of the manuscript was written by (Núñez-López Jesús Manuel) and all the authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

10. Data availability

Data concerning this manuscript will be made available on reasonable request.

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Figures

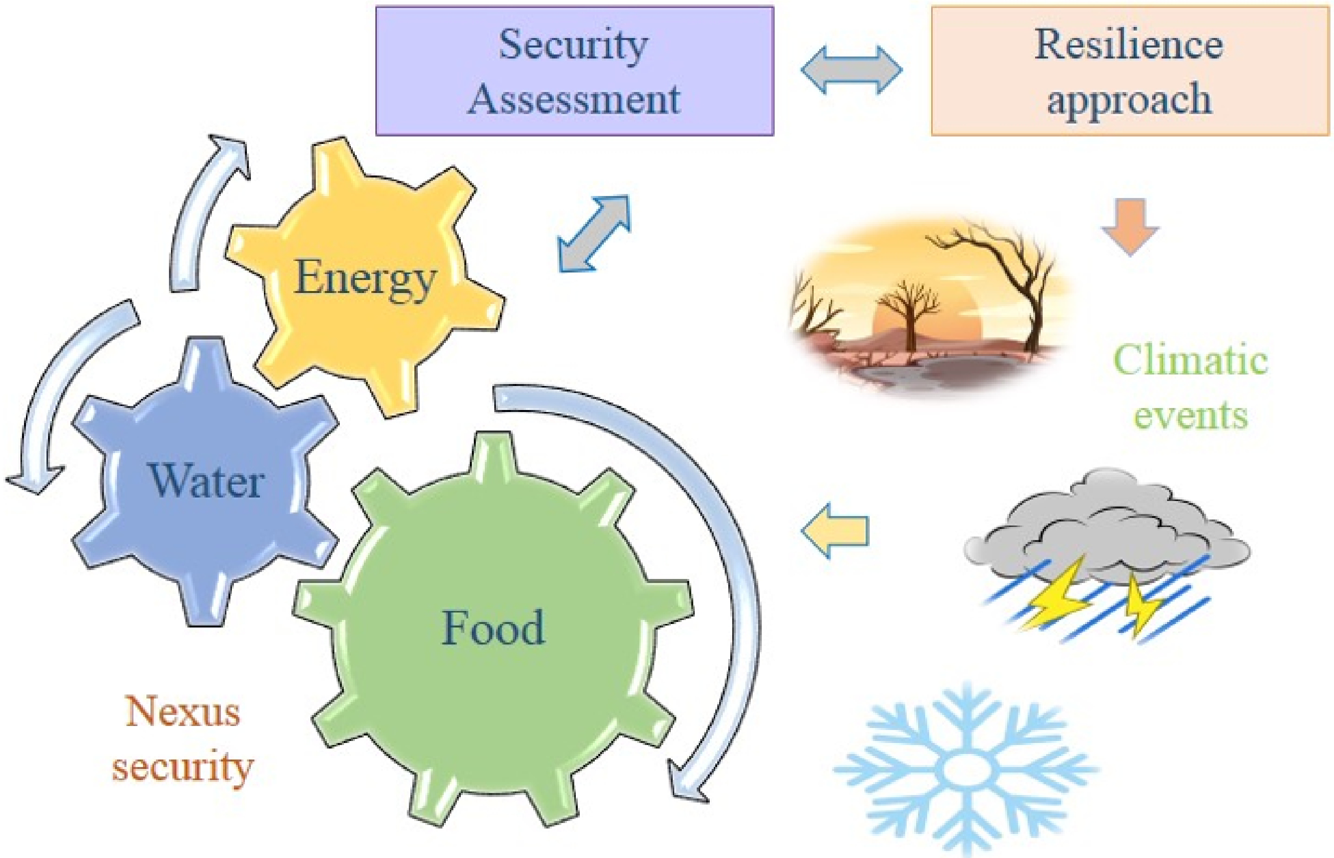

Figure 1

Problem statement.

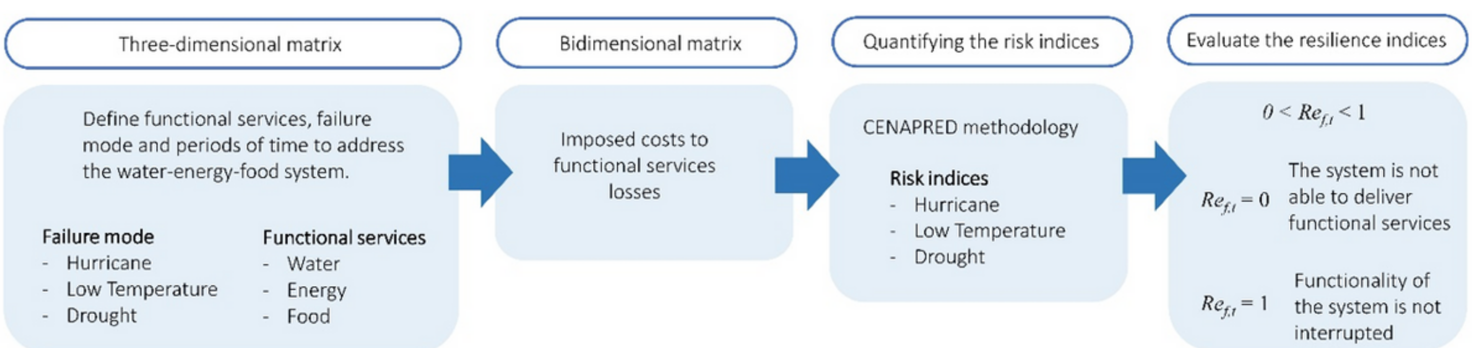

Figure 2

Resilience methodology.

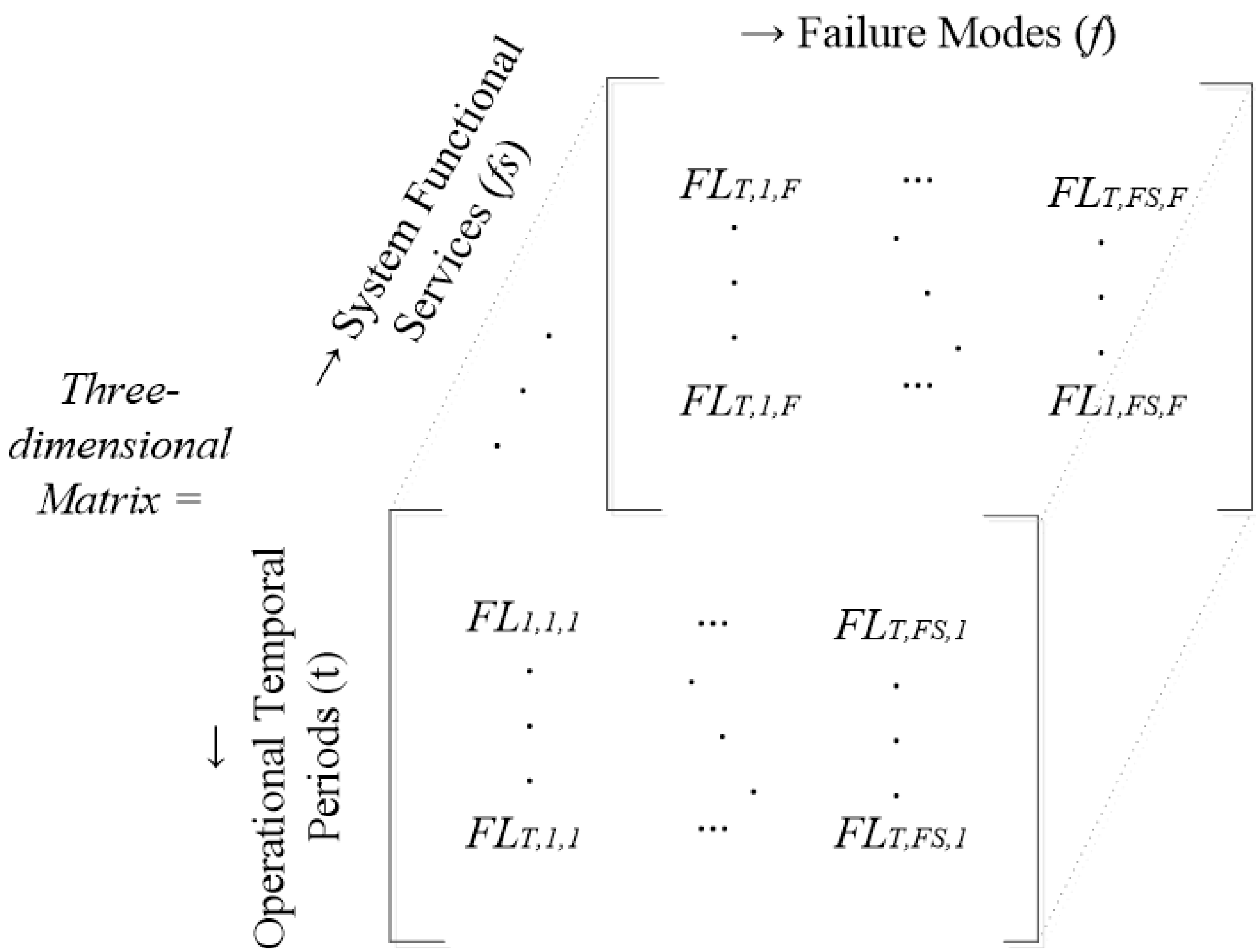

Figure 3

Three-dimensional matrix representation.

$$\textit{Bidimensional Matrix} = \begin{bmatrix} \mathrm{ImpCost}_{1,1} & \cdots & \mathrm{ImpCost}_{1,FS} \\ \vdots & \ddots & \vdots \\ \mathrm{ImpCost}_{T,1} & \cdots & \mathrm{ImpCost}_{I,FS} \end{bmatrix}$$

Figure 4

Bidimensional matrix representation.

$$Resilience\ Matrix = \begin{bmatrix} Re_{1,1} & \cdots & Re_{1,fs} \\ \vdots & \ddots & \vdots \\ Re_{t,1} & \cdots & Re_{t,fs} \end{bmatrix}$$

Figure 5

Resilience Matrix representation.

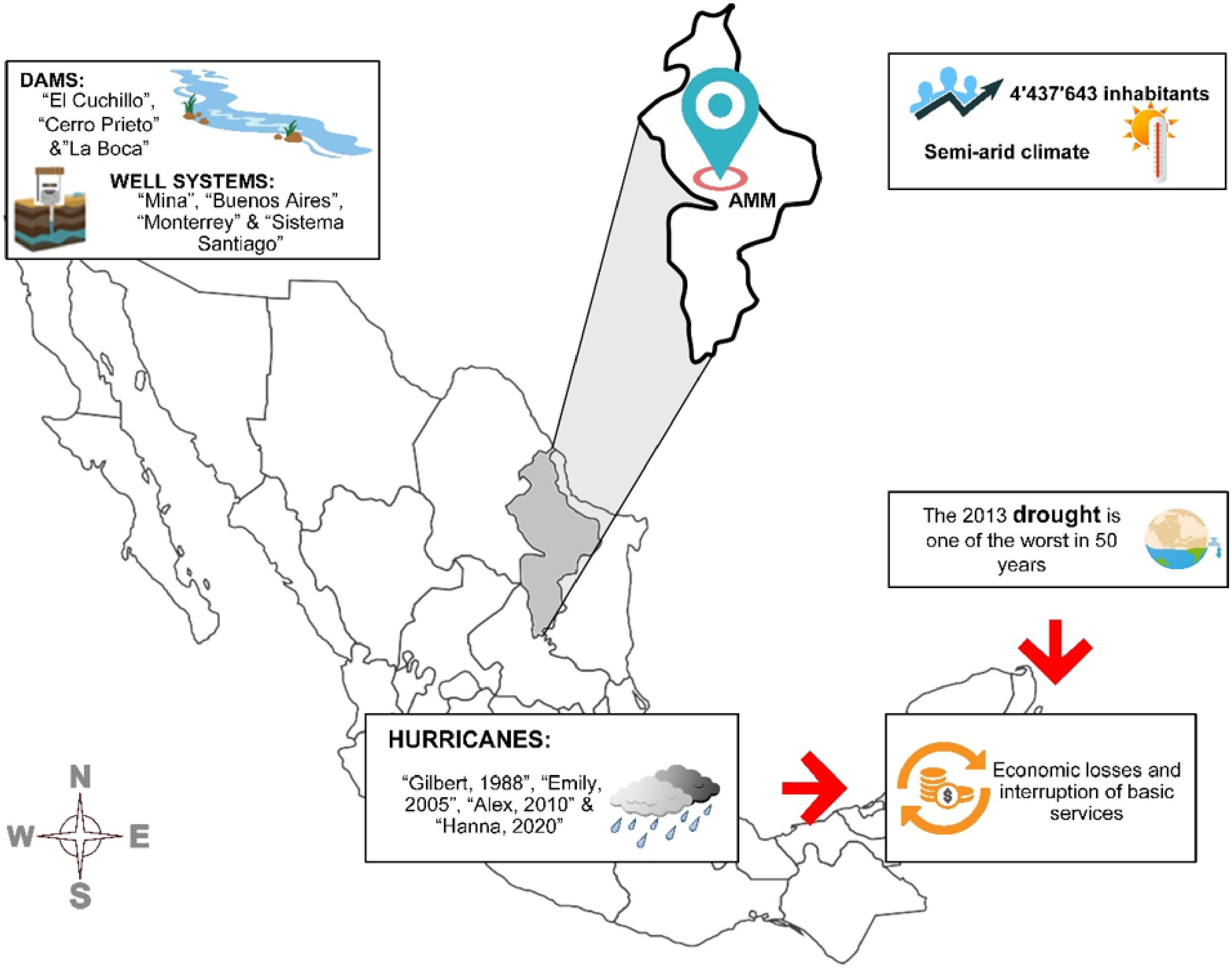

Figure 6

Monterrey case study.

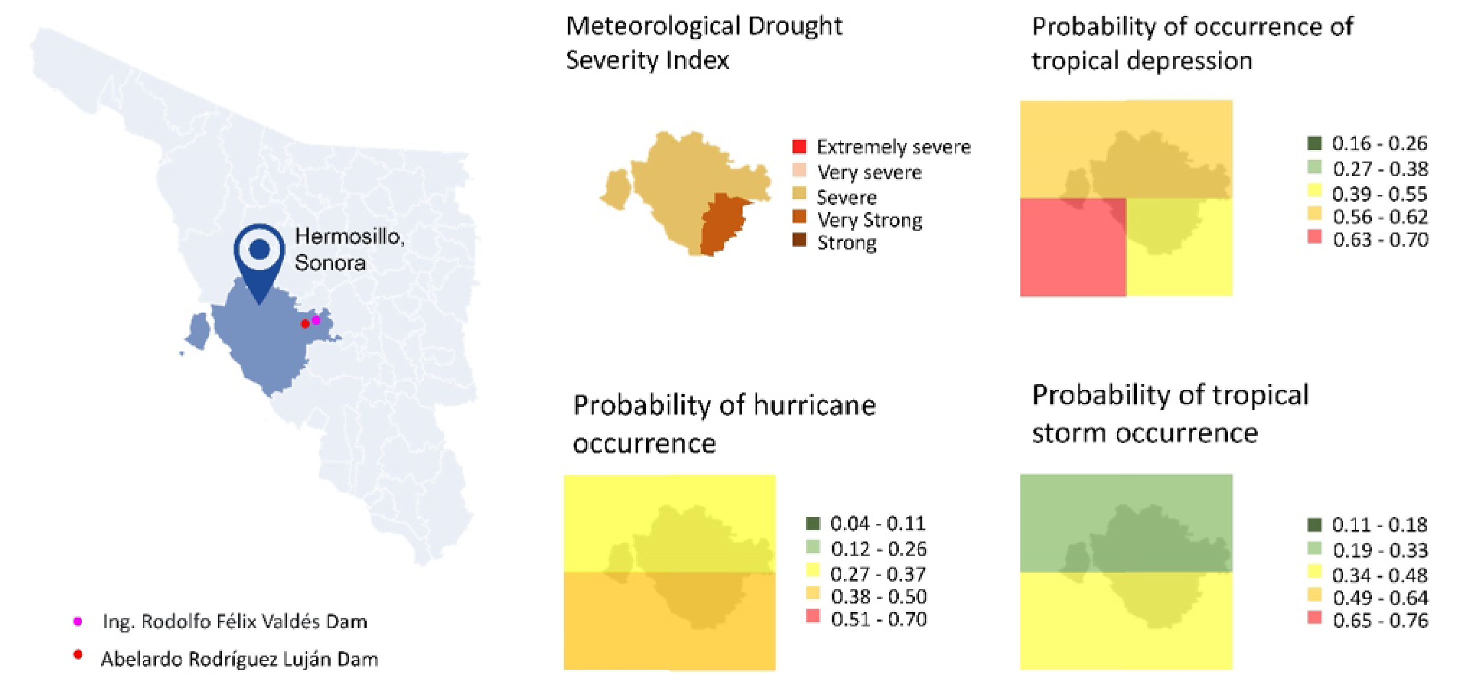

Figure 7

Hermosillo case study.

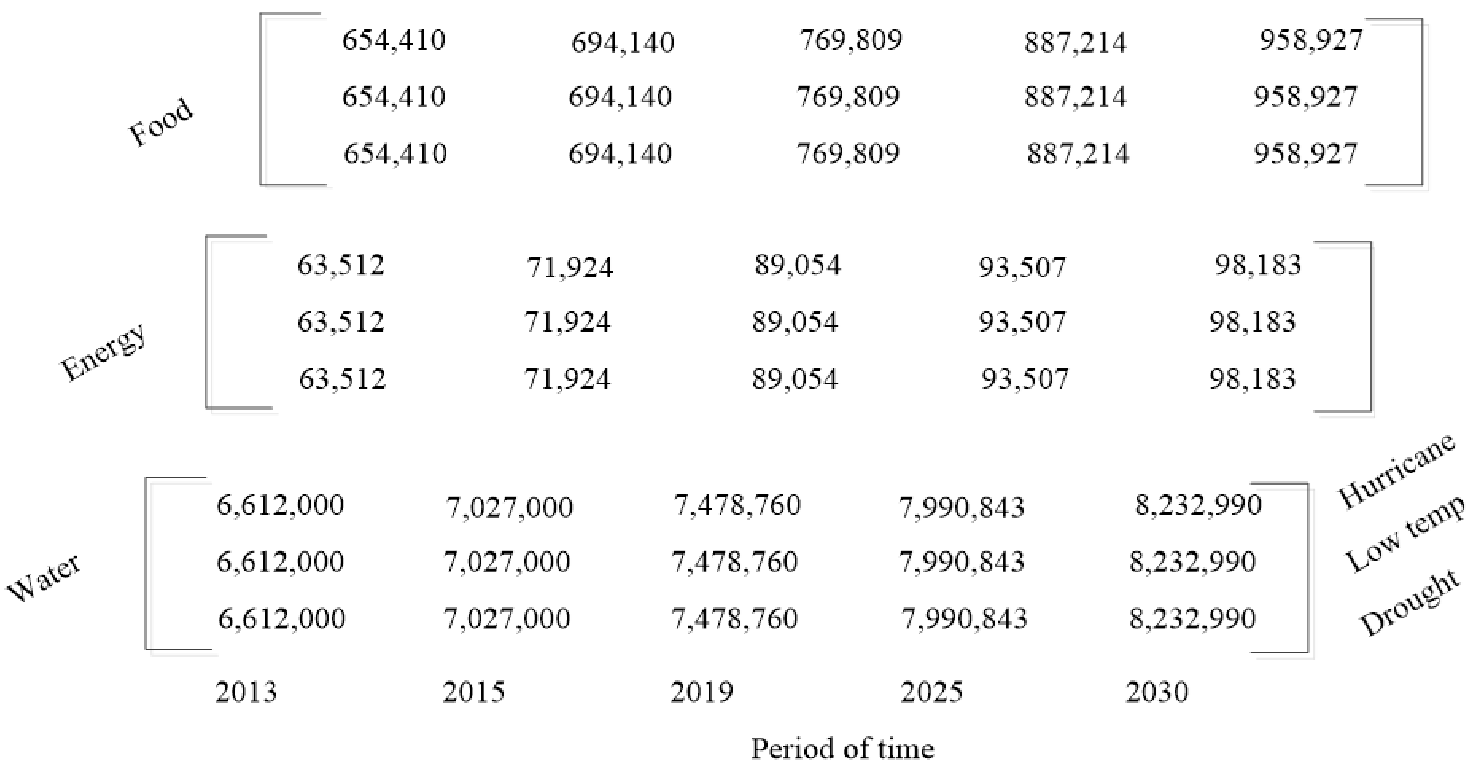

Figure 8

Tridimensional matrix for Hermosillo case study.

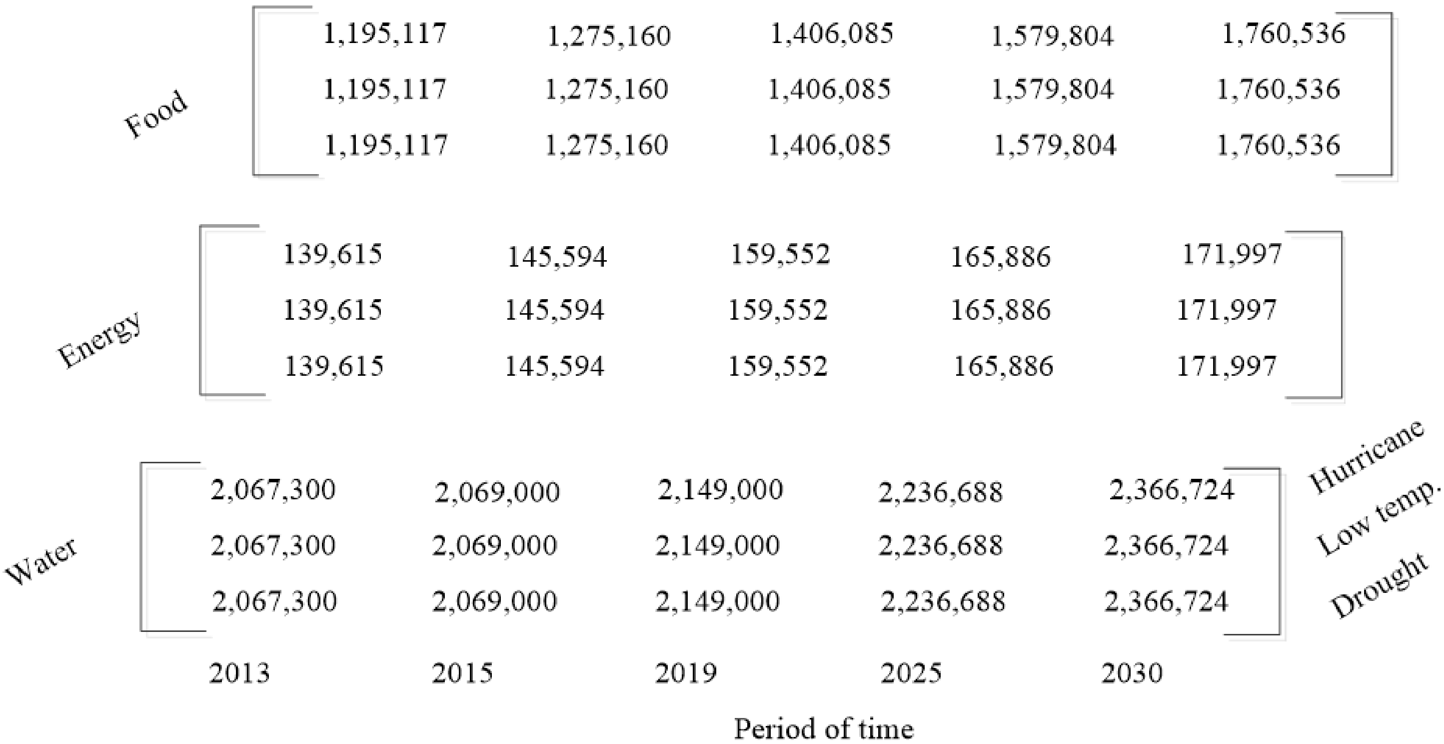

Figure 9

Tridimensional matrix for Monterrey case study.

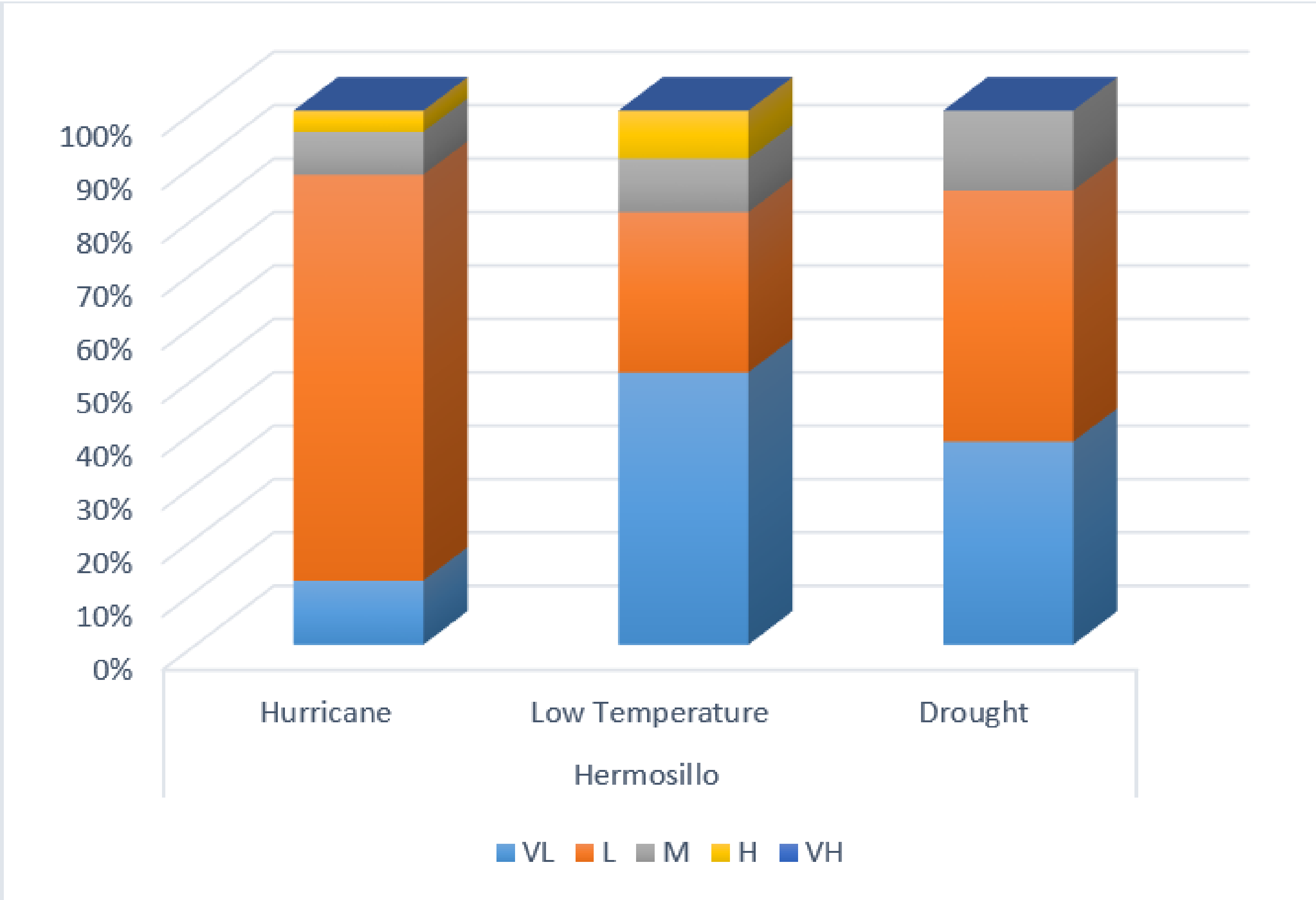

Figure 10

Risk indices for Hermosillo.

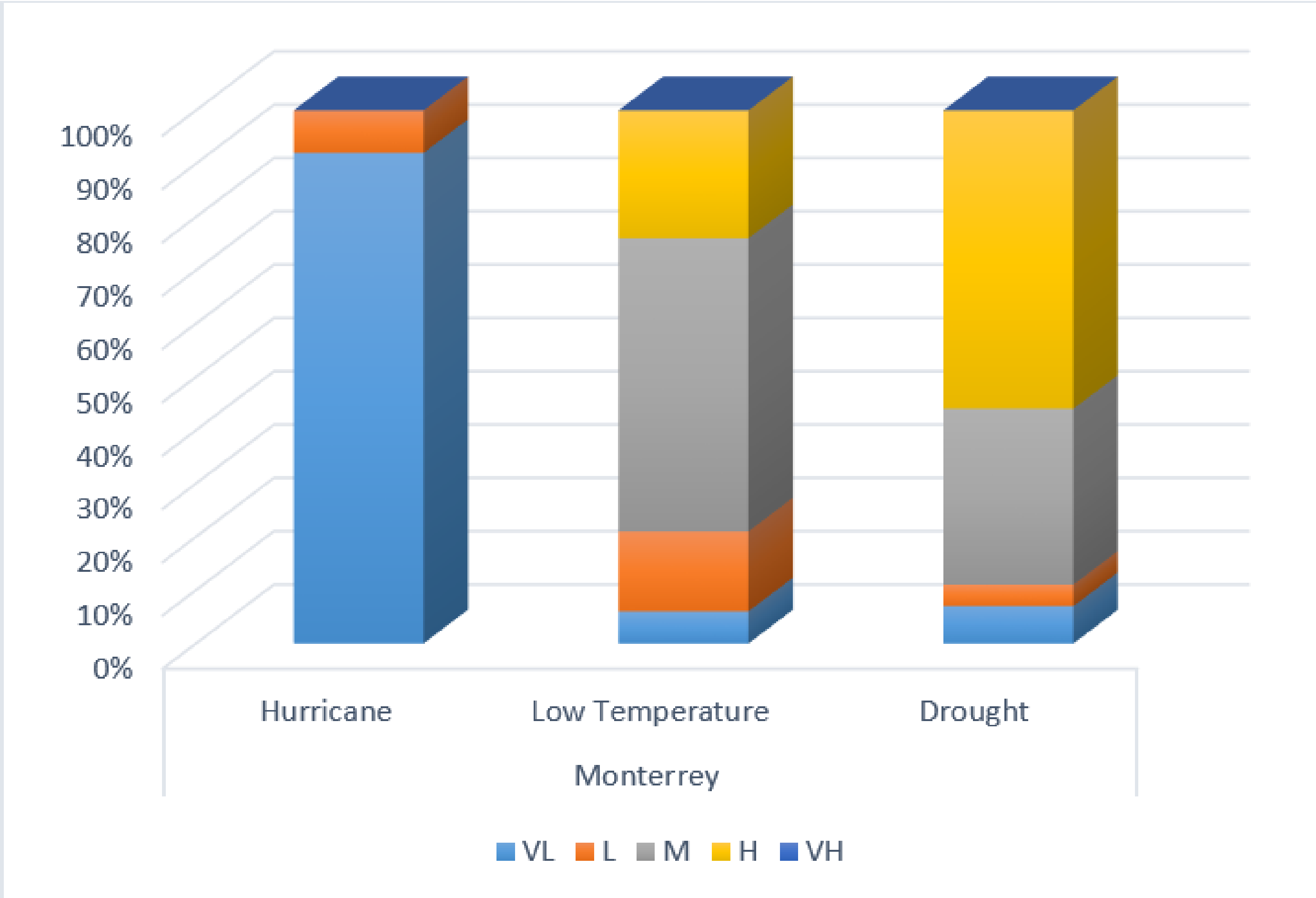

Figure 11

Risk indices for Monterrey.

Supplementary Files

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