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Theory and Applications

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Synopsis

In the last decades, the perception of dealing with disasters focuses on emergency response; however, it has been recognized that not only is the hazard related to coping with disasters but also reducing disaster risk, helping to prevent losses, and alleviating disasters impact.

This book comes up with contributions focused on optimization approaches that support the decision-making process in the challenge of managing the Disaster Risk Reduction (DRR) problems considering emerging disaster risks in the medium and long terms, as well as international and local applications. The contributions promote works that fill the gap between practical needs and research to suggest specific future research avenues, and last but not least, to inspire academics/researchers to engage in this important research field. Some of the topics covered include network flow problems, discrete optimization, multi-objective programming, approximation techniques, and heuristic approaches.

This book provides an answer to questions such as:

- Is—or should be—the field of humanitarian logistics concerned by the definition, measurement, and management of risk?
- How terms such as risk and those related to it, are conceived by the humanitarian logistics stakeholders?
- How is Disaster Risk Reduction currently integrated within the humanitarian supply chain decision-making?
- How are the humanitarian supply chain stakeholders' concerns are prioritized and integrated within the humanitarian supply chain decision-making?

This book gives strategies that improve the performance of the humanitarian supply chain. On the one hand, a model to distribute the COVID-19 vaccine is proposed, and several optimization algorithms are tested. The proposal is tested in the Argentine scenario. It features an important demonstration of the impact of an optimized distribution of the vaccine.

Also, by integrating the classic p-median problem and the Multiple Vehicle Routing Problem (MVRP), a case study was developed in Mexico. A logistic model to allow the feasible location to establish a warehouse to distribute the supplies for health sector personnel that give attention to people sick with COVID-19 is proposed.

The COVID-19 pandemic has challenged the entire world's health, social and economic systems. For that reason, it is important to analyze the effect of the policies government. This book presents a chapter that seeks to statistically analyze the effect of the policies proposed by the Mexican federal government on the number of weekly COVID-19 cases and deaths. The results show that the effects vary from state to state and depend on the real enforcement of the policies.

In addition, it was designed a geospatial and mathematical tool for the distribution of volunteers during lockdowns to aid vulnerable groups in obtaining supplies in the context of underdeveloped regions with insufficient resources and data. It established the service proximity, senior citizen population, and marginalization as crucial aspects of the modeling.

On the other hand, a vulnerability index comprising the dimensions of hazard, social and economic exposure, and preparedness is part of this book. Three quantitative techniques are combined to identify key indicators comprising the index, determine the relative importance of the vulnerability dimensions, and categorize the states of Mexico according to their level of vulnerability toward hydrological disasters.

Drought is a hydro-meteorological phenomenon with systemic implications that currently affect large territorial extensions in the world. Many factors provoke such a disaster, and this book introduces a better understanding of the construction of the reality of drought by characterizing the hydrological resources available in Mexico. They are supported by a qualitative methodology developed through a descriptive and exploratory analysis of the current conditions of hydrological resources in Mexico through the SINA (National Water System) records and the reports of CENAPRED (National Center for Disaster Prevention).

Furthermore, this book proposes a multi-criteria methodology for designing a relief distribution network that, using the Analytical Hierarchy Process, structures the stakeholders' preferences concerning humanitarian logistics' performance goals, including economic, social, and reliability goals. A sensitivity analysis is conducted to demonstrate that the proposed methodology helps find solutions that achieve very good performance concerning all the considered objectives.

In conclusion, the DRR problems can be managed with logistics strategies, which must be structured and agreed upon by all parties involved; otherwise, the implementation may not function properly. Therefore, logistics strategies take on extreme relevance in processes for future preventive operations.

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About the Editors

Fabiola Regis-Hernández is a Professor-Researcher at Tecnologico de Monterrey. She has 7 years of research experience in network flow problems, discrete optimization, multi-objective programming, approximation techniques, and heuristic approaches. She is the member of the National Council of Researchers (SNI). Her research focuses on real-life applications, such as humanitarian logistics, healthcare, and emergency management systems. Most of her experience has been developed jointly with colleagues from Université Laval (Canada), HEC Montréal (Canada), and the Istituto di Matematica Applicata e Tecnologie Informatiche (Italy).

Jaime Mora-Vargas is the Professor Associate Director for Graduate Programs in Engineering for the School of Engineering and Sciences at Tecnologico de Monterrey. He has more than 19 years of research experience in Complex Systems and Operations Research. His research activities focus on evolutionary computation and on the application of metaheuristic techniques to industrial and business problems, areas in which he has published numerous research papers in conferences and journals. He also served as the Director of Software Development of Adaptive Technologies, a company that developed artificial agent systems for predicting stock price movements. He holds an Engineering Physics degree from the Universidad Autónoma Metropolitana and a Ph.D. in Engineering (Operations Research) from the Universidad Nacional Autónoma de México. Finally, he is a member of the Academia Mexicana de Ciencias (Sciences Mexican Academy) and National Researcher System (Sistema Nacional de Investigadores) in Mexico.

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Part I
Pre-Disaster

Chapter 1
Impact of Mexican Public Policies in the Development of COVID-19 Pandemic

Irais Mora-Ochomogo, Fabiola Regis-Hernández, Adriana Aguirre-Jerez, and Isabel Coria P. V.

Abstract The COVID-19 pandemic has challenged the entire world's health, social and economic systems. More than a year after the declaration of the pandemic, the current situation of the different countries is defined by the actions taken towards containing the spread of the virus and reducing the number of deaths. Mexico has had one of the highest COVID-19 death tolls in the world and the policies implemented by the government have been questioned by some international agencies. This chapter seeks to statistically analyze the effect of the policies proposed by the Mexican federal government in the number of weekly COVID-19 cases and deaths. The results show that the effects vary from state to state, this depends on the real enforcement of the policies.

Keywords Humanitarian Response Distribution Center (HRDC's) · Humanitarian Logistics (HL) · P-median model · Vulnerability · Development indices

1.1 Introduction

The COVID-19 pandemic caused by the SARS-COV2 virus started an important shift in the way of life worldwide. On March 11th, 2020, the World Health Organization (WHO) characterized COVID-19 as a pandemic, recognizing that it was affecting the

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public health sector as well as the economic, social, educational sectors. With this, the WHO was making a call to build a comprehensive strategy to prevent contagions, saves lives, and minimize the impact in other sectors (WHO 2021a).

One year after this declaration, there have been more than 116 million cases and 2 million deaths worldwide (WHO 2021b). Even though the development of the vaccine and its daily administration promises a brighter future, each country's current situation highly depends on decisions made in the past year to control and mitigate the effects of the pandemic.

Each country has taken a different path of action towards handling the pandemic. Some of the most common policies implemented include closing international borders, establishing complete lockdowns, or having curfew or schedules for people to go out for essential activities. Some of the biggest questions about this topic can be, which of these policies are more effective to control the spread of the virus? And which countries are implementing them properly?

It is important to state that these measures should react to the current situation and should also attempt to prevent possible negative courses of action. Regarding this, the Sendai Framework for Disaster Risk Reduction provides a structured set of guiding principles that aim to prevent and reduce existing disaster risk with a vision that includes the economic, structural, legal, social, health, cultural, educational, environmental, technological, political, and institutional sectors.

Internationally, several studies have analyzed the different actions taken by governments to confront the effects of the pandemic. This to identify which countries have delt with it best and which have not. Among these studies there are the ones done by The Wall Street Journal (WSJ 2021), the Organization for Economic Co-operation and Development (OECD 2020) and the World Economic Forum (World Economic Forum 2020).

Another example of these studies is the indicator proposed by Bloomberg (Bloomberg 2021), in this indicator they seeks to identify the best and worst countries to be at during this pandemic. They used this indicator to develop the "Covid Resilience Ranking".

This ranking only includes the countries with an economy greater than $200 billion USD before the pandemic, that gives us a total of 53. These countries are evaluated according to 11 metrics and depending on each country's metrics a 0–100 score is assigned, and it gives them a place in the ranking (Hong et al. 2021).

The indicators used to determine each country's score are the following:

1. COVID-19 cases per 100,000 people over the past month.
2. COVID-19 deaths as a share of cases over the past month.
3. COVID-19 deaths per one million people since the start of the pandemic.
4. Percentage of COVID-19 tests that come back positive, based on latest available data
5. Percentage of population covered by vaccine supply agreements.
6. Number of COVID-19 vaccine doses administered per 100 people.
7. Lockdown severity - A high score indicates that social and economic activity are tightly restricted by government policy.

8. Movement of people to offices and retail spaces compared to a pre-pandemic baseline.
9. Year-on-year GDP change forecast for 2021.
10. The strength of a healthcare system, derived through the effectiveness of 23 aspects of health coverage, ranging from preventative measures like childhood vaccines to treatment of serious illness like cancer.
11. The well-being of a population is defined by three measures: life expectancy, access to education, income per capita.

As it can be observed in the metrics, the computed score comprehends beyond the health sector to determine the ranking. It includes the fundamental COVID-19 indicators of new cases and deaths as well as information about the vaccination process. Also, attending the country's economic sector includes mobility in working and retail places and GDP forecasts. Finally, they include the social sector with aspects such as health, education, and population income.

According to the indicators in the ranking, as of February 24th, 2021, the top countries that are the best to be during this pandemic are led by New Zealand, followed by Australia, Singapore, Finland, Norway, and China. In contrast, the lowest countries ranking up the last places of the 53 slots are Brazil in the 50th place, followed by Czech Republic, Peru, and Mexico in the last place.

Common strategies of the countries on the top of the Bloomberg Resilience Score include staying in strict lockdown until cases are low, opportunely, and fully closing borders for a longer or shorter period of time and relying on health experts for policy development.

As one example of success; New Zealand, which has not had local cases for over three months and social distancing measures were removed. The latter could be achieved without the vaccination, but only with the measures taken by the government. These measures include that the country closed borders and implemented a 2-week supervised quarantine for returning residents starting on March 19th. A few days later, they declared a state of emergency and executed strong containment measures, such as the closure of all non-essential businesses, cancellation of all events and gatherings, and closing schools.

Tracking and tracing the cases was also crucial for success in New Zealand; the app called *NZ COVID Tracer* made it easier to keep track of where people have been in contact with if they test positive (Ministry of Health 2021).

Unlike New Zealand, Latin American countries have not performed well on this ranking. Chile appears in the 32nd position, and the rest have a score that leaves them in the bottom ten countries of this list. The two countries that come last are Brazil and Mexico, which have taken similar paths towards containing the pandemic; neither of them has closed their borders to foreign flights. Nevertheless, Brazil did place restrictions to enter the country by land and requested a negative COVID-19 test to enter the county (Forbes 2020).

International agencies such as the World Health Organization and the Pan American Health Organization (PAHO) have made statements regarding the situation in Mexico and the policies that the country implemented during this COVID-19 pandemic. In June 2020, the PAHO remarked that in Mexico, not only the new cases and deaths kept increasing, but also the negative social and economic impact, additional to the general confusion on the social distancing measures within the red and orange of the color-coded system.

The main goal of this chapter is to identify the statistic effect that the policies implemented in Mexico at a federal level had on the number of new cases and deaths. Since the policies mainly include mobility restrictions, the effect on the mobility was also included.

The remaining document presents the situation in Mexico regarding government policies and measures in Sect. 1.2. Section 1.3 provides the information and methodology used for the numerical analysis. Section 1.4 presents the numerical analysis results that evaluate the relationship of the government policies and mobility indicators as factors to explain and predict new cases and deaths in each state. Finally, Sect. 1.5 presents the conclusions of this study.

1.2 How Has Mexico Dealt with the COVID-19?

Mexico has a population of 126 million people approximately (INEGI 2020). Since the pandemic started and until March 2021, Mexico had confirmed more than 2 million cases and about 190,500 deaths, becoming the third country with the most COVID-19 deaths in the world (WHO 2021b). Nevertheless, local authorities have highlighted that numbers are likely to be higher than those reported in the news (BBC News 2020). This situation has led us to the question: how efficient has been the pandemic management in Mexico? In the remainder of this section, an overview of the country's economic and health system and its public policies will be provided.

This section describes the public health measures that have been implemented during this crisis as well as their impact on the economic and health care systems.

1.2.1 Public Policies and Their Social Impact

Mexico is divided into 32 states, including its capital, Mexico City. As other countries like the US, Mexico has decided to manage the pandemic situation by state, acknowledging that each state presents its particularities and challenges. For example, Mexico City, the most densely populated state in the country with 6,163 people per km^2 and the one with the highest COVID-19 cases nationwide (INEGI 2021), also holds an important number of economic, social, and governmental activities, making the task of containing the pandemic an overall challenge.

On June 1st, 2020, Mexico announced the COVID-19 monitoring system to track the level of epidemiological risk in each state. This monitoring system follows a color-coded mechanism that determines what activities are safe to resume and the social distancing restrictions in each state. This color-coded framework consists of four colors, each color (i.e., green, yellow, orange, and red) represents a level of epidemiological risk characterized by specific safety measures.

To estimate this epidemiological risk, the Ministry of Health considers the following indicator guidelines for risk assessment (Secretaría de Salud 2021):

1. COVID-19 effective reproductive number (R).
2. Incidence rate of estimated active cases per 100 000 habitants.
3. Mortality rate per 100,000 inhabitants.
4. Hospitalizations rate per 100 000 inhabitants.
5. Percentage of general occupied beds in designated hospitals treating severe acute respiratory infections.
6. Percentage of occupied beds with ventilators in designated hospitals treating severe acute respiratory infections.
7. Weekly percentage of positive cases.
8. Trends in hospitalization cases per 100 000 habitants.
9. Trend in COVID-19 syndrome cases per COVID-19 syndrome.
10. Trend in mortality rate per 100 000 habitants.

According to each of the colors, different restrictions and policies are in place, Table 1.1 presents an overview of the policies that apply under each of the colors (Gobierno de México 2020).

Several recommendations for each color integrate this color-coded framework at a federal level. These are intended to reduce the risk of infection in each entity by reducing the mobility of people. Each state's government oversees the enforcement of the recommendations. Also, the state and local governments have the liberty of implementing extra restrictions to adapt better to each state's circumstances. These additional measures may result in different rates for new cases and deaths.

Mexico has found in the pandemic a challenge of keeping the economic sector active while promoting the compliance of the public health measures to reduce the number of new cases and deaths. A further description of the Mexican economic

Table 1.1 Description and policies according to the traffic light in each state

COVID-19 framework	Policies
Red	Just essential economic activities are allowed.
Orange	Besides essential economic activities, it is allowed for not essential business to work with their 30% capacity, always considering the operational safety measures, especially for people with a higher risk in case of contagion. Public spaces will be open but with reduced capacity.
Yellow	All working activities are allowed, having special considerations for people with a higher risk in case of contagion. Public open spaces are open as regular, and enclosed public spaces can be open but with reduced capacity.
Green	All activities are allowed, including schools.

sector and the Impact the COVID-19 has had on the health care system of the country are explained in this section.

1.2.2 Economic Impact

In Mexico, micro, small, and medium enterprises (SMEs) are considered the main engine of the economy since they generate 72% of employment and use 52% of the country's Gross Domestic Product (GDP). According to a national survey on Productivity and Competitiveness of Micro, Small and Medium Enterprises in México, 99% of the manufacturing and service companies are micro and small industries (International Finance Corporation 2018).

According to Forbes (2021), the economic situation derived from the COVID-19 is the worst since the great depression. It also reports a fall of 8.5% of constant prices and 10.2% regarding industrial activities in the Mexican economic sector.

Despite these alarming results, a slow recovery can be observed in the Gross Domestic Product (GDP), this tendency is shown in Fig. 1.1. The recovery happened in the last quarter of 2020 and it is the result from a slow removal of restrictions, just after the strict period of lockdown in the second quarter of the year (Cullell 2021).

The effects of the pandemic in the economic and healthcare areas have shown an inverse relationship between them. As mentioned before, the economy seems to improve with the decreasing of the restrictions imposed by the government. However, the removal of restrictions also showed an effect in the increase of new cases, affecting the healthcare system.

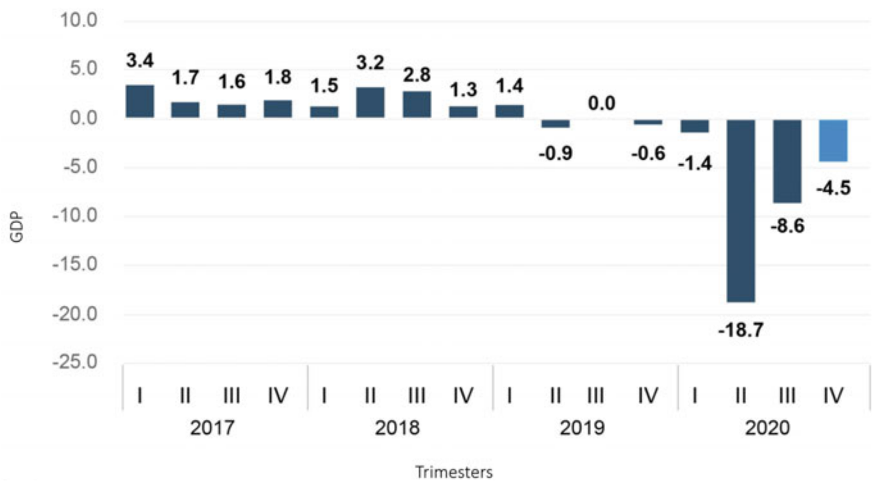

Fig. 1.1 GDP growth comparison (Cullell 2021)

1.2.3 Health Care System and Vulnerable Population

The pandemic has raised several questions related to the healthcare system's capacity to handle the situation. It is essential to mention that Mexico has dealt with two main issues in this sector, the capacity of the public health care system and the vulnerability of a significant part of the population.

As presented in Sect. 1.2.1, the percentage of hospital beds occupied is one indicator used for the epidemiological risk assessment to determine the color in the color-coded system. According to the Organization for Economic Co-operation and Development (OECD) when the pandemic started, Mexico had an average of one bed per 1,000 inhabitants, this number positions Mexico as the second country with the least beds just after India. This number is low compared with other countries such as China, that had 4.3 beds per 1,000 inhabitants and by now has successfully tackled the pandemic (Bloomberg 2021; OECD 2019).

An overview that presents some of the most representative countries that belong to the OECD can be observed in Fig. 1.2.

In addition to the lack of public infrastructure, Mexico has one of the highest percentages of people with comorbidities worldwide including obesity, hypertension, diabetes, among others. These comorbidities have proven to increase the vulnerability in COVID-19 patients (CDC 2020). This means that the Mexican population has a

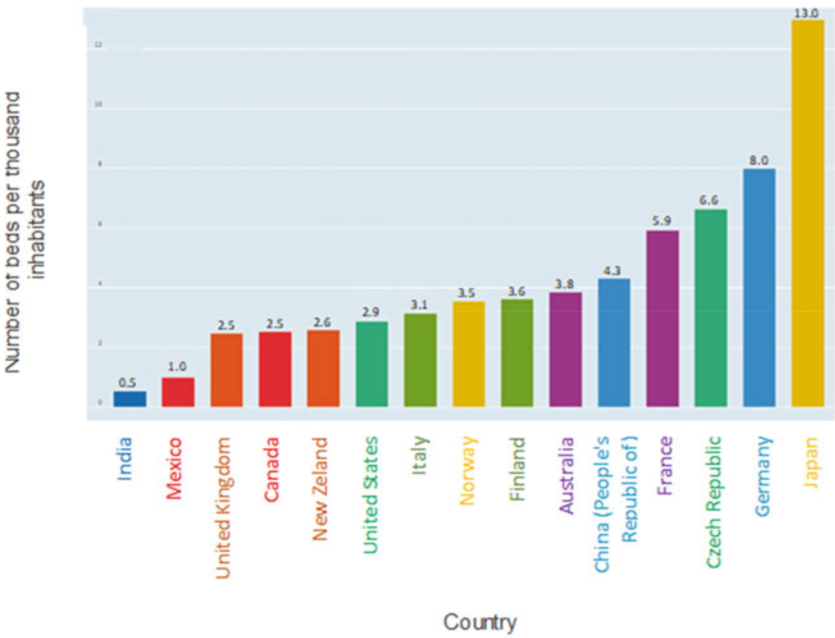

Fig. 1.2 Hospital beds per 1 000 inhabitants, 2019 or latest available

higher probability of having severe complications, leading to a higher use of the ICU and the saturation of this service.

As an example of this situation, is presented in Table 1.2 where the case of three states: Mexico City, State of Mexico and Chiapas is provided. These states were chosen due to some particularities. Mexico City is the state with the most COVID-19 cases, State of Mexico is the most populated state, and Chiapas is the least infected and one of the least populated.

The numbers in Table 1.2 lead us to the hypothesis that the density of the population has a vital role in the quick propagation of the virus. Thus, the density of the population is an essential factor that should be considered when analyzing the progress of the disease in different states.

Table 1.2 Comparison table of population statistics, COVID-19 cases and comorbidities in three representative Mexican states

	Mexico City	State of Mexico	Chiapas
Confirmed cases	584,927	225,760	10,833
Population density (people/km2)	5,967.29	724.23	71.17
Total cases per 100,000 inhabitants	7,132	1,500	208
Population without affiliation to health services (%)	20.78	20.63	17.28
Max. general hospital beds occupancy (%)	91.98[a]	85.73[b]	14.93[c]
Hospital beds with ventilator occupancy (%)	85.52[a]	78.16[b]	10.83[c]
ICU hospital beds with ventilator occupancy (%)	91.84[a]	85.71[b]	7.14[c]
%population > 19 years old			
With **obesity**	36	33	29
With **hypertension**	20	16	16
With **diabetes**	13	9	8
% population > 59 years old			
With **obesity**	34	34	24
With **hypertension**	47	37	34
With **diabetes**	34	20	21

[a] Mexico City presented its occupancy peak on January 9th, the data collected corresponds to this day according to the Health Minister of Mexico

[b] The State of Mexico presented its occupancy peak on January 17th, the data collected corresponds to this day according to the Health Minister of Mexico.

[c] Chiapas presented its occupancy peak on January 14th, the data collected corresponds to this day according to the Health Minister of Mexico. (Secretaría de Salud and UNAM 2021)

1.3 Methodology

This section describes the database used for the numerical analysis, the goals and hypotheses sought in this research, as well as the specific methodology used to validate those hypotheses.

1.3.1 Database

The database for the numerical analysis was built mainly with the official information of the Mexican government. Another external source was the Google mobility indexes (Google 2021). The data used is from March 16th, 2020, when the lockdown and social distancing measures started in some states, to February 21st, 2021. As the crisis is still going on, further analysis with updated data is recommended.

All the variables used for the numerical analysis, their description, and the sources are presented in Table 1.3.

As stated before, most of the information used is from the Mexican government's official database. This information includes the weekly color assigned to each state, weekly new cases, weekly deaths, the proportion of new cases, and weekly deaths. These two last variables were computed considering the population reported in the official COVID-19 database.

It is important to highlight that the new cases and deaths have a one-week offset from the assigned color and the mobility index variables. This offset was included to consider the virus's incubation time. Experts have found that the median of the incubation period after exposure is of four to five days (CDC 2021); therefore, the effects of the policy and mobility changes would develop after this time. The states are named and ordered according to the Mexican Government COVID-19 database and were assigned the corresponding number.

Finally, the mobility variation index was developed by Google, using the anonymized cell phone location of the Google Maps users to track the general mobility of specific locations worldwide. These reports intend to provide important information into what has changed in response to the different policies set to reduce the spread of the virus. The reports record the movement trends over time by geography in the different categories mentioned in Table 1.4 (Google 2021). In Mexico, the information of each category is provided nationally and per state. These variables of the mobility index were scaled for a more accurate analysis. The technique used was min–max scaling.

Table 1.3 Description of variables used for the numerical analysis

Variable	Description	Source
State	*Categorical variable.* It provides the state of Mexico to which the data corresponds. This variable has 32 values corresponding to the states in Mexico.	Mexican government official database
Weekly new cases	*Numerical variable.* It provides the number of new COVID-19 cases accumulated in a week per state. The sum comprises from Monday to Sunday for each week.	
Weekly deaths	*Numerical variable.* It provides the data of accumulated deaths due to COVID-19 in a week per state. The sum comprises from Monday to Sunday for each week.	
Proportion new cases	*Numerical variable.* It provides the fraction of weekly new cases per state concerning the state's population.	
Proportion deaths	*Numerical variable.* It provides the fraction of weekly deaths per state concerning the state's population.	
Color-coded framework	*Categorical variable.* It provides the policies being applied per week in each state. This variable has five values, including red, orange, yellow, green, and no color. The last one corresponding to the early weeks when the traffic light was not being applied.	Weekly reports on updates of color-coded policies framework
Google Mobility variation index	*Numerical variable.* It provides the mobility tendencies compared to a baseline per state and for each place's category. The categories included are retail and recreation, grocery and pharmacy, parks, transit stations, workplaces, and residential.	COVID-19 Community Mobility Reports from Google

Table 1.4 Identification number for the 32 states in Mexico

ID	State	ID	State	ID	State	ID	State
1	Aguascalientes	9	Distrito Federal	17	Morelos	25	Sinaloa
2	Baja California	10	Durango	18	Nayarit	26	Sonora
3	Baja California Sur	11	Guanajuato	19	Nuevo Leon	27	Tabasco
4	Campeche	12	Guerrero	20	Oaxaca	28	Tamaulipas
5	Chiapas	13	Hidalgo	21	Puebla	29	Tlaxcala
6	Chihuahua	14	Jalisco	22	Queretaro	30	Veracruz
7	Coahuila	15	Mexico	23	Quintana Roo	31	Yucatan
8	Colima	16	Michoacán	24	San Luis Potosi	32	Zacatecas

1.3.2 Goal of the Numerical Analysis

The general goal of the numerical analysis is to prove statistically the effect of the policies implemented by the federal government in Mexico with the color-coded framework. The effect will be measured considering the increase or decrease of mobility in each category and the proportion of weekly new cases and deaths at a national and state level.

From that general goal it can be defined as a set of more specific goals. These goals are the following:

1. Define the impact of the color-coded framework on the population mobility at a national level.
2. Define the relationship between population mobility and weekly COVID-19 cases and deaths.
    a. At a national level
    b. At a state level
3. Define the effect of the color-coded framework on the proportion of weekly COVID-19 cases and deaths.
    a. At a national level
    b. At a state level.

1.3.3 Methodology Selection

The methodology selection to achieve the previously stated goals, required an initial analysis of the response variables, i.e., the weekly new cases and deaths. This analysis includes histograms to identify the behavior of the variables. These histograms are shown in Fig. 1.3.

One of the methods used to define the relationship between numerical values is the correlation coefficients. A correlation coefficient measures the extent of the

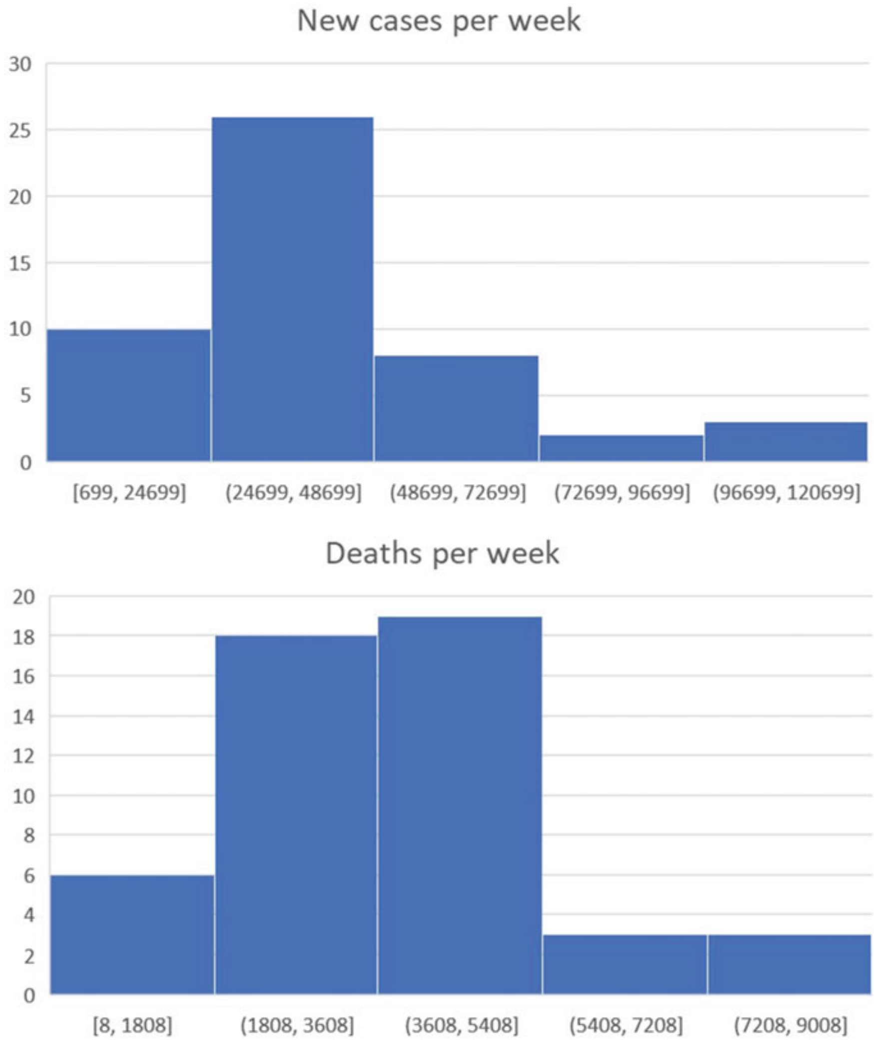

Fig. 1.3 Histogram for response variables

relationship between two numerical variables, it shows the strength of the association between these two variables as well as the direction of it. The coefficients Pearson and Spearman were used for this purpose.

The Pearson coefficient measures a linear relationship between the two variables, while the Spearman coefficient evaluates the monotonic[1] association between two variables.

[1] Being monotonic means that both variables tend to change together, but not necessarily at a constant rate.

The values of these coefficients range between −1 and 1. A value closer to 1 means a strong direct relationship between the variables, while a value close to −1 shows a strong inverse relationship between the variables. Finally, a close value to 0 in both coefficients depicts a non-existent relationship between the two variables (Kackson 2015; Peck 2015).

For the relationship, including categorical values, the tendencies of the response variables must be considered. As presented in the histograms, neither of the response variables comply with the normal distribution assumption for parametrical tests. Therefore, the statistical methods used for the analysis were non-parametrical, specifically the Kruskal–Wallis and the Wilcoxon test. To perform these tests, it was stated that the medians of each group are statistically equal as the null hypothesis $H_0 : \tau_1 = \tau_2$; $H_a : \tau_1 \neq \tau_2$ (Hollander et al. 2014; Linebach et al. 2014).

The results were computed using the statistical software Minitab 19 and R.

1.4 Numerical Analysis

This section includes the results of the numerical analysis of the specific goals presented in Sect. 1.3.2. For each goal, the methodology used was described, present the highlights of the results, and discuss some of the most important practical implications.

1.4.1 Goal 1: Impact of the Color-Coded Policy Framework on Mobility

As mentioned previously, public policies, to a great extent, seek to reduce the mobility of the people to avoid crowds. Goal 1 seeks to validate if the color-coded policy framework's policies impact the Google mobility index. This goal was verified with the Wilcoxon test for each mobility index.

The results for the tests are presented in Fig. 1.4. Each intersection of the tables represents a p-value, where the red circle means the rejection of the null hypothesis ($p \leq 0.05$). In contrast, the green circle means not rejecting the null hypothesis ($p > 0.05$). Therefore, there is not enough evidence to reject the null hypothesis, and the medians are not statistically different.

The places that were more regulated and restricted were the places of retail and recreation. The results show that the mobility in those places is not affected once the color reaches orange. This behavior is also present in the workplaces and residential areas, this behavior will be further explored in Goal 2.

The rest of the places were mostly regulated in terms of the allowed capacity in the closed establishments. The results do not show a conclusive tendency of the change in mobility.

Fig. 1.4 Results from Wilcoxon test on the effect of the different factors on mobility

1.4.2 Goal 2: Define the Relationship of Population Mobility and Weekly COVID-19 Cases and Deaths

Lockdowns and social distancing policies have been the go-to policies in most countries to limit the COVID-19 spread. These policies restrict mobility and avoid the concentration of a lot of people in closed and open places. Some research studies have tested the efficacy of the different levels of mobility restriction and concluded that social distancing and lockdowns do have an impact in the spread (Ando et al. 2021; Gondauri and Batiashvili 2020).

Indeed, Goal 2 seeks to identify a direct relationship between the mobility indexes reported by Google and the number of weekly new cases and deaths at both a national and state level.

1.4.2.1 Goal 2.i Impact at a National Level

The Pearson and Spearman coefficients were computed with each of the mobility indexes and the two response variables, number of weekly deaths and weekly new cases. The results are presented in Tables 1.5 and 1.6 correspondingly.

It can be seen that the values obtained for both indexes are very close to zero, even though the values tend to increase in the Spearman coefficient compared to the Pearson coefficient.

Since they are not high or low enough, these values mean that the mobility, expressed in this case by the Google mobility indexes, does not explain clearly either the variables of new cases or deaths.

Table 1.5 Pearson Coefficients for mobility coefficients and deaths or new cases

	Retail and recreation	Grocery and pharmacy	Parks	Transit stations	Workplaces	Residential
Deaths	−0.043	0.098	−0.111	−0.043	−0.095	0.126
New cases	−0.009	0.088	−0.091	0.016	−0.055	0.063

Table 1.6 Spearman Coefficients for mobility coefficients and deaths or new cases

	Retail and recreation	Grocery and pharmacy	Parks	Transit stations	Workplaces	Residential
Deaths	0.048	0.181	−0.053	0.024	0.006	0.028
New cases	0.164	0.26	0.047	0.178	0.129	−0.105

1.4.2.2 Goal 2.ii Impact at a State Level

With the database divided by state, the two correlation coefficients were determined once again to identify specific patterns or tendencies different from the national trend. For each state, 12 coefficients were obtained, considering the six mobility indexes and the two response variables.

The results showed that most states followed the national tendency of a weak correlation between the mobility index and the number of new cases and deaths for both coefficients except for a few states. For this analysis, the correlation indexes of more than 0.5 or less than −0.5 were accounted as a significant correlation.

The states Aguascalientes, Chiapas, Coahuila, Nuevo León, and Zacatecas showed a significant linear correlation in at least six of the twelve significant Pearson coefficients. On the other hand, the states that showed a non–linear correlation with at least six of the twelve significant Spearman coefficients are Aguascalientes, Coahuila, Jalisco, Querétaro, and Zacatecas. The ones that coincide in both are Aguascalientes, Coahuila y Zacatecas.

In general terms, it can be seen that on one side, from the states that showed a significant correlation, there is a pattern of direct relation of the mobility in places such as Retail and recreation, Grocery and pharmacy, Transit stations, and Workplaces with the increase of cases and deaths in these states.

Also, from these states, an inverse relation can be identified with the mobility in Residential areas. This finding means that in these states, the recommendation of staying at home does reduce the incidence of new COVID-19 cases and deaths. Tables 1.7 and 1.8 present an example of this pattern with the coefficients of Aguascalientes.

Even though they have not reached the green in the color-coded framework, Aguascalientes, along with Zacatecas, were placed among the top ten states with the best regulation practices in a state of emergency, according to a study made by ESZ Smart Solutions and the National Commission for Regulatory Improvement at the end of 2020 (Ortega Neri 2020).

Table 1.7 Aguascalientes Results–Pearson correlation coefficient

	Retail and recreation	Grocery and pharmacy	Parks	Transit stations	Workplaces	Residential
Deaths	0.637	0.584	−0.293	0.561	0.633	−0.637
New Cases	0.527	0.524	−0.346	0.522	0.617	−0.554

Table 1.8 Aguascalientes Results–Spearman correlation coefficient

	Retail and recreation	Grocery and pharmacy	Parks	Transit stations	Workplaces	Residential
Deaths	0.603	0.566	−0.266	0.622	0.625	−0.601
New Cases	0.516	0.596	−0.28	0.644	0.633	−0.566

In the case of Aguascalientes, more severe mobility restrictions were implemented with the increase of new cases at the beginning of 2021, and specific guidelines were developed according to the type of business or activity (Gobierno del Estado de Aguascalientes 2021).

As much as these coefficients give us valuable insight into the behavior, the results obtained cannot derive a particular conclusion. To perform this analysis using another mobility index or mobility indicator and contrast the result with the ones presented could help validate them.

1.4.3 Goal 3: Impact of the Color-Coded Framework on New Cases and Deaths

Goal 3 seeks to identify the impact of the implemented color-coded policy framework on the proportion of new cases and deaths at national and state levels.

1.4.3.1 Goal 3.i Impact at a National Level

Goal 3.i focuses on the national level. This hypothesis was tested with two non-parametrical tests Kruskal–Wallis and Wilcoxon, using the weekly fraction of new cases and deaths as the response variable. The factor used for these tests was the categorical variable of the different colors of the color-coded policy framework, including five levels, red, orange, yellow, green, and no color. The "no color" level represents the first weeks of the development of the pandemic in Mexico when no federal regulations were implemented, and the policies were defined on each state's emergency level.

Table 1.9 presents the computed statistic and p-value for a fraction of new cases and deaths. It can be seen that in both cases, the p-value at a national level is significantly

Table 1.9 Value of the statistic and p-value of the Kruskal–Wallis test for fraction of new cases and fraction of deaths

Response variable	Kruskal–Wallis statistic	p-value
Fraction of new cases	649.08	< 2.2e-16
Fraction of deaths	624.3	< 2.2e-16

lower than 0.05. With this p-value, the null hypothesis can be rejected and prove that at least one median of the different colors is statistically different with a level of confidence of 95%.

This result implies that there is an effect of at least one color on the proportion of new cases and deaths at a national level.

Once one median was different, the Wilcoxon test was performed to establish which medians could be considered statistically equal or different.

Figure 1.5 presents two tables with the levels of the color framework variable. Each intersection of the tables represents a p-value, where the red circle means the rejection of the null hypothesis ($p \leq 0.05$). In contrast, the green circle means accepting the null hypothesis ($p > 0.05$). Therefore, there is not enough evidence to reject the null hypothesis, and the medians are not statistically different.

For both response variables, the null hypothesis was rejected for most of the p-values, meaning that the color-coded policy framework does impact the increase or decrease of the fraction of new cases and deaths.

The hypothesis that there was no difference between a red or orange color according to the color-coded policy framework cannot be rejected for the variable new cases. This conclusion means that, at a national level, there is no significant difference between being in either of those two colors.

The latter could be due to two causes (1) the additional restrictions implemented when the color is red do not have an effective outcome on reducing the fraction

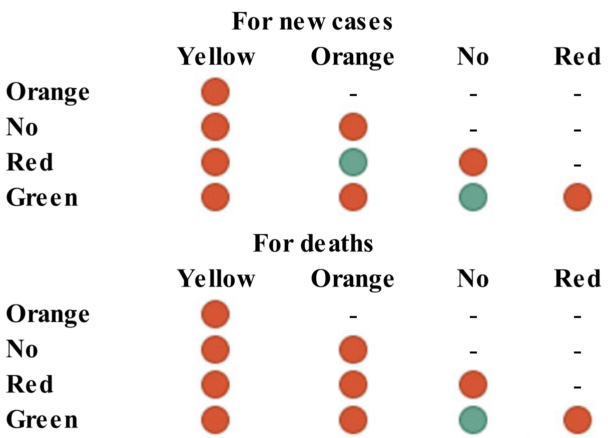

Fig. 1.5 Results from Wilcoxon test on the effect of the different factors on the fraction of new cases and deaths

of new cases, or (2) the population nationwide lacks understanding or compliance regarding the restrictions.

1.4.3.2 Goal 3.ii Impact at a State Level

Since compliance of the population is vital for the effectiveness of the policies, goal 2.ii seeks to identify the states where the implemented restrictions affect stopping the spread and decreasing the death rate.

To test this hypothesis, the same non-parametrical tests used for Goal 2.i were applied but this time considering only the data per state. First, the Kruskal–Wallis test was implemented. Table 1.10 presents the results of the test for each response variable (Resp.). The results include the test statistic and the p-value, the ID used for each state are the ones assigned in Table 1.4. These results show that for all states at least one median is statistically different, therefore all p-values are below 0.05.

Figure 1.6 presents two regions in Mexico (i.e., Nuevo León and Mexico City) that have only been assigned with colors red and orange along with the pandemic, including the period where no national color-coded policy framework was implemented. This situation means that both regions had high levels of new cases and deaths, but, as the results show, the effect of the color-coded policy framework implementation had a different impact. For both cases, the proportion of new cases was not affected by the change of emergency level (i.e., color from red to orange) following the national tendency.

For the proportion of deaths in each state, the two states present the opposite scenarios. In the case of Nuevo León, any change of color represents a statistical chance in the fraction of deaths; however, in Mexico City, the fraction of deaths does not change independently of the current color.

Mexico City has been the state with more deaths nationwide; therefore, the lack of impact at any emergency state to the availability of oxygen tanks and ventilators, the saturation of hospitals, or the lack of proper resources to treat COVID-19 patients can be attributed.

The states that present an impact in at least half of the policies are defined as high impact while the ones that have less than half of significant relations are defined as low impact. This classification is presented in Table 1.11, the numbers presented are the corresponding to Table 1.4.

The results show no conclusive behavior in the impact of the policies since there are exactly half of the states with a high and low policy impact. Therefore, other factors such as additional state policies, effective compliance to the policies, and more robust health systems could have a more critical effect on the response variables of some states.

Table 1.10 Value of the statistic and p-value of the Kruskal–Wallis test for fraction of new cases and fraction of deaths per state

ID	Resp.	Stats	*p*-value	ID	Resp.	Stats	*p*-value
1	NC	26.322	8.166e-06	17	NC	10.956	0.01196
	D	24.967	1.569e-05		D	14.645	0.002146
2	NC	17.346	6.00E-04	18	NC	26.762	6.603e-06
	D	19.825	0.0001845		D	27.29,	5.119e-06
3	NC	25.069	1.494e-05	19	NC	29.191	4.585e-07
	D	26.838	6.365e-06		D	25.505	2.895e-06
4	NC	25.382	4.216e-05	20	NC	21.512	8.242e-05
	D	30.643	3.62e-06		D	22.624	4.836e-05
5	NC	18.299	0.001079	21	NC	26.2	8.661e-06
	D	18.702	0.0008993		D	29.016	2.223e-06
6	NC	17.533	0.0005491	22	NC	25.907	9.977e-06
	D	11.864	0.007863		D	25.79	1.055e-05
7	NC	25.943	9.802e-06	23	NC	22.429	5.311e-05
	D	29.615	1.663e-06		D	8.7026	0.03352
8	NC	33.694	2.299e-07	24	NC	25.138	1.445e-05
	D	32.019	5.187e-07		D	24.623	1.851e-05
9	NC	19.279	6.51e-05	25	NC	15.138	0.001703
	D	5.3779	0.06795		D	18.351	0.0003723
10	NC	26.345	8.077e-06	26	NC	28.22,	3.266e-06
	D	25.293	1.341e-05		D	31.774	5.84e-07
11	NC	27.437	4.768e-06	27	NC	29.311	1.927e-06
	D	32.599	3.913e-07		D	26.948	6.036e-06
12	NC	16.133	0.001065	28	NC	28.904	2.346e-06
	D	12.803	0.005083		D	32.966	3.275e-07
13	NC	25.632	2.716e-06	29	NC	28.576	2.749e-06
	D	17.782	0.0001376		D	30.899	8.926e-07
14	NC	27.835	9.032e-07	30	NC	22.021	0.0001985
	D	25.403	3.046e-06		D	23.988	8.033e-05
15	NC	15.346	0.0004653	31	NC	27.361	4.947e-06
	D	16.262	0.0002942		D	19.369	0.0002294
16	NC	25.05	1.508e-05	32	NC	25.573	2.798e-06
	D	29.848	1.485e-06		D	24.707	4.314e-06

NC: New cases; **D:** Deaths

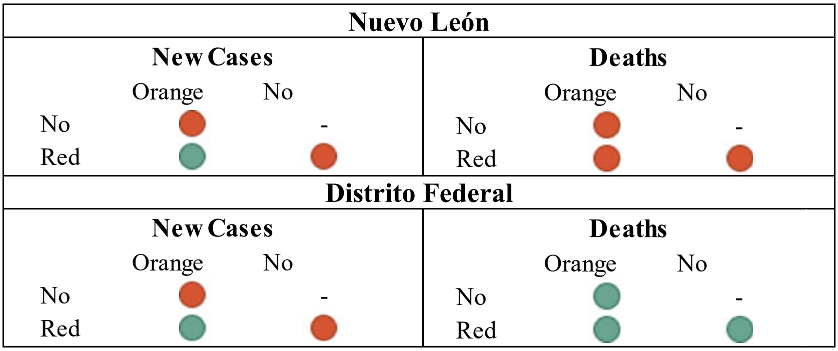

Fig. 1.6 Results from Wilcoxon test on the effect of the different factors on the fraction of new cases and deaths for the state of Nuevo León and Distrito Federal

Table 1.11 Classification of states according to the impact of the color-coded policies

Low Policy Impact				High Policy Impact			
2	6	12	24	1	14	19	27
3	7	17	25	8	15	20	28
4	9	22	30	11	16	21	29
5	10	23	31	13	18	26	32

1.5 Conclusions

The COVID-19 pandemic has challenged the entire world's health, social and economic systems. More than a year after the declaration of the pandemic the current situation of the different countries is defined by the actions and measures taken towards containing the spread of the virus and reducing the number of deaths.

Mexico has had one of the highest COVID-19 death tolls and the policies implemented by the government have been questioned by some international agencies. Therefore, in an effort contribute to the analysis of the effect of these policies, the objective of this research was to use the data provided by the Mexican government to validate the statistical effect of the policies in the number of weekly COVID-19 cases and deaths.

The policies on a federal level were dictated by a color-coded framework with specific restrictions applied on a state level. These restrictions were mostly focused on limiting the mobility of the population and avoid concentration of people. To determine each state's color, there was a weekly evaluation of different indexes regarding mostly the number of active cases and hospital occupancy. Even though the color-coded policy framework was defined at a federal level, each state was in charge of the compliance of the restrictions and were free to incorporate additional if they saw fit.

The specific goals of this research addressed the relationship among the color of the framework, a mobility index developed by Google and the number of weekly cases and deaths due to COVID-19 on a national and state level. Goal 1 made a non-parametric analysis if there was a statistical impact of the policies implemented and the mobility at a national level. The Wilcoxon test performed included all the combinations of colors in each of the categories given in the mobility index. The results showed that for most of the categories the difference was statistically significant with a p-value of less than 0.05. The combination that was not significant in five out of six categories was the one between the green and yellow colors. With this it can be seen that either the mobility policies did not change in those two colors or the population did not change their mobility pattern.

Goal 2 observed the relationship of the mobility index with the proportion of new cases and deaths at a national and state level. This relationship was measured with the correlation coefficients Pearson and Spearman. The results of this analysis showed that there was no direct relationship between the Google mobility index and the increase or decrease of new cases or deaths at a national level. In the analysis by state, the behavior was similar in most states.

Finally, goal 3 focused on the impact of the entire set of policies stated by color on the number of new cases and deaths. This analysis was also made at a national and state level. The statistical analysis was made with the Kruskall-Wallis and Wilcoxon tests. The results for the national case showed that for new cases, the chance of color from red to orange did not have a significant relevance while for deaths most of the changes of policies had an impact.

The results of this study contribute to the understanding of the effect of the different policies on the development of the pandemic and could be compared with other type of analysis in order to develop better strategies for the future.

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Chapter 2
Clustering of Highly Vulnerable Mexican Municipalities to Develop Humanitarian Public Policies

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Abstract The topic of Humanitarian Logistics (H.L.) is vital because it refers to the processes and systems involved in mobilizing people, resources, skills, and knowledge to help vulnerable people when some phenomenon negatively impacts them. For this intervention, it is necessary to have planning and coordination among the different actors involved in Humanitarian Aid. They need to know the risks and the vulnerabilities of the zone and the actors that could participate. The purpose of this paper is to provide a precise segmentation of the vulnerable zones and support the national strategic decisions at the time of planning, coordinate, and delivering humanitarian aid. Eleven statistical methods of clustering were used in order to suggest the k-clusters for the Mexican municipalities. The best number of clusters was selected through the analysis of 26 indexes. We took two vulnerability studies previously developed by other institutions. One study concluded that there are 319 vulnerable municipalities, and the other concluded 412 vulnerable municipalities. For this research, high and very highly vulnerable municipalities were considered, and the frequency of hydro-meteorological events impacted the zone. For instance, the proposed cluster was two or three, while two were four or two.

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Keywords Vulnerability · Humanitarian logistics · Clustering analysis · Humanitarian aid · Public politics

2.1 Introduction

A disaster is a severe disruption of a community's functioning or a society with human, environmental, material, and economic losses, which exceed the affected community or society's ability to cope using its resources (International Academy of Astronautics 2010). This disruption can be reduced if the community has a previous preparation that mitigates the negative impacts (Caballero-Morales et al. 2018). Therefore, it is essential to be resilient and still more because, according to data from the International Disaster Database (EM-DATA 2015a), the Americas is the second-largest continent with more frequent natural disasters.

In Mexico, according to the statistics generated from 1999 to 2012, the more frequent natural disaster that impacts the country is the hydrometeorology type, like extreme temperatures, rains, and floods, which is conjoined make 70%. In 2012, the affected population totaled just over one million people; damaged homes totaled 52 377, a level much lower than those registered during 2010 that totaled more than 227 000; and the affected schools were 718 being less compared to 3,889 that were counted in 2011 (CENAPRED 2013).

Mainly, these damage and losses affect with more severity to the vulnerable population. In the 64.5% of the municipalities declared as the disaster in 2012, the population had high poverty and marginalization (CONEVAL, retrieved June 2017; INEGI, retrieved June 2017). For many government programs such as the Special Program of Science, Technology, and Innovation (PECiTI 2014–2018), Special Climate Change Program (ECCP 2014–2018), and National Space Activities Program 2013–2018; the priority issue is to reduce the vulnerability of the population and productive sectors, increasing their resilience and resistance to strategic infrastructure. It is crucial to consider vulnerability because societies can respond to climate change (Ibarrarán et al. 2010).

Therefore, it is vital to strengthen the knowledge about disaster risk management and humanitarian logistics in Mexico because a successful disaster response is not improvised; it must be planned. The objective of this paper suggests the clustering of municipalities recognized as highly and very highly vulnerable as well as the frequency of hydro-meteorological events impacted in the zone, through of making a benchmarking among eleven hierarchical and partitioning statistical methods in order to provide a precise segmentation of the vulnerable zones and can support the national strategic decisions.

2.2 Literature Review

An essential question in Humanitarian Logistics (H.L.) is when and how the key actors should collaborate and how they should be coordinated (Van Wassenhove, 2006). One attempt to solve these problems with a cluster system proposed by Jahre et al. (2010) is essentially a template of how coordination should be carried out in several areas. The cluster concept is defined functionally in terms of activity areas—for example, water and sanitation, health, shelter, and nutrition—which typically reflects the essential and somewhat separate areas of relief work, often referred to as sectors.

Clustering is "the process of organizing objects into groups whose members are similar in some way." A cluster is, therefore, a collection of objects, which are "similar" to each other and "dissimilar" to the objects belonging to other clusters (Backer et al. 1981). As an essential tool for data exploration, cluster analysis examines unlabeled data by either constructing a hierarchical structure or forming a set of groups according to a pre-specified number. This process includes a series of steps, ranging from preprocessing and algorithm development to solution validity and evaluation.

These algorithms evolve from different research communities, solve different problems, and have their pros and cons (Xu 2005). For example, in cancer research for classifying patients into subgroups according to their gene expression profile. It can be useful for identifying patients' molecular profiles with excellent or bad prognostic and understanding the disease and marketing for market segmentation, identifying subgroups of customers with similar profiles and who might be receptive to a particular form of advertising. According to their type, value, and location (Kassambara 2017).

The cluster system proposed by Jahre and applied in humanitarian relief is now called Logistics Cluster (L.C.). The Logistics Cluster is relatively a new concept (OCHA 2011). Cluster focus on providing logistics coordination and information management services (including mapping, road accessibility studies, and civil-military liaison) and provide cost-effective logistics service alternatives to humanitarian actors utilizing all transport modes (boats, barges, trucks, and air for both humanitarian personnel and cargo) (MENA Report 2014).

Other authors have used the concept of a cluster to determine the most appropriate location for support centers in the State of Veracruz, which is one of the most affected regions in Mexico (Caballero-Morales et al. 2018). They develop a metaheuristic based on the K-Means Clustering (KMC) algorithm, which is extended to integrate (a) the associated capacity restrictions of the support centers, (b) a micro Genetic Algorithm μGA to estimate a search interval for the most suitable number of support centers, (c) a variable number of assigned elements to centers in order to add flexibility to the assignation task, and (d) random-based decision model to improve the final assignments further. This research is vital because there are diverse natural disasters in Mexico, and efficient logistic systems must provide prompt support.

A lack of inter-organizational cooperation and coordination can create big losses of human and material resources in a humanitarian logistics context. The coordination concept is an essential tool to obtain the big picture of an emergency case (Ramazan et al. 2014). For example, on December 26th, 2004, an earthquake and resulting tsunami in South Asia claimed some 227,000 lives and displaced 1.7 million people. The world responded by donating more than $13 billion and initiating the most significant relief effort in history. Despite the cautions that aid agencies put out against sending unsolicited items, they were confronted with a stream of gifts sent by well-meaning donors. Sri Lanka's Colombo airport reported that 288 freighter flights had arrived without airway bills to drop off humanitarian cargo within two weeks of the tsunami. Some carried much-needed supplies. Of course, credible humanitarian organizations had cleared that.

Nevertheless, a large number brought unsolicited and inappropriate items (such as used western clothes, baked beans, and carbonated beverages), which piled up at the airport, clogged warehouses, and remained unclaimed for months. Worse yet, these prepaid flights refueled and then returned empty when they could have carried commercial cargo. As a result, the airport ran out of fuel for the scheduled flights. After that, many companies' offers of help were met with "no thanks." (Tomas et al. 2006).

On January 26th, 2001, an earthquake measuring 7.9 on the Richter scale struck at 8:50 in the morning in Gujarat, on the west coast of India. It ravaged the country, destroying five districts and killing over 20,000 people. This devastation devastates the difficulties of working in a politically sensitive area rife with local conflict and under heavy army presence. Its proximity to the Pakistani border was also not to be taken lightly. The local airport was destroyed, and the infrastructure was severely damaged, and there was very little information in the early stages of the disaster. During the first 30 days of the disaster, along with 35 partner organizations, the International Federation of the Red Cross's Logistics Emergency Unit arranged the delivery of 255,000 blankets, 34,000 stores, 120,000 plastic sheets, and large quantities of other items. More than 300 other global, regional, national, local, and United Nations agencies similarly mobilized their personnel and resources (Samii et al. 2002). All this facing unpredictable and uncontrollable conditions, knowing that the survival of vulnerable people depends on the relief supplies' timely arrival.

So, it is necessary to have a plan able to react to the current and future crisis as well as a trustworthy and predictable leadership at a global and local level; unbreakable alliance between United Nations (U.N.) bodies, Non-Governmental Organizations (NGOs), and local authorities (Ramazan et al. 2014).

How many clusters are required in a country, and which organization is the best to lead each of them. These are based on the specific needs identified in the response plan. The goal is to clarify labor division, defining the roles and responsibilities among all humanitarian organizations within the sectors (OCHA 2011).

It is why L.C. makes sense. This paper suggests the clustering of Mexican municipalities that provide a precise segmentation of the vulnerable zones. Eleven statistical methods were used in this cluster solution. The main objective is that the results can support the national strategic decision, is that to say, to plan from the global perspective and then prepared for a particular location before the event occurs, identifying the specific needs, and thus making specifics proposals in Humanitarian Aid Policy. As has already been said, planning and cooperation are essential to have an adequate response.

2.3 Problem Description

Because of its geographic location, Mexico is highly susceptible to meteorological events. The municipalities with a high frequency of heavy rains, floods, frost, and hail are more exposed and vulnerable to damage (Monterroso et al. 2015). Some of the consequences of this kind of phenomena are intense streams of water in rivers, streams with sediment in mountain slopes, mass movements carrying mud, rocks, sand, trees, and other objects that can destroy houses, throwing bridges, and breaking road sections (CENAPRED 2018).

So far, there are many qualitative and quantitative studies to determine vulnerability in parts of the Mexican Republic (Luers et al. 2004) and others that consider the Mexican Republic (Monterroso et al. 2014a) entirely. In this research, we will use the studies of vulnerability made by other researchers using municipal data across the country; we selected this spatial scale because it is the basic unit of administration and economic planning in Mexico (Monterroso et al. 2015).

The municipalities to be considered in this study are those designated as highly and very highly vulnerable following Monterroso et al. (2014b). Monterroso et al. with historical data from 1980 to 2005, conducted a risk study reflecting the interaction of sociodemographic, socioeconomic, and frequency of different natural phenomena; thus, they obtained an index of vulnerability for each municipality. This index is very low, low, medium, high, and very high, and this information is contained in the Virtual Interactive Atlas Map, now called National Risk Atlas (National Risk Atlas, Retrieved August 31st, 2018). In this map, 412 municipalities classified as high and very high vulnerable were found; see Appendix 2.A.

Another study of vulnerability was developed by the National Institute of Ecology and Climate Change (INECC), a national organization whose goal is to contribute to the formulation, conduct, and evaluation of the national policy on climate change, green growth, and sustainability through the preparation, coordination, and dissemination of studies scientific or technological research (INNEC, retrieved July 2017). As a result of one study, the Climate Change Special Program 2014–2018 was developed and contain a list of 319 municipalities with high vulnerability see Appendix 2.B (PECC 2014–2018).

Therefore, this study considers two instances; on the one hand, 412 municipalities classified as high and very high vulnerability contented in the Virtual Interactive Atlas Map. On the other hand, the INECC study, through various studies, defined 319 municipalities with high vulnerability. In this research, all the municipalities will be considered as very highly vulnerable municipalities.

Moreover, all these municipalities were analyzed based on the impact of some natural disasters. According to the Declarations of Emergency and Disaster Contingency Climatological database, those had emergency and disaster designation between the year 2000 and the end of 2018 (CENAPRED 2018).

2.4 Methodology

For the development of this research, two instances were used, the first will be the INECC study, and the second instance was the Virtual Interactive Atlas Map study. In both cases, coordinates in longitude and latitude were required and were obtained through an Automated Data Collection (ADC) in real-time of Geocode Google's API. Subsequently, the NbClust R package developed by Charrad et al. (2014) was used to determine the best number of clusters in a dataset; and also was used the Cross-Entropy Clustering (CEC) R Package developed by Kamieniecki et al. (2015) for the same purpose. The methods contented in the NbClust R package consider Euclidean distances, while the CEC method uses radial measure.

We analyze 26 indexes for determining the best clustering scheme. The calculated indexes were: "kl", "ch", "hartigan", "ccc", "scott", "marriot", "trcovw", "tracew", "friedman", "rubin", "cindex", "db", "silhouette", "duda", "pseudot2", "beale", "ratkowsky", "ball", "ptbiserial", "frey", "mcclain", "dunn", "hubert", "sdindex", "dindex", "sdbw"; and all these measure the dispersion of the data clustered into q clusters. The Majority Rule was applied over the indexes to decide the best number of clusters as well as the variation of all combinations of number of clusters, distance measures, and clustering methods.

The distance measures were written for two vectors x, and y. They are used when the data is a dimensional vector arising from measuring d characteristics on each of n objects or individuals. Usually, the Euclidean distance uses the square distance between the two vectors (2.1). In Appendix 2.C y 2.D are presented the Euclidean distances of each scenario.

$$d(x, y) = \left(\sum_{j=1}^{d} (x_j - y_j)^2 \right)^{1/2} \quad (2) \tag{2.1}$$

The range of a minimal number of clusters was 2. The maximal number of clusters was equal to 15, the significance value for Beale's index was selected as 0.10 to reject the null hypothesis, and the hierarchical clustering methods to be used were "ward.D", "ward.D2", "single," "complete," and "average"; the partitioning clustering methods were "equity," "median," "centroid," "k-means," "Gaussian mixture."

In the Cross-Entropy Clustering (CEC) method, it divides the data into Gaussian type clusters. It automatically reduces unnecessary clusters while simultaneously allowing the simultaneous use of various type Gaussian mixture models applying spherical clusters. The minimal number of clusters was 2, and the maximal number of clusters was equal to 15, with a minimal cluster cardinality of 5%. If cluster cardinality becomes less than 5%, the cluster is removed.

The spherical cluster G (.I) (radial) Gaussian densities mean those Gaussians for which the covariance is proportional to identity. The clustering will try to divide the data into balls of arbitrary sizes (2.2).

$$\sum G_{(.I)}(X) = \frac{tr(\sum_x)}{N} I \tag{2.2}$$

$$H^x\left(X||G_{(.I)}\right) = \frac{N}{2}\ln(2\pi e/N) + \frac{N}{2}\ln(tr\sum_x)$$

The result should be interpreted as clustering of very high vulnerable Mexican municipalities, where Humanitarian Country Teams (HCTs) can plan and coordinate logistics activities.

2.5 Results

When the analysis was carried out for the second instance was found data with significant variance, this belongs to one of Chihuahua's municipalities located in the North of the country, while the rest of the municipalities' data were located to the Southwest and Southeast of the country. Thus, this point was removed from the data in order to have a more quality solution. Handling 411 municipalities instead of 412, the municipality removed is proposed as a unique cluster and can be seen with the color red in Fig. 2.1.

Once the output data were obtained, we applied a Majority Rule based on selecting several clusters by the majority of indexes; see Appendix 2.E for more information about the Best Cluster (B.C.) and Value Index (VI). For instance, one—INECC, according to the Majority Rules, the best number of clusters are 2 or 3, while the second option is 2. For instance, two—Virtual Interactive Atlas Map, according to the Majority Rule, the best number of clusters are four or the second option are 2, see Table 2.1.

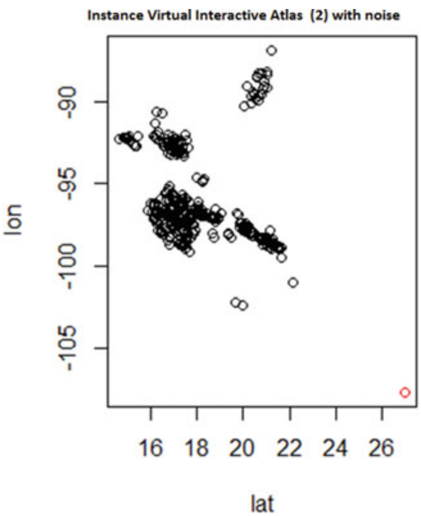

Fig. 2.1 Municipality removed of the data

Table 2.1 Number of Clusters obtained of each instance

Instances	INECC (319 Municipalities) (1)		Virtual interactive atlas (412 municipalities) (2)	
	Number of clusters			
Method	1rst option	2nd option	1rst option	2nd options
Ward.D	4	2	4	2
Ward.D2	3	2	4	2
single	2	10	2	5
complete	2–3	4	4	3
average	2–3	13	4	2
mcquitty	3	2	4	2
median	2	13	4	3
centroid	2	4	2–4	6
kmeans	3	10	2	3–10
Gaussian mixture	9	NA	9	N.A
Majority results	2–3	2	4	2

Analyzing the best number of clusters proposed by the majority index in the instance one and two we can plot the results (see Figs. 2.2 and 2.3). For visualizing more clusters suggested by each method, see Appendix 2.F.

In instance one—INECC, the median and k-means methods are suggested. K-means clustering is a straightforward and fast algorithm. It can efficiently deal with

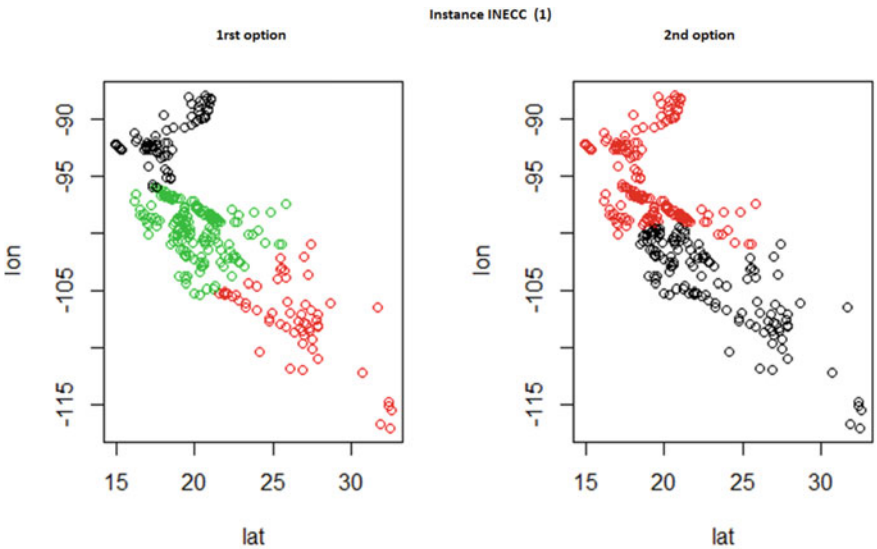

Fig. 2.2 Number of Cluster as the first option and the second option, for instance, one

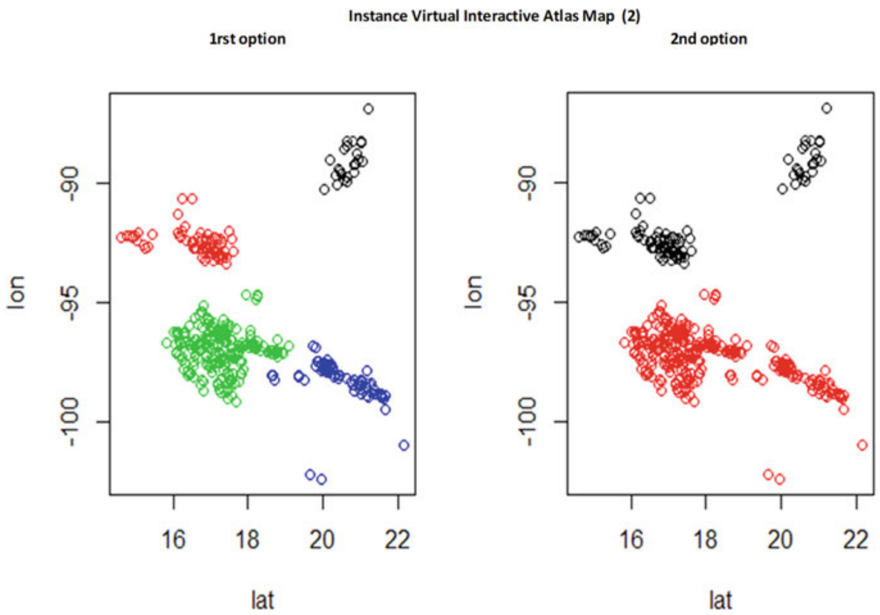

Fig. 2.3 Number of Cluster as the first option and the second option, for instance

enormous datasets. However, there are some weaknesses, including (a) it assumes prior knowledge of the data and requires the analyst to choose the appropriate number of clusters (k) in advance; (b) the final results obtained is sensitive to the initial random selection of cluster centers. Why is this a problem? It may choose a different set of initial centers for every different run of the algorithm on the same data set. It may lead to different clustering results on different runs of the algorithm; c) it is sensitive to outliers; and (d) if it rearranges the data, it is possible to get a different solution every time the ordering of the data are changed (Kassambara 2017).

Possible solutions to these weaknesses include the solution to issue (a) Compute k-means for a range of k values by varying k between 2 and 10. Then, choose the best k by comparing the clustering results obtained for the different k values. The solution to issue (b) Compute K-means algorithm several times with different initial cluster centers. The run with the lowest total within-cluster sum of the square is selected as the final clustering solution (Kassambara 2017).

In instance two—Virtual Interactive Atlas Map again the median, k-means are selected; also the Ward.D2 method is suggested.

The Ward method minimizes the total within-cluster variance. At each step, the pair of clusters with minimum cluster distance are merged. At each step, to implement this method, find the pair of clusters that leads to a minimum increase in total within-cluster variance after merging. The option "ward.D2" implements the criterion of (Murtagh et al. 2014).

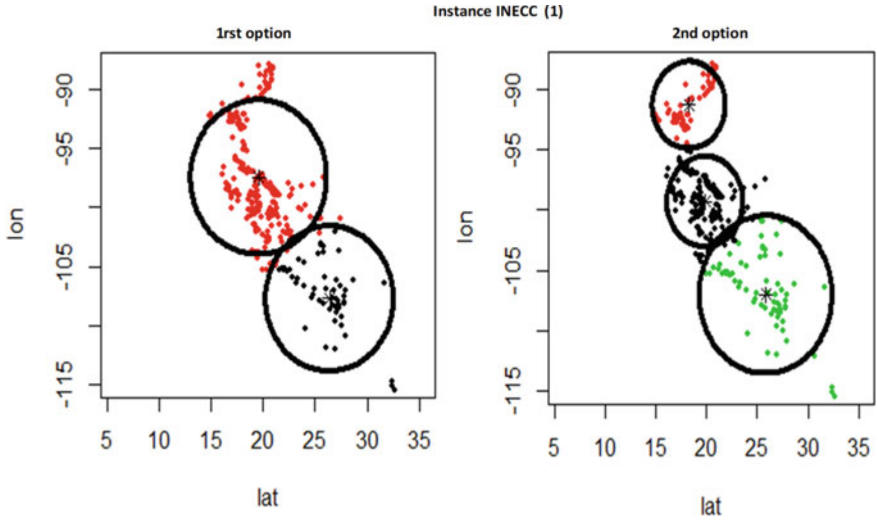

Fig. 2.4 Number of Cluster as the first option and the second option for instance one with CEC method

Once we obtained the solution with the first package, we proceeded to answer the CEC method. It does not require the user to specify the number of clusters to be generated and enables easy adaptation to cluster complicated data sets. For instance number one, the best results were two, three, four, and nine clusters. For instance two, the best results were two, three, and four. In Figs. 2.4 and 2.5 is possible to

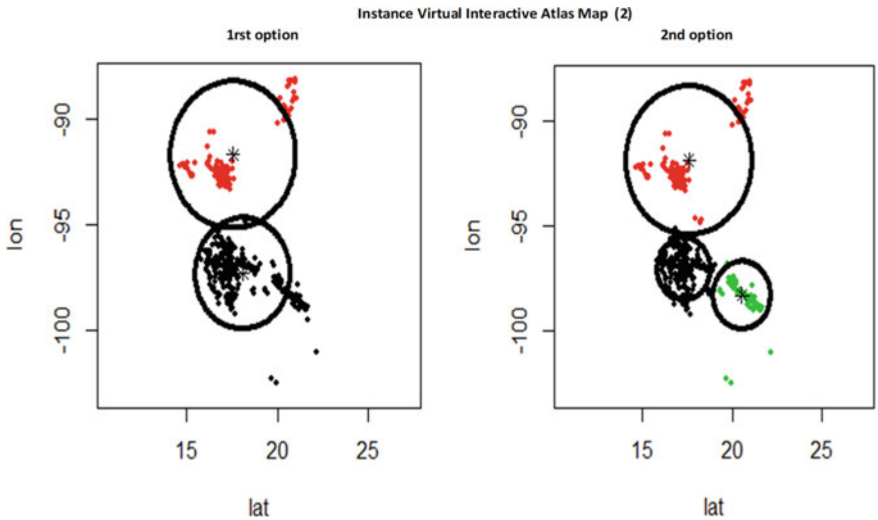

Fig. 2.5 Number of Cluster as the first option and the second option for instance two with CEC method

see the results of the CEC method, only were plotted similar results to those already obtained. Appendix 2.G is shown the proposed clustering for both instances.

By mapping in ArcGIS online the results obtained, the following maps were obtained. We can observe in Figs. 2.6 and 2.7. The results correspond to instance one. The INECC instance accounts for less vulnerable municipalities but considers the impacts of droughts, frosts, hails, rains, and floods that correspond to meteorological

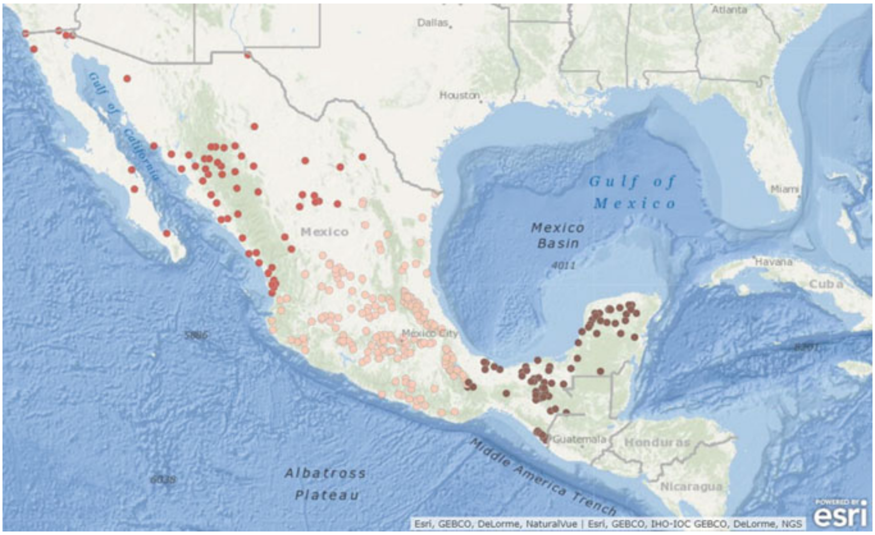

Fig. 2.6 The map that contains the result of the instance one—3 clusters—k-means method

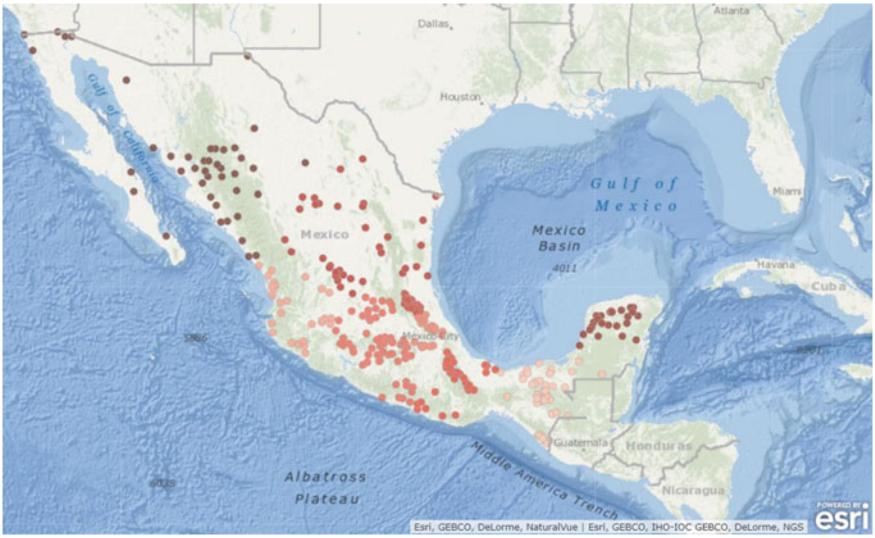

Fig. 2.7 The map that contains the result of the instance one—9 clusters—CEC method

phenomena. For this reason, vulnerable municipalities can be seen throughout the country. The CEC method results can be the best option with nine clusters due to fewer distances among clusters and visibly cover the country's areas.

In Figs. 2.8 and 2.9 corresponding to instance two, it can be seen that most of the vulnerable municipalities are in the south and southeast of the country because, in the Virtual Interactive Atlas Map, the information is filtered explicitly by hydro-meteorological phenomena because they are the events that appear most frequently. It can also be observed that the states of Oaxaca and Chiapas are the most vulnerable.

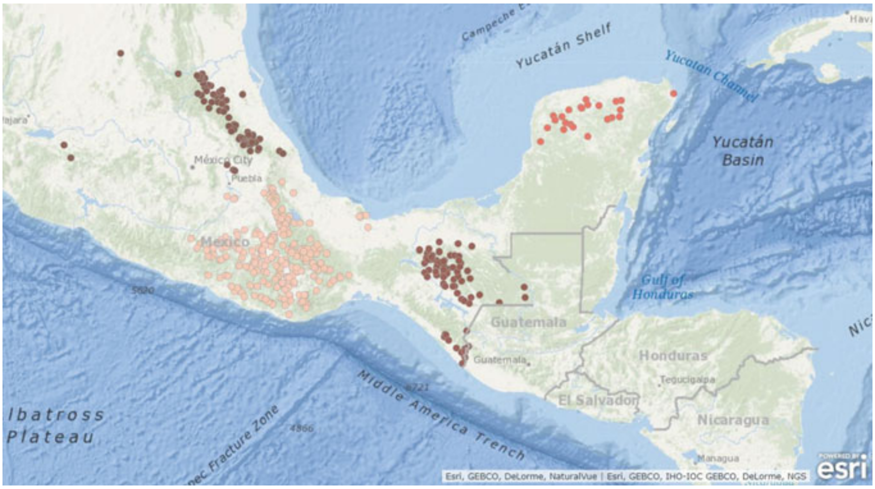

Fig. 2.8 The map that contains the result of the instance two—4 clusters—median method

Fig. 2.9 The map that contains the result of the instance two—3 clusters—CEC method

Maybe a recommendation would be more cluster in order to have a more managed area.

According to the instances analyzed, the observation that can be made is that with the information of the instance one cannot define the type of phenomenon that negatively impacts the municipalities. However, we can be sure that it includes the appearance of all the Meteorological Phenomena for the previous analysis carried out with the database of CENAPRED. Regarding the information of instance two, the Virtual Interactive Atlas Map allows us to know the type of phenomenon that negatively impacts the municipalities and carry out more focused studies. Though, its disadvantage lies in obtaining the information manually. It is suggested that the consulted information in this interactive map can be downloaded in files with a.csv extension or some that can let easy access to the information. The access to information efficiently and quickly translates into new knowledge that helps real decision-making.

In summary, two instances were analyzed, and each one has two or three options of clusters. Therefore, the HCTs must decide the number of clustering of vulnerable Municipalities based on experience, skills, resources, and other considerations. This decision includes government, heads of agencies, and operational coordination managers. Furthermore, in this way, to provide humanitarian assistance.

2.6 Government Intervention Protocol of Mexico

Government protocols in Mexico to intervene in a disaster have a hierarchical structure according to the agreement that establishes the Natural Disaster Fund (FONDEN) Emergency Care Fund Guidelines (DOF, retrieved April 2nd, 2019). This type of government is selected to avoid corruption and have greater control over interventions, but there are cases every day that this type of governance has not worked completely (IMCO 2018).

2.7 Public Politics of Humanitarian Aid Suggested

Natural disasters have increased over time due to global climate change caused mainly by unsustainable human activities such as deforestation, intensive agriculture, and rapid urbanization (Bae et al. 2015). Paradoxically, the government response to natural disasters worldwide has been inefficient in most cases (Kapucu and Garayev 2016). One of the main reasons for this governmental limitation comes from the classic and rigid top-down hierarchical—bureaucratic model applied to disaster management (Waugh and Streib 2006). Therefore, a different public management style based on inter-organizational and intergovernmental collaboration is needed to deliver a more flexible and rapid response to complex situations such as the adverse impact of natural disasters (Daly et al. 2017; Jung and Song 2014; Nolte et al. 2012).

Disaster management literature has currently turned its attention to the "Collaborative public management" (Agranoff and McGuire 2003) as the appropriate approach to effectively respond to natural disasters. McGuire (2006) defines *Collaborative public management* as "… the process of facilitating and operating in multiorganizational arrangements in order to remedy problems that cannot be solved by single organizations" (p. 33). In contrast with the traditional top-down governing system existing in traditional organizations, collaborative public management is formed by network structures that facilitate vertical and horizontal cooperation among organizations (Kapucu et al. 2010).

Regarding disaster management, collaborative networks are crucial for planning and responding to disasters (McGuire and Silvia 2010). Besides, these networks enable the involvement of multiple actors (from the public, private and nonprofit sectors) to provide resources and support to the community, thus accelerating and enhancing its capacities to recover from disasters (Waugh Jr. and Streib 2006). The effectiveness of collaborative networks in disaster management lies in their flexibility and adaptability to provide solutions under circumstances of high complexity and uncertainty (Nolte and Boenigk 2013).

Even though all levels of government (national, state, and local) are responsible for creating collaborative networks in order to manage disasters and crises; local governments play a crucial role in the delivery of effective disaster management strategies as they are the first affected by the natural disasters (Kapucu and Hu 2014). Hence, improving local governments' capacity to generate collaborative networks must prioritize any disaster management plan (Bae et al. 2016). At a local level, collaborative networks may be formed in two dimensions: vertical collaboration (across upper levels of government) and horizontal collaboration (with other local governments and/or other organizations) (Junand Song 2014).

Both types of collaborative networks are relevant to empower local governments in disaster management (Aoki 2014; Kapucu et al. 2009). Vertical collaborations are necessary for local governments as they require resources, technical support, and guidance provided by state and national governments (Jun and Song 2014). On the other hand, horizontal collaborations among other local governments and organizations generate reciprocal cooperation and mutual support, which contributes to improving communities' resilience to disasters (Kapucu et al. 2010). Due to the vastness of collaborative networks at the local level, the current research will focus specifically on local governments' horizontal collaborations.

This specific type of collaborative network is worth analyzing as the range of disaster impact is broad, and hence, it affects multiple municipalities (Jun and Song 2014). According to Bae et al. (2016), local governments effectively deliver adaptive and effective responses to disasters because they better understand unique local needs and assets than the national government. However, it does not mean that local governments can deal with the whole situation without higher government levels participation Aoki (2014) asserts that the national government can help interlocal cooperation by coordinating and delineating local governments' strategic tasks.

Based on those mentioned above, the study aims to develop a clustering analysis to provide a precise segmentation of the vulnerable zones. This analysis may be instrumental in supporting national strategic decisions aimed at planning and coordinating local governments to deliver humanitarian aid. The cluster analysis was applied to Mexican municipalities. The researchers considered Mexico an appropriate context to test the cluster analysis due to multiple areas across the country prone to be impacted by a natural or human-made disaster. In the next section, a thorough description of the problem will be provided.

2.8 Conclusions and Future Work

Disasters caused by natural phenomena cause suffering to humanity and are inevitable and hard to predict. For this reason, it is essential that, based on studies of researchers, the scientific community, the government, and the humanitarian actors have a sighting of the most vulnerable areas in the country. In this study, vulnerability clusters were performed considering municipalities with low capacity to respond to climate change.

We propose two options of clusters for the two instances analyzed. The optimal number of clusters is somehow subjective and depends on the method used for measuring similarities and the parameters used for partitioning. For that, no clustering algorithm can be universally used to solve all problems. Usually, algorithms are designed with certain assumptions and favor some biases. In this sense, it is not accurate to say "best" in the context of clustering algorithms, although some comparisons are possible. These comparisons are mostly based on specific applications under certain conditions, and the results may become quite different if the conditions change.

With these results, it is possible to visualize the vulnerable zones and make Logistics Clusters plan and coordinate all the humanitarian actors that intervene in humanitarian attention, providing cost-effective logistics service. This coordination can organize the resources, give the ability to understand disaster risks to which they may face, mitigate and respond to disasters that may minimize any loss or damage to the life, livelihood, property, infrastructure, economic activity, and the environment.

It allows future research where it would be useful to analyze the existing action procedures of HCTs and how many teams there are or how many can be created to know how they manage and how can be planned the humanitarian aid. It could provide direction for the further creation of Clusters Logistics.

Besides, we suggest following the four critical observations about the cluster concept, which tie into the theoretical review by Jahre et al. (2010): (1) there are challenges in defining standards for necessary logistics information as well as logistics operating procedures; (2) information management is crucially related to participation from members of all clusters; (3) the global cluster leads are working on building spare capacity and buffer stocks; and (4) examples of supply chain control include the cluster United Nations Joint Logistics Centre (UNJLC), such as cargo prioritization and air traffic control.

Appendices

Appendix 2.A

See Table 2.A

Appendix 2.B

See Table 2.B

Appendix 2.C

Euclidean distances of 412 municipalities classified as high and very high vulnerability.

Appendix 2.D

Euclidean distances of 319 municipalities classified with high vulnerability.

Appendix 2.E

Information about the Best Cluster (B.C.) and de Value Index (VI) by each instance. The Hubert and D indexes are a graphical method.

Appendix 2.F

Visualization of clusters suggested by each method, for instance one - INECC and two - Virtual Interactive Atlas MapVisualization of clusters suggested by each method, for instance one—INECC and two—Virtual Interactive Atlas Map.

Table 2.A 412 municipalities classified as high and very high vulnerability

ID	lat	lon	location_type	formatted_address	long_name	place_id
1	20.04097	– 90.22555	Approximate	Tenabo, Campeche, Mexico	Tenabo	ChIJ8WbrgYNu-IURO8JeEfXmEOM
2	20.37086	– 90.05047	Approximate	Calkini, Campeche, Mexico	Calkini	ChIJn5iMeO6A-IURL1YejNysIms
3	27.03039	– 107.73623	Approximate	Batopilas, Chihuahua, Mexico	Batopilas	ChIJTU_Ljmg8v4YRKU6WKyB6AeQ
4	15.34203	−92.67476	Approximate	Acacoyagua, Chis., Mexico	Acacoyagua	ChIJj6VE5O8UkoURZM7-B_SK9lo
5	15.27953	−92.69064	Approximate	30,580 Acapetahua, Chis., Mexico	Acapetahua	ChIJ_8FCQYERkoUR48tZx-3UBXA
6	16.91683	−92.68720	Approximate	Aldama, Chis., Mexico	Aldama	ChIJQXh5de1p7YURbdQlTnkRqbY
7	16.73430	−92.03622	Approximate	Altamirano, Chis., Mexico	Altamirano	ChIJfeh4M5jF8oURx8IBsGM2McE
8	17.37151	−92.81801	Approximate	Amatán, Chis., Mexico	Amatán	ChIJFcijU9Oj7YUR-Lt8TlsOFpk
9	15.43400	−92.11693	Approximate	Atenango de La Frontera, Chis., Mexico	Atenango de La Frontera	ChIJi_u6OLC_jYURvifC0HN5q_E
10	16.52780	−92.43780	Approximate	Amatenango del Valle, Chis., Mexico	Amatenango del Valle	ChIJX86Wc8mq8oURFGwWBqEEA-c
11	16.51428	−90.65410	Approximate	Benemérito de las Américas, Chis., Mexico	Benemérito de las Américas	ChIJr2rPoT4ri4UR-ZmjuaXijos

(continued)

Table 2.A (continued)

ID	lat	lon	location_type	formatted_address	long_name	place_id
12	16.99655	−92.89638	Approximate	Bochil, Chis., Mexico	Bochil	ChIJHw7ZvS4R7YURAISca0D5-Dc
13	14.99582	−92.16713	Approximate	Cacahoatán, Chis., Mexico	Cacahoatán	ChIJ43oSft0KjoURX3CS_tuK2F8
14	16.96345	−92.61645	Approximate	Chalchihuitán, Chis., Mexico	Chalchihuitán	ChIJgwBWeyBm7YURdTtUU8ZvoCY
15	16.78694	−92.68759	Approximate	Chamula, Chis., Mexico	Chamula	ChIJFQRuFRpE7YURg-gX_Dhqk-k
16	16.65367	−92.25601	Approximate	Chanal, Chis., Mexico	Chanal	ChIJhWF_1AWx8oURmhXFE60vwdA
17	17.33939	−93.12970	Approximate	Chapultenango, Chis., Mexico	Chapultenango	ChIJ8dTzBY1U7IURVnaJAxY3xXs
18	16.89813	−92.62415	Approximate	Chenalho, Chis., Mexico	Chenalho	ChIJC47kKwJo7YURFder1C4TtC4
19	16.56862	−92.72121	Approximate	Chiapilla, Chis., Mexico	Chiapilla	ChIJjz-BqdS0koURjo2ay3n5nhM
20	17.10468	−92.27366	Approximate	Chilon, Chis., Mexico	Chilon	ChIJX6HYksWP8oURNiKwetLMNbo
21	17.09656	−93.21061	Approximate	Copainalá, Chis., Mexico	Copainalá	ChIJE0BX8Rf77IURwDXeAXsVukQ
22	17.06247	−92.72100	Approximate	El Bosque, Chis., Mexico	El Bosque	ChIJ68i_VJRt7YURZRzSIYGV7P4
23	15.32325	−92.65862	Approximate	Escuintla, Chis., Mexico	Escuintla	ChIJHZRPZLoTkoURX2L_pTFcuzo

(continued)

Table 2.A (continued)

ID	lat	lon	location_type	formatted_address	long_name	place_id
24	14.77580	−92.17640	Approximate	Frontera Hidalgo, Chis., Mexico	Frontera Hidalgo	ChIJKY31mQ8TjoUR2UoL4UrKjRA
25	15.01942	−92.38085	Approximate	Huehuetán, Chis., Mexico	Huehuetán	ChIJCYmjnAj-jYUR43R7_4DrmtI
26	17.17056	−92.68534	Approximate	Huitiupán, Chis., Mexico	Huitiupán	ChIJc4eq8k5 × 7YURKoiccE0gV0I
27	16.71115	−92.45426	Approximate	Huixtán, Chis., Mexico	Huixtán	ChIJuyOg1aul8oURSyWuCVQVGpU
28	16.79904	−92.89638	Approximate	Ixtapa, Chis., Mexico	Ixtapa	ChIJyQgY1oU87YURNX8dirXVNtA
29	17.29259	−93.00857	Approximate	Ixhuatán, Chis., Mexico	Ixhuatán	ChIJwXheHaWr7YURoHK8_00iBd8
30	17.42955	−93.09733	Approximate	Ixtacomitán, Chis., Mexico	Ixtacomitán	ChIJafKvHcNS7IURItLUAIOyjJ4
31	17.06672	−92.86038	Approximate	Jitotol, Chis., Mexico	Jitotol	ChIJxaUuAfcR7YUR2sYJj1DcohU
32	16.25173	−92.02171	Approximate	La Independencia, Chis., Mexico	La Independencia	ChIJXXtHMno7jYURyggD65qpgxg
33	16.11889	−92.05182	Approximate	La Trinitaria, Chis., Mexico	La Trinitaria	ChIJS4ELlUYWjYURP93l-7tRQw0
34	16.88202	−92.71204	Approximate	San Andrés Larráinzar, Chis., Mexico	San Andrés Larráinzar	ChIJKU-BZ−9B7YURI5qVn62Fpws
35	16.32244	−91.79106	Approximate	Chiapas, Chis., Mexico	Chiapas	ChIJjatjkszZjIUR_KgKeasZPEg

(continued)

Table 2.A (continued)

ID	lat	lon	location_type	formatted_address	long_name	place_id
36	16.36078	−92.36729	Approximate	Las Rosas, Chis., Mexico	Las Rosas	ChIJcedOt7hQjYURXWxnSZ5jDGA
37	16.14097	−91.29272	Approximate	Maravilla Tenejapa, Chis., Mexico	Maravilla Tenejapa	ChIJVxkjirGYjIUR3W0wsTm1Ofw
38	16.26422	−90.62103	Approximate	Marqués de Comillas, Chis., Mexico	Marqués de Comillas	ChIJl30GEjgni4URJIKb5S-ne3k
39	14.84045	−92.18849	Approximate	Metapa, Chis., Mexico	Metapa	ChIJOcE9yFMMjoURvX96dYkZub8
40	16.86083	−92.62823	Approximate	Mitontic, Chis., Mexico	Mitontic	ChIJYwUqsMZC7YUR7lq_qydrdw8
41	17.22564	−93.16416	Approximate	Ocotepec, Chis., Mexico	Ocotepec	ChIJzYTk8-L-7IURdEmXTJdcFuc
42	16.90872	−92.09437	Approximate	Ocosingo, Chis., Mexico	Ocosingo	ChIJlwTOu3Xq8oURArA-xrQP4IE
43	17.40778	−93.33543	Approximate	Ostuacán, Chis., Mexico	Ostuacán	ChIJNS4A5H5b7IURAnOu2m8JHLA
44	16.93597	−93.09172	Approximate	Osumacinta, Chis., Mexico	Osumacinta	ChIJiZ2FS9Mf7YURoYMYXzpv0po
45	16.78420	−92.34421	Approximate	Oxchuc, Chis., Mexico	Oxchuc	ChIJv9DghoK78oUR4tXGHehTPVY
46	17.51098	−91.99305	Approximate	Palenque, Chis., Mexico	Palenque	ChIJKTvaAEZP8oUR8XOZc3PNatE
47	17.00510	−92.46907	Approximate	Pantelhó, Chis., Mexico	Pantelhó	ChIJAS4v8AZi7YURFOBSjcDes2I

(continued)

Table 2.A (continued)

ID	lat	lon	location_type	formatted_address	long_name	place_id
48	17.18814	−93.04984	Approximate	Pantepec, Chis., Mexico	Pantepec	ChIJnXzaqHEB7YURiNYmJcbTwXE
49	17.15783	−92.89968	Approximate	Pueblo Nuevo Solistahuacán, Chis., Mexico	Pueblo Nuevo Solistahuacán	ChIJv639LicP7YURsrxUA4cStk8
50	17.20080	−93.01177	Approximate	Rayón, Chis., Mexico	Rayón	ChIJF79NbskG7YURHh6Nn7KpIdU
51	17.28228	−92.55176	Approximate	Sabanilla, Chis., Mexico	Sabanilla	ChIJoyUqIiyH7YUR6bsskoB-hHw
52	17.55625	−92.34311	Approximate	Salto de Agua, Chis., Mexico	Salto de Agua	ChIJacULQ35 × 8oURneWJZrVbT5o
53	17.13280	−92.80475	Approximate	San Andrés Duraznal, Chis., Mexico	San Andrés Duraznal	ChIJ_xKwpOMM7YUREyp9KI5f7wA
54	16.86943	−93.20709	Approximate	San Fernando, Chis., Mexico	San Fernando	ChIJJ_4ZyJDd7IURmg6EagNp9cI
55	16.89191	−92.37078	Approximate	San Juan Cancuc, Chis., Mexico	San Juan Cancuc	ChIJef1oRQ-i8oURzvgQ60f6IIQ
56	16.60875	−92.71902	Approximate	San Lucas, Chis., Mexico	San Lucas	ChIJ6Taxzd9L7YUR2b6CUW_H978
57	17.14058	−92.71090	Approximate	Simojovel, Chis., Mexico	Simojovel	ChIJbWXtCs9z7YUREtVvx3s4HrU
58	16.94006	−92.71454	Approximate	Santiago el Pinar, Chis., Mexico	Santiago el Pinar	ChIJ-d1p0jRq7YUR5dSjaMG1f5s
59	17.02441	−92.30585	Approximate	Sitalá, Chis., Mexico	Sitalá	ChIJA7YLlHaa8oURvtUjAow84Qs

(continued)

Table 2.A (continued)

ID	lat	lon	location_type	formatted_address	long_name	place_id
60	16.22465	−92.25164	Approximate	Ochuxhjob, Chis., Mexico	Ochuxhjob	ChIJRalQiL1DjYUR47I33w1brFw
61	16.89057	−92.92273	Approximate	Soyaló, Chis., Mexico	Soyaló	ChIJjwWcCj497YUR7sHJeMQjbzc
62	14.62519	−92.24393	Approximate	Suchiate, Chis., Mexico	Suchiate	ChIJz0uYUJU9joURFVMlIIgU7UY
63	14.90556	−92.26341	Approximate	Tapachula de Córdova y Ordoñez, Chis., Mexico	Tapachula de Córdova y Ordoñez	ChIJscFxXjkPjoURiyK4ALi5KF0
64	17.18984	−93.10461	Approximate	Tapalapa, Chis., Mexico	Tapalapa	ChIJLVYpfRn-7IURDpZsWtaZisQ
65	17.25017	−93.01678	Approximate	Tapilula, Chis., Mexico	Tapilula	ChIJ39618TEB7YURg-kQ0waPlCs
66	16.54148	−92.47262	Approximate	Teopisca, Chis., Mexico	Teopisca	ChIJh3AQRzFU7YURAVujHVU_0lE
67	16.75693	−93.12924	Approximate	Chiapas, Mexico	Chiapas	ChIJZ85Xl7REjYURFdYZRoIzAM8
68	17.30232	−92.42334	Approximate	Tila, Chis., Mexico	Tila	ChIJQXPSz7V_8oURorySNrat4rE
69	16.54523	−92.68297	Approximate	Totolapa, Chis., Mexico	Totolapa	ChIJo3cDwpO0koURDozb9W9xVhg
70	17.27699	−92.31590	Approximate	Tumbalá, Chis., Mexico	Tumbalá	ChIJhZQRAx198oUR-Ndu94qCCgU
71	14.93743	−92.16713	Approximate	Tuxtla Chico, Chis., Mexico	Tuxtla Chico	ChIJwcjPCMUKjoURJBrBQ9bS5AI

(continued)

Table 2.A (continued)

ID	lat	lon	location_type	formatted_address	long_name	place_id
72	16.18227	−92.18455	Approximate	Tzimol, Chis., Mexico	Tzimol	ChIJH1mcVa1BjYURNV33Ub4YAJs
73	15.06454	−92.08118	Approximate	Unión Juárez, Chis., Mexico	Unión Juárez	ChIJlwOpsibfjYURVUDpM0kv3G0
74	15.21272	−92.57623	Approximate	Villa Comaltitlán, Chis., Mexico	Villa Comaltitlán	ChIJwUH5mbgPkoURYjzRqbtRNYs
75	17.17349	−92.32956	Approximate	Yajalón, Chis., Mexico	Yajalón	ChIJIfoPmNCF8oURWmA0mRW_Uhw
76	16.75948	−92.72163	Approximate	Zinacantán, Chis., Mexico	Zinacantán	ChIJe9ACPYc47YUR_9-hUBzBKzk
77	16.73715	−98.42814	Approximate	Acatepec, Guerrero, Mexico	Acatepec	ChIJsXLPpLJKyIURAY0GqXO_uHQ
78	17.46089	−98.38520	Approximate	Alcozauca de Guerrero, Gro., Mexico	Alcozauca de Guerrero	ChIJwSZiCzrnyIURra5Yx6RHjlU
79	17.31356	−98.60408	Approximate	Atlamajalcingo del Monte, Guerrero, Mexico	Atlamajalcingo del Monte	ChIJ0zq3uDwbyYURMawVBpvY4-0
80	17.56162	−98.93436	Approximate	Atlixtac, Gro., Mexico	Atlixtac	ChIJ9TutwY5ByYURZlIDPKLCIzg
81	17.19339	−98.45539	Approximate	Cochoapa el Grande, Guerrero, Mexico	Cochoapa el Grande	ChIJ_Suwanr-yIURaPmqUyYxNYg
82	17.46235	−98.71333	Approximate	Copanatoyac, Gro., Mexico	Copanatoyac	ChIJkbUlO-c9yYURJvUex4wogus

(continued)

Table 2.A (continued)

ID	lat	lon	location_type	formatted_address	long_name	place_id
83	17.45129	−99.02661	Approximate	José Joaquín de Herrera, Gro., Mexico	José Joaquín de Herrera	ChIJscqHpWxoyYURUr7SzIfVH1w
84	17.24527	−98.67184	Approximate	Malinaltepec, Gro., Mexico	Malinaltepec	ChIJtYVBWp0PyYURcX0wsKVeM20
85	17.19374	−98.40854	Approximate	Metlatónoc, Guerrero, Mexico	Metlatónoc	ChIJvaScKb_5yIURxXJnXqd9p0I
86	16.80707	−98.73501	Approximate	San Luis Acatlán, Gro., Mexico	San Luis Acatlán	ChIJZ1-a6UK5yYUR2dsxz4oaQxo
87	16.81053	−98.30009	Approximate	Tlacoachistlahuaca, Gro., Mexico	Tlacoachistlahuaca	ChIJr_CGcSNGyIUR7_nzGnpoEpQ
88	17.26248	−98.74828	Approximate	Tlacoapa, Gro., Mexico	Tlacoapa	ChIJkRYdh98NyYUREe1eXi6Lxok
89	17.54837	−98.56661	Approximate	Tlapa de Comonfort, Guerrero, Mexico	Tlapa de Comonfort	ChIJ7TAOj9EjyYUR26TW4lP4B2k
90	17.46739	−98.60782	Approximate	Xalpatláhuac, Gro., Mexico	Xalpatláhuac	ChIJDbCbMoEYyYURDUg6TP2OCpo
91	16.79185	−98.24209	Approximate	Xochistlahuaca, Guerrero, Mexico	Xochistlahuaca	ChIJE63YNiBHyIURqxnDQ6RAl9w
92	17.42034	−98.78149	Approximate	Zapotitlán Tablas, Guerrero, Mexico	Zapotitlán Tablas	ChIJK-XN4FEUyYUROjYfK4BKXtQ
93	17.68854	−99.18582	Approximate	Zitlala, Guerrero, Mexico	Zitlala	ChIJyYx3um_9y4URrP6hfyhIlSw
94	21.01695	−98.34444	Approximate	Atlapexco, Hgo., Mexico	Atlapexco	ChIJ-d-j380v14URdDXbTKqfCws

(continued)

Table 2.A (continued)

ID	lat	lon	location_type	formatted_address	long_name	place_id
95	21.15843	−98.90384	Approximate	Chapulhuacán, Hidalgo, Mexico	Chapulhuacán	ChIJCY4T_7e-1oUR-Y2QKPUghlQ
96	21.03170	−98.28686	Approximate	Huautla, Hidalgo, Mexico	Huautla	ChIJ2_wH0bUx14UROfT51UuyVaE
97	20.97859	−98.50689	Approximate	Huazalingo, Hgo., Mexico	Huazalingo	ChIJJSoE3HTW1oUR7hUp6oPVuqM
98	20.46049	−98.07516	Approximate	Huehuetla, Hgo., Mexico	Huehuetla	ChIJ1YbIf0SU0IURSzaSqihfPiY
99	21.13672	−98.41222	Approximate	Huejutla de Reyes, Hidalgo, Mexico	Huejutla de Reyes	ChIJRU5tfJMm14URWYiA1msxQ0k
100	21.13299	−98.53777	Approximate	Jaltocan, Hidalgo, Mexico	Jaltocan	ChIJY7oPZDzZ1oURoablyjL0S_4
101	20.84017	−98.71646	Approximate	Lolotla, Hidalgo, Mexico	Lolotla	ChIJT6PHMj4z0YUR1zEPBUF5NAg
102	21.19437	−99.00599	Approximate	Pisaflores, Hidalgo, Mexico	Pisaflores	ChIJLQKtcim91oURuSpJeo-CMNI
103	20.40138	−98.20079	Approximate	San Bartolo Tutotepec, Hidalgo, Mexico	San Bartolo Tutotepec	ChIJ59l7xFST0IUR8oGUnxUus3A
104	21.16907	−98.61332	Approximate	Orizatlán, Hidalgo, Mexico	Orizatlán	ChIJKReZAS3c1oURDE4cHRDv2NE
105	21.01403	−98.84041	Approximate	Tepehuacán de Guerrero, Hidalgo, Mexico	Tepehuacán de Guerrero	ChIJD47Xvda31oURfJsqZINy6qs

(continued)

Table 2.A (continued)

ID	lat	lon	location_type	formatted_address	long_name	place_id
106	20.98947	−98.65731	Approximate	Tlanchinol, Hgo., Mexico	Tlanchinol	ChIJNXTHz-HR1oURmQ3QvhXqUPI
107	20.83427	−98.28490	Approximate	Xochiatipan, Hidalgo, Mexico	Xochiatipan	ChIJpbLxJ6PN0IURXbMHyc8Amc4
108	20.95327	−98.38052	Approximate	Yahualica, Hidalgo, Mexico	Yahualica	ChIJa1l2jWot14URUZ7Kp–1EK8
109	19.95392	−102.43295	Approximate	Tangamandapio, Michoacán, Mexico	Tangamandapio	ChIJcz3ijkeLLoQRygCg-i2g9xw
110	19.64912	−102.25045	Approximate	Charapan, Michoacán, Mexico	Charapan	ChIJuYVLEddxLoQRZ2_Fy3g23dk
111	17.38524	−97.35274	Approximate	Magdalena Yodocono de Porfirio Díaz, Oaxaca, Mexico	Magdalena Yodocono de Porfirio Díaz	ChIJJ_1mNy1ExoURSXVpJ6cNc9Y
112	16.76015	−96.72061	Approximate	Asunción Ocotlán, Oaxaca, Mexico	Asunción Ocotlán	ChIJUdESGq1Bx4URKzoGJvJO8To
113	17.43728	−96.60971	Approximate	Abejones, Oax., Mexico	Abejones	ChIJBytcQr7FxoURs4rOG2cFGYU
114	17.67284	−96.12877	Approximate	Ayotzintepec, Oax., Mexico	Ayotzintepec	ChIJ2Q8GvV9BwYURFJR3QSstgIw
115	16.11056	−97.12250	Approximate	La Perla, Oax., Mexico	La Perla	ChIJCXH29w9huIUR69CnqWALAm8
116	17.53206	−98.27816	Approximate	Calihualá, Oaxaca, Mexico	Calihualá	ChIJS0ZycOXCyIUR6UKPb6YQNcc

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Table 2.A (continued)

ID	lat	lon	location_type	formatted_address	long_name	place_id
117	17.99583	−96.74545	Approximate	Chiquihuitlán de Benito Juárez, Oaxaca, Mexico	Chiquihuitlán de Benito Juárez	ChIJ977G32MfxIURVj7hEympEzE
118	16.53775	−96.66800	Approximate	Coatecas Altas, Oaxaca, Mexico	Coatecas Altas	ChIJpxgDvolbx4URVo9vIJj6o24
119	17.27127	−98.27412	Approximate	Coicoyán de las Flores, Oaxaca, Mexico	Coicoyán de las Flores	ChIJJyD-RFDwyIURnLdDZ_pKNt8
120	17.84210	−96.88157	Approximate	Concepción Pápalo, Oaxaca, Mexico	Concepción Pápalo	ChIJ59R7N9GexoURsRhQrzw7ftQ
121	17.03788	−97.94319	Approximate	Constancia del Rosario, Oaxaca, Mexico	Constancia del Rosario	ChIJP9–01h7yIURkwDDmJMI56M
122	18.17616	−96.87705	Approximate	Eloxochitlán de Flores Magón, Oaxaca, Mexico	Eloxochitlán de Flores Magón	ChIJV61Duq47xIURXb0D0FwGk1E
123	16.79254	−95.36807	Approximate	Guevea de Humboldt, Oaxaca, Mexico	Guevea de Humboldt	ChIJO1hlgeEUwIURVy1p_G5LrwM
124	18.10169	−96.79893	Approximate	Huautepec, Oaxaca, Mexico	Huautepec	ChIJL6ZFdOAixIUR9MZejPqrsIM
125	18.13109	−96.84314	Approximate	Huautla de Jiménez, Oaxaca, Mexico	Huautla de Jiménez	ChIJHSjrI1IjxIURpjvkKCZ4ahg
126	17.51062	−98.04899	Approximate	Ixpantepec Nieves, Oaxaca, Mexico	Ixpantepec Nieves	ChIJ8RZTBOuVyIURiXjEPmn8UPg

(continued)

Table 2.A (continued)

ID	lat	lon	location_type	formatted_address	long_name	place_id
127	17.33218	−96.48736	Approximate	Ixtlán de Juárez, Oaxaca, Mexico	Ixtlán de Juárez	ChIJK6WAxDLSxoURQHaOZr-1sXE
128	17.38524	−97.35274	Approximate	Magdalena Yodocono de Porfirio Díaz, Oaxaca, Mexico	Magdalena Yodocono de Porfirio Díaz	ChIJJ_1mNy1ExoURSXVpJ6cNc9Y
129	16.89865	−96.90330	Approximate	Magdalena Mixtepec, Oaxaca, Mexico	Magdalena Mixtepec	ChIJZVB5t_MRx4URpqo6DWiV3-c
130	17.23555	−97.55045	Approximate	Magdalena Peñasco, Oaxaca, Mexico	Magdalena Peñasco	ChIJVRjYQdwzxoUR7XL9L6vAT3g
131	16.90467	−96.55966	Approximate	Magdalena Teitipac, Oaxaca, Mexico	Magdalena Teitipac	ChIJk19h56gwx4URxRu_8IG3j0w
132	18.03331	−96.91557	Approximate	Mazatlán Villa de Flores, Oax., Mexico	Mazatlán Villa de Flores	ChIJi78dXPclxIURW8nCD1_8g7I
133	16.42708	−97.97659	Approximate	Pinotepa de Don Luis, Oaxaca, Mexico	Pinotepa de Don Luis	ChIJa23DJiEdyIURpcbF8NFEfiQ
134	17.61132	−98.01474	Approximate	San Agustín Atenango, Oaxaca, Mexico	San Agustín Atenango	ChIJcx-L7I-7yIURY12TRpxCizs
135	17.19260	−96.76373	Approximate	San Agustín Etla, Oaxaca, Mexico	San Agustín Etla	ChIJ35zh7f4fx4URinY43WWDh2A
136	17.23879	−97.10429	Approximate	San Andrés Nuxiño, Oaxaca, Mexico	San Andrés Nuxiño	ChIJebf4nV5WxoURI6-hJRCSPfQ

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Table 2.A (continued)

ID	lat	lon	location_type	formatted_address	long_name	place_id
137	17.27205	−96.23620	Approximate	San Andrés Solaga, Oaxaca, Mexico	San Andrés Solaga	ChIJKYtuPB8mwYURwZHGLYdcZ2Y
138	17.29442	−96.15261	Approximate	San Andrés Yaá, Oax., Mexico	San Andrés Yaá	ChIJjzW0Yv8jwYUROt2JdNYBpoI
139	16.59905	−96.85799	Approximate	San Andrés Zabache, Oaxaca, Mexico	San Andrés Zabache	ChIJJQ1Wnotlx4URl759-h4-Uns
140	17.15228	−97.56603	Approximate	San Antonio Sinicahua, Oaxaca, Mexico	San Antonio Sinicahua	ChIJbf8djNQyxoURNvs0QoHjqRo
141	17.22611	−96.22100	Approximate	San Baltazar Yatzachi el Bajo, Oaxaca, Mexico	San Baltazar Yatzachi el Bajo	ChIJWexIVbgnwYUR9Ka4BRtq2I0
142	17.59053	−97.30690	Approximate	San Bartolo Soyaltepec, Oaxaca, Mexico	San Bartolo Soyaltepec	ChIJU-NlDP1oxoURGFXe64ktkak
143	16.42726	−95.97431	Approximate	San Bartolo Yautepec, Oaxaca, Mexico	San Bartolo Yautepec	ChIJ07fdbRhiv4URrc8lmqGX8NU
144	17.24231	−96.24423	Approximate	San Bartolomé Zoogocho, Oaxaca, Mexico	San Bartolomé Zoogocho	ChIJh6zK84gowYURw2X8qJSBuwQ
145	16.82418	−96.89783	Approximate	San Bernardo Mixtepec, Oaxaca, Mexico	San Bernardo Mixtepec	ChIJW_ZfFusSx4URXwqjD7jG6_E

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Table 2.A (continued)

ID	lat	lon	location_type	formatted_address	long_name	place_id
146	16.31948	−96.41017	Approximate	San Cristóbal Amatlán, Oaxaca, Mexico	San Cristóbal Amatlán	ChIJ47DOhsqsuIURCaRe6gofO_Q
147	18.06993	−96.53542	Approximate	San Felipe Jalapa de Díaz, Oaxaca, Mexico	San Felipe Jalapa de Díaz	ChIJay4PNlgExIURDiGmYXy_kTU
148	16.89340	−97.30508	Approximate	San Francisco Cahuacúa, Oaxaca, Mexico	San Francisco Cahuacúa	ChIJRTIDWnC7 × 4URWFfmxOlRX7g
149	17.17223	−96.25098	Approximate	San Francisco Cajonos, Oax., Mexico	San Francisco Cajonos	ChIJ50Hnfo7XwIURoUcKwi5296U
150	17.95111	−96.73849	Approximate	Santa María Tlalixtac, Oaxaca, Mexico	Santa María Tlalixtac	ChIJ6S9uy7CfxoURr71KovFRbXM
151	18.19667	−96.94745	Approximate	San Francisco Huehuetlán, Oaxaca, Mexico	San Francisco Huehuetlán	ChIJ6zYASh0xxIURMx-7eMmQ4Nc
152	16.09921	−96.22182	Approximate	San Francisco Ozolotepec, Oax., Mexico	San Francisco Ozolotepec	ChIJpXzKJ8RHv4URATtbTwpgMD0
153	16.51519	−96.97495	Approximate	San Francisco Sola, Oaxaca, Mexico	San Francisco Sola	ChIJKYvWe4h7 × 4URHulURHAQRHw
154	17.84920	−97.49630	Approximate	San Francisco Teopan, Oaxaca, Mexico	San Francisco Teopan	ChIJjx7p17ELxoURvRTbr9OYwLc

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Table 2.A (continued)

ID	lat	lon	location_type	formatted_address	long_name	place_id
155	17.48411	−98.26857	Approximate	San Francisco Tlapancingo, Oaxaca, Mexico	San Francisco Tlapancingo	ChIJlQFCcDLoyIUR38nuOjyaMtI
156	16.09461	−97.08156	Approximate	San Gabriel Mixtepec, Oaxaca, Mexico	San Gabriel Mixtepec	ChIJTUeIyvaLuIUR3U5KbVgXynM
157	16.51927	−96.98258	Approximate	San Ildefonso Sola, Oaxaca, Mexico	San Ildefonso Sola	ChIJpU3zYox7 × 4URvgDscSArryQ
158	17.33860	−96.15238	Approximate	San Ildefonso Villa Alta, Oaxaca, Mexico	San Ildefonso Villa Alta	ChIJB0YGbn0kwYUR-5fUkIFIOPU
159	16.23102	−96.87050	Approximate	San Jerónimo Coatlán, Oaxaca, Mexico	San Jerónimo Coatlán	ChIJx4-LMJ2QuIUR6rqEoMUrGvY
160	18.23975	−96.64644	Approximate	San José Independencia, Oaxaca, Mexico	San José Independencia	ChIJGXMmR_UTxIURmu70ULDWvlQ
161	16.68588	−96.68440	Approximate	San José del Progreso, Oaxaca, Mexico	San José del Progreso	ChIJi_f7ZtdDx4UR2XvwG1jrpFk
162	18.15169	−96.71863	Approximate	San José Tenango, Oax., Mexico	San José Tenango	ChIJya7hQ6MXxIURXUU-pPSU564
163	18.13096	−96.84943	Geometric_Center	San Juan, 68,500 Huautla de Jiménez, Oax., Mexico	San Juan	ChIJTZzCTEQ7xIURiqtfihbm20s

(continued)

Table 2.A (continued)

ID	lat	lon	location_type	formatted_address	long_name	place_id
164	18.05763	−96.15098	Geometric_Center	Oaxaca, San Juan Bautista Tuxtepec, Oax., Mexico	Oaxaca	ChIJVQUODWLhw4URi8ztbhd-qNg
165	17.53086	−96.83054	Approximate	San Juan Bautista Atatlahuca, Oaxaca, Mexico	San Juan Bautista Atatlahuca	ChIJ2bMm4gLtxoURt6R5KURqmTg
166	18.04855	−96.76262	Approximate	San Juan Coatzóspam, Oax., Mexico	San Juan Coatzóspam	ChIJz5viKm0ixIURuJXN0nn2u3U
167	16.45982	−97.95436	Approximate	San Juan Colorado, Oaxaca, Mexico	San Juan Colorado	ChIJtzPt9G4EyIURPdjQMxHKbZs
168	17.33649	−95.97731	Approximate	San Juan Comaltepec, Oaxaca, Mexico	San Juan Comaltepec	ChIJnQL-QE0awYURbbAn3QhDtd4
169	17.28383	−97.37767	Approximate	San Juan Diuxi, Oaxaca, Mexico	San Juan Diuxi	ChIJ_YJEJ-pOxoURzgIC8WUZ4V4
170	17.74044	−98.28994	Approximate	San Juan Ihualtepec, Oax., Mexico	San Juan Ihualtepec	ChIJZcPBCzfOyIUR7mbVVPs285g
171	17.35591	−96.30467	Approximate	San Juan Juquila Vijanos, Oax., Mexico	San Juan Juquila Vijanos	ChIJOThwo5cuwYURVgW61LrhGyg
172	16.93423	−95.91673	Approximate	San Juan Juquila Mixes, Oax., Mexico	San Juan Juquila Mixes	ChIJdbCMZhLuwIURQGnY9CsLvp4
173	16.59013	−96.54868	Approximate	San Juan Lachigalla, Oaxaca, Mexico	San Juan Lachigalla	ChIJWbgtzEVQx4URXNL_EzKSczE

(continued)

Table 2.A (continued)

ID	lat	lon	location_type	formatted_address	long_name	place_id
174	17.47005	−95.87839	Approximate	San Juan Lalana, Oaxaca, Mexico	San Juan Lalana	ChIJRd2aWRMOwYURc39Wjb25ssQ
175	17.36000	−97.83272	Approximate	San Juan Mixtepec, Oaxaca, Mexico	San Juan Mixtepec	ChIJhfkdc-OcyIURVUcdZcedrOY
176	16.13157	−96.25885	Approximate	San Juan Ozolotepec, Oaxaca, Mexico	San Juan Ozolotepec	ChIJ2Wp_q5RIv4URM9E0g4spyQ4
177	17.46835	−96.03596	Approximate	San Juan Petlapa, Oaxaca, Mexico	San Juan Petlapa	ChIJe8orfGUWwYURj6FDGgsHlQM
178	17.16029	−97.22686	Approximate	San Juan Tamazola, Oaxaca, Mexico	San Juan Tamazola	ChIJ0xJYZiqtx4UR7oVMXA02_x4
179	17.09698	−97.41515	Approximate	San Juan Teita, Oaxaca, Mexico	San Juan Teita	ChIJp5sBfRe1 × 4URZe2GkIlGN2s
180	17.43092	−96.28274	Approximate	San Juan Yaeé, Oaxaca, Mexico	San Juan Yaeé	ChIJs2JJsw8xwYURyFWEoLb4c7Q
181	18.20500	−96.91300	Approximate	San Lorenzo Cuaunecuiltitla, Oaxaca, Mexico	San Lorenzo Cuaunecuiltitla	ChIJE5TQSQ86xIURADvzimxk0S4
182	16.39275	−97.87413	Approximate	San Lorenzo, Oax., Mexico	San Lorenzo	ChIJ18NGjwECyIURBrEF9CP0XcM
183	16.58459	−97.19899	Approximate	San Lorenzo Texmelucan, Oaxaca, Mexico	San Lorenzo Texmelucan	ChIJr0aYXriEx4URE4bqcvbU_aY
184	16.94195	−95.71302	Approximate	San Lucas Camotlán, Oax., Mexico	San Lucas Camotlán	ChIJO2r-dLlYwIURrnFk1DJAnTQ

(continued)

Table 2.A (continued)

ID	lat	lon	location_type	formatted_address	long_name	place_id
185	18.05878	−96.39430	Approximate	San Lucas Ojitlán, Oaxaca, Mexico	San Lucas Ojitlán	ChIJ1yCZjLj5w4URj_i4tfJ2GlI
186	16.89509	−96.46869	Approximate	San Lucas Quiaviní, Oaxaca, Mexico	San Lucas Quiaviní	ChIJj7lVV3I0 × 4URQJglWycWnRc
187	18.13532	−96.90584	Approximate	San Lucas Zoquiapam, Oaxaca, Mexico	San Lucas Zoquiapam	ChIJvVbRyL06xIURnXrpbKESES4
188	18.08255	-63.05225	Approximate	Collectivity of Saint Martin	Collectivity of Saint Martin	ChIJ_U5xCKxvDowRp4huTgqDGbk
189	17.22839	−97.88142	Approximate	San Martín Itunyoso, Oaxaca, Mexico	San Martín Itunyoso	ChIJLyzw1RyEyIURNzyK6sPagPE
190	16.61051	−96.84999	Approximate	San Martín Lachilá, Oaxaca, Mexico	San Martín Lachilá	ChIJS4DRS_Vlx4URC_Lfi4Nt8Qc
191	17.15986	−96.20731	Approximate	San Mateo Cajonos, Oax., Mexico	San Mateo Cajonos	ChIJp59rYUXYwIUR3VN1aQ8_NN4
192	17.65627	−98.41610	Approximate	San Mateo Nejapam, Oaxaca, Mexico	San Mateo Nejapam	ChIJlaDf5urZyIURkaP2uaeBnwE
193	17.14980	−97.53191	Approximate	San Mateo Peñasco, Oaxaca, Mexico	San Mateo Peñasco	ChIJ2ee_zKzMx4URjJziBek5s_w
194	17.25143	−96.15501	Approximate	San Melchor Betaza, Oaxaca, Mexico	San Melchor Betaza	ChIJC2zPjf0mwYURENrFQlN_D3g
195	17.41162	−96.69250	Approximate	San Miguel Aloápam, Oaxaca, Mexico	San Miguel Aloápam	ChIJedlsCAnDxoURpTrtegFqxto

(continued)

Table 2.A (continued)

ID	lat	lon	location_type	formatted_address	long_name	place_id
196	17.63761	−97.19370	Approximate	San Miguel Chicahua, Oaxaca, Mexico	San Miguel Chicahua	ChIJ80ae5-tjxoURb4XX57w761Q
197	16.19546	−96.69456	Approximate	San Miguel Coatlán, Oaxaca, Mexico	San Miguel Coatlán	ChIJ29HQwBm8uIURbSKCUNeZ9Ac
198	17.04672	−97.62070	Approximate	San Miguel el Grande, Oax., Mexico	San Miguel el Grande	ChIJa7U−9dHRx4URbUYW80rY1cI
199	17.73961	−97.14358	Approximate	San Miguel Huautla, Oaxaca, Mexico	San Miguel Huautla	ChIJ44G-hdB8xoURdsJEvKCRUfg
200	16.77744	−96.95812	Approximate	San Miguel Mixtepec, Oax., Mexico	San Miguel Mixtepec	ChIJaYhP-dtyx4URZMkCdB0OvYs
201	16.25908	−97.37867	Approximate	San Miguel Panixtlahuaca, Oaxaca, Mexico	San Miguel Panixtlahuaca	ChIJkTkj4ktyuIUR_bqKMpzVxsU
202	16.97515	−95.76325	Approximate	San Miguel Quetzaltepec, Oax., Mexico	San Miguel Quetzaltepec	ChIJoUWcDq33wIURCMzDNZegZYA
203	17.91811	−96.79780	Approximate	San Miguel Santa Flor, Oaxaca, Mexico	San Miguel Santa Flor	ChIJN8IcHfWexoURPgD16mn8EyU
204	16.78088	−96.58114	Approximate	San Miguel Tilquiapam, Oaxaca, Mexico	San Miguel Tilquiapam	ChIJE4ECVd5Hx4UR_UStQIVjI_E

(continued)

Table 2.A (continued)

ID	lat	lon	location_type	formatted_address	long_name	place_id
205	16.41484	−98.06316	Approximate	San Miguel Tlacamama, Oaxaca, Mexico	San Miguel Tlacamama	ChIJqcUNrGgeyIURA90zWJXw7kI
206	17.45735	−98.00562	Approximate	San Miguel Tlacotepec, Oaxaca, Mexico	San Miguel Tlacotepec	ChIJ-ZU_yv2WyIURwT9Bfkx7DZc
207	17.37226	−96.33394	Approximate	San Miguel Yotao, Oax., Mexico	San Miguel Yotao	ChIJoaVYu_AtwYUR5QGmC23tj2I
208	16.42482	−96.74262	Approximate	San Nicolás, Oaxaca, Mexico	San Nicolás	ChIJU7DRQ3Zgx4URUoYHt8Et8DI
209	17.53324	−96.55403	Approximate	San Pablo Macuiltianguis, Oax., Mexico	San Pablo Macuiltianguis	ChIJ0zEfuSPJxoURDlys7L1kvYI
210	16.22314	−96.78430	Approximate	San Pablo Coatlán, Oaxaca, Mexico	San Pablo Coatlán	ChIJz6u6xJSQuIURryxX-o6Wb_k
211	16.98263	−96.89131	Approximate	San Pablo Cuatro Venados, Oax., Mexico	San Pablo Cuatro Venados	ChIJkz9zTXYQx4UR0Nc0y_bHY5I
212	16.92132	−96.36251	Approximate	San Pablo Villa de Mitla, Oaxaca, Mexico	San Pablo Villa de Mitla	ChIJsfvbxWLMwIURsPNLM6dkMYM
213	17.14652	−96.22832	Approximate	San Pablo Yaganiza, Oax., Mexico	San Pablo Yaganiza	ChIJzaEQyNLZwIURaKodutHD85o
214	16.48802	−97.98711	Approximate	San Pedro Atoyac, Oaxaca, Mexico	San Pedro Atoyac	ChIJk92V-WUbyIUR1NmMDulCgLY

(continued)

Table 2.A (continued)

ID	lat	lon	location_type	formatted_address	long_name	place_id
215	17.49950	−97.13792	Approximate	San Pedro Coxcaltepec Cántaros, Oaxaca, Mexico	San Pedro Coxcaltepec Cántaros	ChIJ2StPY1NexoURhLHgMc-4BRE
216	17.76834	−97.07844	Approximate	San Pedro Jocotipac, Oaxaca, Mexico	San Pedro Jocotipac	ChIJZYgNZDKBxoUR8rkK_TByrFw
217	16.74279	−96.71060	Approximate	San Pedro Mártir, Oax., Mexico	San Pedro Mártir	ChIJCU8ZPGVqx4URmWpRUYS-Tnc
218	16.27072	−96.28505	Approximate	San Pedro Mixtepec, Oaxaca, Mexico	San Pedro Mixtepec	ChIJRynVAMxRv4URVeVnA6mS5v4
219	17.10391	−97.54071	Approximate	San Pedro Molinos, Oaxaca, Mexico	San Pedro Molinos	ChIJhaqdRxbNx4UR1QOzQUDk4SE
220	17.68743	−97.03707	Approximate	San Pedro Jaltepetongo, Oaxaca, Mexico	San Pedro Jaltepetongo	ChIJ5RCUhOaFxoURsLKu5Cq-yn0
221	17.80260	−97.54014	Approximate	San Pedro Nopala, Oax., Mexico	San Pedro Nopala	ChIJP9NSkIsOxoURLDLJi2QdYjw
222	16.78259	−96.03142	Approximate	San Pedro Quiatoni, Oax., Mexico	San Pedro Quiatoni	ChIJ8xXMqgaVwIUROdRBr5i1fc0
223	17.82616	−96.66379	Approximate	San Pedro Sochiapam, Oaxaca, Mexico	San Pedro Sochiapam	ChIJp7B9IAikxoUR65Opc7sCEek
224	16.63749	−96.53678	Approximate	San Pedro Taviche, Oaxaca, Mexico	San Pedro Taviche	ChIJ9y3lvMxPx4URdogNZAoCEl8

(continued)

Table 2.A (continued)

ID	lat	lon	location_type	formatted_address	long_name	place_id
225	17.34044	−97.37885	Approximate	San Pedro Tidaá, Oaxaca, Mexico	San Pedro Tidaá	ChIJa5AfK5xIxoURQoNuScoJ5Tc
226	17.09371	−96.73523	Approximate	San Pedro & San Pablo, Santo Tomas, 68,043 Oaxaca, Oax., Mexico	San Pedro	Ej9TYW4gUGVkcm8gJiBTYW4gUGFibG8s IFNhbnRvIFRvbWFzLCA2ODA0MyBPYXhhY2 EsIE9heC4sIE3DqXhpY28
227	17.02646	−96.07584	Approximate	San Pedro y San Pablo Ayutla, Oax., Mexico	San Pedro y San Pablo Ayutla	ChIJZX80p1vdwIURj_hpiXvtYhA
228	17.41906	−96.35518	Approximate	San Pedro Yaneri, Oax., Mexico	San Pedro Yaneri	ChIJ1e0NaVEywYURbdFlWO4_N6I
229	16.99228	−96.58788	Approximate	San Sebastián Abasolo, Oaxaca, Mexico	San Sebastián Abasolo	ChIJK-iac606 × 4URY3iDAAOelFI
230	16.54482	−98.14612	Approximate	San Sebastián Ixcapa, Oax., Mexico	San Sebastián Ixcapa	ChIJ_UHTwbwiyIURDqqHW5YQdOw
231	17.82755	−98.00427	Approximate	San Simón Zahuatlán, Oax., Mexico	San Simón Zahuatlán	ChIJfZL-H62zyIURJwfcVVXyqck
232	17.45719	−97.44219	Approximate	San Vicente Nuñú, Oaxaca, Mexico	San Vicente Nuñú	ChIJ3UwEYnc_xoUROdh78eIS1Dc
233	16.70420	−97.01816	Approximate	San Vicente Lachixío, Oaxaca, Mexico	San Vicente Lachixío	ChIJARsGi4p1 × 4URQkUn0dlx2ro

(continued)

Table 2.A (continued)

ID	lat	lon	location_type	formatted_address	long_name	place_id
234	16.99613	−96.00911	Approximate	Santa María Tepantlali, Oax., Mexico	Santa María Tepantlali	ChIJSTm0sJbowIURCRQeWrvRvrg
235	16.99197	−96.46945	Approximate	Santa Ana, Oax., Mexico	Santa Ana	ChIJtaZ1enMyx4URyQ1f6ezrrS8
236	18.21069	−96.90549	Approximate	Santa Ana Ateixtlahuaca, Oax., Mexico	Santa Ana Ateixtlahuaca	ChIJBYdYevY5xIURxNXP68X5WG4
237	16.65434	−95.90951	Approximate	Santa Ana Tavela, Oaxaca, Mexico	Santa Ana Tavela	ChIJ04l6YQ-awIURN5_y17CgOVI
238	17.39681	−96.60859	Approximate	Santa Ana Yareni, Oaxaca, Mexico	Santa Ana Yareni	ChIJt5tvpxfFxoURNPL3DstOGUQ
239	16.32157	−96.26422	Approximate	Santa Catalina Quierí, Oaxaca, Mexico	Santa Catalina Quierí	ChIJBxH7VjVRv4URKBQR_QZdUgA
240	16.30333	−96.64592	Approximate	Santa Catarina Cuixtla, Oaxaca, Mexico	Santa Catarina Cuixtla	ChIJf5g-cN2iuIURh4gwpSTllRY
241	17.26749	−96.47267	Approximate	Santa Catarina Lachatao, Oax., Mexico	Santa Catarina Lachatao	ChIJn6mqV1HUxoURGC8wjgssVJc
242	16.31460	−96.28439	Approximate	Santa Catarina Quioquitani, Oaxaca, Mexico	Santa Catarina Quioquitani	ChIJ7RBiiRxRv4URo0-urd2vfb0

(continued)

Table 2.A (continued)

ID	lat	lon	location_type	formatted_address	long_name	place_id
243	16.06752	−96.75474	Approximate	Santa Catarina Loxicha, Oax., Mexico	Santa Catarina Loxicha	ChIJV3F_oAqWuIURQhPSkTIYUNU
244	17.58084	−98.22417	Approximate	Santa Cruz de Bravo, Oaxaca, Mexico	Santa Cruz de Bravo	ChIJTdIvZTLByIURcG8Z_kjaoOM
245	16.91802	−97.49195	Approximate	Santa Cruz Tacahua, Oax., Mexico	Santa Cruz Tacahua	ChIJEacX_1fGx4URa781tEC8Dyo
246	16.32153	−96.67369	Approximate	Santa Cruz Xitla, Oaxaca, Mexico	Santa Cruz Xitla	ChIJHePKdIqjuIURHqBAsLVBV08
247	18.16216	−96.87670	Approximate	Santa Cruz Acatepec, Oax., Mexico	Santa Cruz Acatepec	ChIJC2971Ag7xIURaxS2qd6DCeQ
248	16.53343	−97.49533	Approximate	Santa Cruz Zenzontepec, Oaxaca, Mexico	Santa Cruz Zenzontepec	ChIJhSfQBbHzx4URRG4rNV1CWXM
249	16.18538	−96.61801	Approximate	Santa Lucía Miahuatlán, Oaxaca, Mexico	Santa Lucía Miahuatlán	ChIJDROCZui6uIURsnVgVZAqcbQ
250	16.97155	−97.66484	Approximate	Santa Lucía Monteverde, Oax., Mexico	Santa Lucía Monteverde	ChIJ16LNmY_Qx4UR6s9XLd8-G4o
251	16.73655	−96.67953	Approximate	Santa Lucía Ocotlán, Oaxaca, Mexico	Santa Lucía Ocotlán	ChIJowuy-hRBx4URkUvX2sCvm1E
252	17.09322	−95.85467	Approximate	Santa María Alotepec, Oax., Mexico	Santa María Alotepec	ChIJ_UNWQp_7wIUR5Ta5Nfch450

(continued)

Table 2.A (continued)

ID	lat	lon	location_type	formatted_address	long_name	place_id
253	17.63279	−97.09991	Approximate	Santa María Apazco, Oax., Mexico	Santa María Apazco	ChIJaYFC2HNgxoURQD0tPVhY2oM
254	17.09170	−96.76814	Approximate	Santa María Atzompa, Oaxaca, Mexico	Santa María Atzompa	ChIJpamkMiMfx4URnkf2Sp5ScmI
255	18.23322	−96.82965	Approximate	Santa María Chilchotla, Oaxaca, Mexico	Santa María Chilchotla	ChIJ8Z9LWfE7xIURb7sj0ewvZfA
256	16.73682	−95.35394	Approximate	Santa María Guienagati, Oaxaca, Mexico	Santa María Guienagati	ChIJ4yYniHcTwIURprwjlDv5nlQ
257	17.66081	−97.33531	Approximate	Santa María Natívitas, Oaxaca, Mexico	Santa María Natívitas	ChIJFYLeIJJuxoURDSbRW6gvTuk
258	16.13066	−96.36962	Approximate	Santa María Ozolotepec, Oax., Mexico	Santa María Ozolotepec	ChIJP0ivnQtLv4URwm3vA5jpSYY
259	16.16307	−97.19565	Approximate	Santa María Temaxcaltepec, Oaxaca, Mexico	Santa María Temaxcaltepec	ChIJK9El1mhkuIURSaDowCzQheI
260	17.38056	−96.16189	Approximate	Santa María Temaxcalapa, Oax., Mexico	Santa María Temaxcalapa	ChIJR-xJbEk7wYURh0CIcOtX-Lc
261	17.71264	−97.06396	Approximate	Santa María Texcatitlán, Oaxaca, Mexico	Santa María Texcatitlán	ChIJcS1w6TmGxoUR8JR5qqIcXTM

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Table 2.A (continued)

ID	lat	lon	location_type	formatted_address	long_name	place_id
262	17.09492	−96.06130	Approximate	Santa María Tlahuitoltepec, Oaxaca, Mexico	Santa María Tlahuitoltepec	ChIJWyoXNVHnwIURnu2Xl6Gfdew
263	16.60128	−95.62190	Approximate	Santa María Totolapilla, Oaxaca, Mexico	Santa María Totolapilla	ChIJdyo4Ywp7wIUR_Oef0ZA5zkE
264	16.99613	−96.00911	Approximate	Santa María Tepantlali, Oax., Mexico	Santa María Tepantlali	ChIJSTm0sJbowIURCRQeWrvRvrg
265	16.87220	−97.57651	Approximate	Santiago Yosondúa, Oaxaca, Mexico	Santiago Yosondúa	ChIJ2-GIe4PEx4UR7vhAySoMVII
266	17.78222	−96.79753	Approximate	Santa María Pápalo, Oaxaca, Mexico	Santa María Pápalo	ChIJHY45_quZxoURIjIkTHf9DGA
267	17.52479	−97.28291	Approximate	Santa María Chachoápam, Oax., Mexico	Santa María Chachoápam	ChIJB1DyAkZoxoUR1oWZFYddDlg
268	16.65535	−97.33624	Approximate	Santa María Zaniza, Oax., Mexico	Santa María Zaniza	ChIJnWfLtu6Qx4URtahF1TtYS48
269	17.64938	−97.13741	Approximate	Santiago Apoala, Oaxaca, Mexico	Santiago Apoala	ChIJFfF14cxjxoUR-KlJPTJpQVw
270	17.56523	−96.54750	Approximate	Santiago Comaltepec, Oaxaca, Mexico	Santiago Comaltepec	ChIJ_RWJ6tm3xoURvIr8jIJ7Q68
271	17.44497	−96.18501	Approximate	Santiago Camotlán, Oaxaca, Mexico	Santiago Camotlán	ChIJS1J8cLA7wYURNjogsdtMkTI

(continued)

Table 2.A (continued)

ID	lat	lon	location_type	formatted_address	long_name	place_id
272	16.93376	−95.62289	Approximate	Santiago Ixcuintepec, Oaxaca, Mexico	Santiago Ixcuintepec	ChIJX9NdEotbwIURX5j5AjeelA0
273	16.56548	−97.65208	Approximate	Santiago Ixtayutla, Oaxaca, Mexico	Santiago Ixtayutla	ChIJD_osKtn6 × 4URWA1hB6EgXg0
274	16.28169	−97.82093	Approximate	Santiago Jamiltepec, Oaxaca, Mexico	Santiago Jamiltepec	ChIJJSgL1Bf5t4URHng9WAd2VD8
275	17.53556	−95.94417	Approximate	Santiago Jocotepec, Oax., Mexico	Santiago Jocotepec	ChIJGcdW5-MSwYUR8tNygEpIUp8
276	16.68395	−95.53441	Approximate	Santiago Lachiguiri, Oaxaca, Mexico	Santiago Lachiguiri	ChIJfT42QbtvwIUR1vGMsH9FvZ0
277	17.42083	−97.37167	Approximate	Santiago Nejapilla, Oaxaca, Mexico	Santiago Nejapilla	ChIJH22YyLhGxoURZ7JD51rpQK8
278	17.01417	−97.76680	Approximate	Santiago Nuyoó, Oaxaca, Mexico	Santiago Nuyoó	ChIJ05rRBTnWx4URNEboAnd_IE8
279	17.32592	−97.00550	Approximate	Santiago Tenango, Oaxaca, Mexico	Santiago Tenango	ChIJe-zKaif6xoURAew17xShVos
280	17.78152	−97.39961	Approximate	Santiago Tepetlapa, Oaxaca, Mexico	Santiago Tepetlapa	ChIJacMvVw5zxoURYRide83e0T8
281	18.20922	−96.96655	Approximate	Santiago Texcalcingo, Oaxaca, Mexico	Santiago Texcalcingo	ChIJl5FLiC43xIURM1MbrScaUng
282	17.28236	−97.33946	Approximate	Santiago Tilantongo, Oaxaca, Mexico	Santiago Tilantongo	ChIJ3 × 4hnilJxoURX9wYu_–22Y

(continued)

Table 2.A (continued)

ID	lat	lon	location_type	formatted_address	long_name	place_id
283	17.03126	−96.99609	Approximate	Santiago Tlazoyaltepec, Oax., Mexico	Santiago Tlazoyaltepec	ChIJVbhjgC0Ex4URxIi5gYbFvoU
284	16.00902	−96.22517	Approximate	Santiago Xanica, Oaxaca, Mexico	Santiago Xanica	ChIJBy-pY8U5v4UR3pQu7QN1TIk
285	16.22689	−97.27086	Approximate	Santiago Yaitepec, Oaxaca, Mexico	Santiago Yaitepec	ChIJNU8e4wNwuIURhB_gWmeRGtM
286	17.33423	−95.69827	Approximate	Santiago Yaveo, Oaxaca, Mexico	Santiago Yaveo	ChIJIwRxraSpwYURkjC14YjK2jE
287	17.21887	−96.30869	Approximate	Santiago Laxopa, Oaxaca, Mexico	Santiago Laxopa	ChIJNVoeWp8pwYUR-IGusUpLpEM
288	17.22191	−96.24118	Approximate	Santiago Zoochila, Oax., Mexico	Santiago Zoochila	ChIJNQDGOHQowYURhFN5iLnL5dg
289	15.83277	−96.66709	Approximate	Santo Domingo de Morelos, Oax., Mexico	Santo Domingo de Morelos	ChIJLbb10ZzcuIURVBRPTDlPlVY
290	17.22315	−97.12242	Approximate	Santo Domingo Nuxaá, Oaxaca, Mexico	Santo Domingo Nuxaá	ChIJ11-HxkZUxoURlJ3gkcCUh4s
291	16.14981	−96.31124	Approximate	Santo Domingo Ozolotepec, Oaxaca, Mexico	Santo Domingo Ozolotepec	ChIJA7kwPuxLv4UR02z6GoglGeI
292	16.81860	−95.14010	Approximate	Santo Domingo Petapa, Oaxaca, Mexico	Santo Domingo Petapa	ChIJi2WlRTMfwIURDwc_d5dnqag

(continued)

Table 2.A (continued)

ID	lat	lon	location_type	formatted_address	long_name	place_id
293	17.33676	−96.11474	Approximate	Santo Domingo Roayaga, Oax., Mexico	Santo Domingo Roayaga	ChIJlySAMKojwYURRr7JG9JwoCY
294	17.40775	−97.34434	Approximate	Santo Domingo Tlatayapam, Oaxaca, Mexico	Santo Domingo Tlatayapam	ChIJ-7jjQiRExoURBcyWpAXf9YQ
295	17.17315	−96.87042	Approximate	Santo Tomás Mazaltepec, Oaxaca, Mexico	Santo Tomás Mazaltepec	ChIJVbVlfIcdx4URW4vCJsK6nPQ
296	17.43777	−97.93868	Approximate	Santos Reyes Tepejillo, Oaxaca, Mexico	Santos Reyes Tepejillo	ChIJ64UIweqZyIURfV0jWbu3bUg
297	17.77815	−98.00176	Approximate	Santos Reyes Yucuná, Oaxaca, Mexico	Santos Reyes Yucuná	ChIJdWCTtoKxyIURoZpGnU3810w
298	17.37550	−96.30129	Approximate	Tanetze de Zaragoza, Oax., Mexico	Tanetze de Zaragoza	ChIJVfP44SEuwYUR7GrlV6nlBwQ
299	16.30492	−97.54669	Approximate	Tataltepec de Valdés, Oaxaca, Mexico	Tataltepec de Valdés	ChIJtUJwpsoOuIURdHfPHEEyNnw
300	17.35287	−96.61084	Approximate	Teococuilco de Marcos Pérez, Oaxaca, Mexico	Teococuilco de Marcos Pérez	ChIJZW76VtvaxoURDnYjn1-5V7w
301	16.45859	−96.78574	Approximate	Yogana, Oax., Mexico	Yogana	ChIJ34l9aU5gx4URJd4afB2IhOU

(continued)

Table 2.A (continued)

ID	lat	lon	location_type	formatted_address	long_name	place_id
302	17.03919	−97.29631	Approximate	Yutanduchi de Guerrero, Oaxaca, Mexico	Yutanduchi de Guerrero	ChIJmeeLFr2xx4URURZ5SciZTCI
303	16.87540	−97.23722	Approximate	Zapotitlán del Río, Oaxaca, Mexico	Zapotitlán del Río	ChIJHYzryGOjx4URuAGunzhOssw
304	17.89007	−97.81883	Approximate	Zapotitlán Palmas, Oaxaca, Mexico	Zapotitlán Palmas	ChIJ-zabudKqyIURepwhTpOFkw4
305	20.42123	−98.02879	Approximate	Tlaxco, Pue., Mexico	Tlaxco	ChIJT-EBYUiR0IURfwIAm-Bf3_g
306	20.32582	−98.06854	Approximate	Tlacuilotepec, Puebla, Mexico	Tlacuilotepec	ChIJC7hkLI2N0IURh2gvSOItUnA
307	20.28118	−98.14751	Approximate	Pahuatlán, Pue., Mexico	Pahuatlán	ChIJe-RmGSTz0IUR4dWp4jBnt4o
308	20.13642	−97.92130	Approximate	Tlaola, Puebla, Mexico	Tlaola	ChIJ84QONXF90IURWhTJhhvxaTU
309	20.09447	−97.93896	Approximate	Chiconcuautla, Pue., Mexico	Chiconcuautla	ChIJYVyeFN180IURU80_Wc_7mvQ
310	20.16284	−97.69280	Approximate	Jopala, Puebla, Mexico	Jopala	ChIJv8rSqvh92oUROaHZY78bhKU
311	20.12250	−97.85136	Approximate	Tlapacoya, Puebla, Mexico	Tlapacoya	ChIJeT25MGh-0IURrFPYmPmuW0k
312	20.09084	−97.79669	Approximate	San Felipe Tepatlán, Pue., Mexico	San Felipe Tepatlán	ChIJMZR0HWp_0IURvJth2DztgxY
313	20.12075	−97.74366	Approximate	Hermenegildo Galeana, Pue., Mexico	Hermenegildo Galeana	ChIJ0yFEevyA2oURLpG41mDXcAg

(continued)

Table 2.A (continued)

ID	lat	lon	location_type	formatted_address	long_name	place_id
314	20.10111	−97.68414	Approximate	Olintla, Puebla, Mexico	Olintla	ChIJf99V-MSG2oURjLVgAnrJ3fA
315	20.05973	−97.73157	Approximate	Coatepec, Pue., Mexico	Coatepec	ChIJ_6xysNCD2oUR6cD9FnRXn-I
316	20.03749	−97.75661	Approximate	Camocuautla, Pue., Mexico	Camocuautla	ChIJ5-OG90qC2oURbrMf2NwZKq0
317	19.97871	−97.72669	Approximate	Zongozotla, Pue., Mexico	Zongozotla	ChIJF1vgXTGD2oURrAD6bMN_Mjk
318	20.00478	−97.79737	Approximate	Tepango de Rodríguez, Puebla, Mexico	Tepango de Rodríguez	ChIJY-Rp_IJ40IURyfl-xBDmIsk
319	20.02634	−97.69803	Approximate	Hueytlalpan, Puebla, Mexico	Hueytlalpan	ChIJmzLJEuSD2oURo-rsYzk-YgE
320	20.00198	−97.71421	Approximate	Zapotitlán de Méndez, Puebla, Mexico	Zapotitlán de Méndez	ChIJGa_BroOE2oURNXFTZIcSzZ4
321	19.97871	−97.72669	Approximate	Zongozotla, Pue., Mexico	Zongozotla	ChIJF1vgXTGD2oURrAD6bMN_Mjk
322	19.96694	−97.84157	Approximate	Tepetzintla, Puebla, Mexico	Tepetzintla	ChIJ8TQceNh50IURtLA7GN8O78Y
323	20.02436	−97.64559	Approximate	Ixtepec, Puebla, Mexico	Ixtepec	ChIJn2TDQKiF2oURw_rAp3Ahbu0
324	20.06457	−97.57509	Approximate	Tuzamapan de Galeana, Pue., Mexico	Tuzamapan de Galeana	ChIJmxdI4S6P2oURS82f4yo0xes

(continued)

Table 2.A (continued)

ID	lat	lon	location_type	formatted_address	long_name	place_id
325	20.03005	−97.57507	Approximate	Jonotla, Pue., Mexico	Jonotla	ChIJyX8J6waP2oURwqY-n083yiQ
326	20.09637	−97.41033	Approximate	Ayotoxco de Guerrero, Puebla, Mexico	Ayotoxco de Guerrero	ChIJ_VF0OJH02oURCW8h_sGFf24
327	20.01738	−97.52209	Approximate	73,560 Cuetzalán del Progreso, Pue., Mexico	Cuetzalán del Progreso	ChIJAcUjxm2N2oURgBFkxQ0ZY6w
328	19.96875	−97.62905	Approximate	Xochitlán de Vicente Suárez, Pue., Mexico	Xochitlán de Vicente Suárez	ChIJhcq8kraa2oURhE6zKSRroWs
329	19.82033	−97.65877	Approximate	Xochiapulco, Puebla, Mexico	Xochiapulco	ChIJAUN2aPeY2oURl_eEs-O0cPc
330	19.83796	−97.45644	Approximate	Atempan, Puebla, Mexico	Atempan	ChIJ3ytGdyGV2oURC5N947BcqMs
331	18.71365	−98.26228	Approximate	Teopantlán, Puebla, Mexico	Teopantlán	ChIJba2vr4Cmz4URkaEkiMRBe_Q
332	18.67922	−98.05053	Approximate	Huatlatlauca, Puebla, Mexico	Huatlatlauca	ChIJJVK5A8Ccz4UR3pAVFu8pSYs
333	18.40415	−96.84946	Approximate	San Sebastián Tlacotepec, Pue., Mexico	San Sebastián Tlacotepec	ChIJlbYhpkBBxIUR6WO8eySraYQ
334	18.17616	−96.87705	Approximate	Eloxochitlán de Flores Magón, Oaxaca, Mexico	Eloxochitlán de Flores Magón	ChIJV61Duq47xIURXb0D0FwGk1E
335	18.64549	−98.07509	Approximate	Chigmecatitlan, Puebla, Mexico	Chigmecatitlan	ChIJkzrgtSSez4URjOGAnbiAxvU

(continued)

Table 2.A (continued)

ID	lat	lon	location_type	formatted_address	long_name	place_id
336	20.10472	−97.62518	Approximate	Huehuetla, Pue., Mexico	Huehuetla	ChIJRQLnXjqG2oURZ4sckdtCMm0
337	20.01297	−97.62392	Approximate	Atlequizayan, Pue., Mexico	Atlequizayan	ChIJHR6oPnCF2oURkpGjjmwsGH8
338	19.88257	−97.44549	Approximate	Hueyapan, Pue., Mexico	Hueyapan	ChIJqQDm-q6U2oURyUVxpJAhz54
339	18.33632	−97.02019	Approximate	Zoquitlán, Pue., Mexico	Zoquitlán	ChIJ86_0VzBKxIURBPCCLVb9nN4
340	21.36953	−98.66126	Approximate	San Martín Chalchicuautla, San Luis Potosí, Mexico	San Martín Chalchicuautla	ChIJVZh36V_v1oURYI896M8Hy94
341	21.40069	−98.73190	Approximate	Tampacan, San Luis Potosí, Mexico	Tampacan	ChIJbYqF3mXu1oURPLQ_BLyowXY
342	21.33716	−98.82767	Approximate	Matlapa, San Luis Potosí, Mexico	Matlapa	ChIJjY7hIT2T1oUR9AoT8fl-MfI
343	21.43934	−98.87212	Approximate	Axtla de Terrazas, San Luis Potosí, Mexico	Axtla de Terrazas	ChIJy8ShbXaN1oURZQkc4-rQiN8
344	21.55666	−98.82069	Approximate	Tampamolón, S.L.P., Mexico	Tampamolón	ChIJ24C_pMb01oURgXC_Zfh2nGo
345	21.54049	−98.90578	Approximate	Coxcatlán, San Luis Potosí, Mexico	Coxcatlán	ChIJX6sEFs2O1oURjIPcZvh-wns
346	21.54593	−98.96647	Approximate	Huehuetlán, San Luis Potosí, Mexico	Huehuetlán	ChIJF8WFR9WO1oUR8eBzq3JJ2fI

(continued)

Table 2.A (continued)

ID	lat	lon	location_type	formatted_address	long_name	place_id
347	22.15647	−100.98554	Approximate	San Luis Potosi, San Luis Potosí, Mexico	San Luis Potosi	ChIJefusBQCiKoQRV4Lhrynu0g4
348	21.66492	−98.88549	Approximate	Tanlajás, San Luis Potosí, Mexico	Tanlajás	ChIJ7wc9Gaph1oUR8HihISJy5GM
349	21.59752	−98.96663	Approximate	Tancanhuitz de Santos, San Luis Potosí, Mexico	Tancanhuitz de Santos	ChIJ6QKQRsuJ1oURrv_IILo9u3U
350	21.62490	−99.01974	Approximate	Aquismón, San Luis Potosí, Mexico	Aquismón	ChIJg89OFU591oURLeBMWOk_Fa4
351	21.65605	−99.49631	Approximate	Santa Catarina, San Luis Potosí, Mexico	Santa Catarina	ChIJZTgcKdvL1YURHvWL4Zmpve4
352	21.25939	−98.78815	Approximate	Tamazunchale, San Luis Potosí, Mexico	Tamazunchale	ChIJEcIhlWLq1oURz2JYOFhpcQE
353	17.59698	−92.82655	Approximate	Tacotalpa, Tabasco, Mexico	Tacotalpa	ChIJF3rbFPu-7YURL-iw8xjVQng
354	19.48641	−98.25639	Approximate	San Lucas Tecopilco, Tlaxcala, Mexico	San Lucas Tecopilco	ChIJu8T3zi8k0IUR56SKhPdurnc
355	19.35572	−98.09836	Approximate	Cuaxomulco, Tlaxcala, Mexico	Cuaxomulco	ChIJHeGE6U_gz4URZB_vjadVzpo
356	19.33678	−98.06317	Approximate	San José Teacalco, Tlaxcala, Mexico	San José Teacalco	ChIJ3QTZAHThz4URUbzNYbtN6xM
357	21.23069	−98.46188	Approximate	Chiconamel, Ver., Mexico	Chiconamel	ChIJSeuhJ0Ug14URDFQtHmLfhOw
358	21.27559	−98.37731	Approximate	Platón Sánchez, Ver., Mexico	Platón Sánchez	ChIJN8GPghoY14URzBRoj3CCUIU

(continued)

Table 2.A (continued)

ID	lat	lon	location_type	formatted_address	long_name	place_id
359	21.16346	−97.85253	Approximate	Tepetzintla, Ver., Mexico	Tepetzintla	ChIJOS88vXtZ14URWfz_PNSTFAU
360	20.78068	−98.44379	Approximate	Ilamatlán, Ver., Mexico	Ilamatlán	ChIJc5-7mn3W0IURu_7tT94-e9I
361	20.76071	−98.34343	Approximate	Zontecomatlán de López y Fuentes, Ver., Mexico	Zontecomatlán de López y Fuentes	ChIJ2YPNbqXR0IURVuSrJGQZa4Y
362	20.62020	−98.20079	Approximate	Tlachichilco, Ver., Mexico	Tlachichilco	ChIJ_YnowcnG0IURoP3e0fPyFVU
363	20.26135	−97.72976	Approximate	Coahuitlán, Ver., Mexico	Coahuitlán	ChIJWwalHjJ52oURNx83YhhxplI
364	20.21039	−97.68125	Approximate	Mecatlán, Ver., Mexico	Mecatlán	ChIJGcOCUst92oUR6wO_jmBONOo
365	20.20827	−97.59413	Approximate	Chumatlan, Ver., Mexico	Chumatlan	ChIJQyVmW0Zj2oURQDxb6jck73I
366	20.18365	−97.58519	Approximate	Coxquihui, Ver., Mexico	Coxquihui	ChIJuw0fZuti2oUR-1iBGyhz0mk
367	19.80782	−96.91595	Approximate	Tenochtitlán, Ver., Mexico	Tenochtitlán	ChIJwyU-2lM924URkDDou_cBM6Y
368	19.74334	−96.81815	Approximate	Chiconquiaco, Ver., Mexico	Chiconquiaco	ChIJO3SFsL4-24URXi9xeErUOSk
369	19.06810	−96.84474	Approximate	Tepatlaxco, Ver., Mexico	Tepatlaxco	ChIJwxNC6QXCxIUR8JVoWS22XgY
370	18.92830	−97.13335	Approximate	La Perla, Ver., Mexico	La Perla	ChIJXcwLWrQdxYURCWB_HRTfEy4

(continued)

Table 2.A (continued)

ID	lat	lon	location_type	formatted_address	long_name	place_id
371	18.90732	−97.08481	Approximate	Atzacan, Ver., Mexico	Atzacan	ChIJQcBnR2LixIURAZl9CYKg-fU
372	18.79883	−96.57138	Approximate	Carrillo Puerto, Ver., Mexico	Carrillo Puerto	ChIJDyzNkz2PxIURL1Q2DFd2D9o
373	18.79510	−97.30886	Approximate	Aquila, Ver., Mexico	Aquila	ChIJ-Uof3LUPxYURE3wHfBGl83Y
374	18.75467	−97.15149	Approximate	Soledad Atzompa, Ver., Mexico	Soledad Atzompa	ChIJWxmnKRsExYURpMyPUKW3V_w
375	18.78820	−97.09300	Approximate	San Andrés Tenejapan, Ver., Mexico	San Andrés Tenejapan	ChIJW4w3eAoCxYURpyiKMXUHWVw
376	18.75790	−97.04773	Approximate	Magdalena Municipality, Ver., Mexico	Magdalena Municipality	ChIJ3RBLeIj-xIURI7FLMNHM99U
377	18.72957	−97.07111	Approximate	Tequila, Ver., Mexico	Tequila	ChIJgR6XUbX_xIUR9D1_skeH33Y
378	18.69719	−97.09068	Approximate	Atlahuilco, Ver., Mexico	Atlahuilco	ChIJB8AGeeD_xIURQCFYZbs7fUs
379	18.64750	−97.15253	Approximate	Xoxocotla, Ver., Mexico	Xoxocotla	ChIJAdQ2_mmqxYURgZbeONh2N3c
380	18.66685	−97.00012	Approximate	Zongolica, Ver., Mexico	Zongolica	ChIJF1WCOvdVxIURb1uHxeq0cvs
381	18.61924	−97.03831	Approximate	Texhuacán, Ver., Mexico	Texhuacán	ChIJ-0duzk9UxIURSEfooT-bPog
382	18.59552	−96.99273	Approximate	Mixtla de Altamirano, Ver., Mexico	Mixtla de Altamirano	ChIJz1QBGCdUxIURWZYiGebnzr8

(continued)

Table 2.A (continued)

ID	lat	lon	location_type	formatted_address	long_name	place_id
383	18.56569	−97.10090	Approximate	Astacinga, Ver., Mexico	Astacinga	ChIJJ3GlyrGsxYURTdYlgTeu-6U
384	18.22103	−94.83827	Approximate	Mecayapan, Ver., Mexico	Mecayapan	ChIJo9Q4ZEju6YUReYZhNM66mZw
385	18.24544	−94.76101	Approximate	Tatahuicapan, Ver., Mexico	Tatahuicapan	ChIJufl7UfLs6YUROapk-YETCJ0
386	18.26237	−94.69213	Approximate	Pajapan, Ver., Mexico	Pajapan	ChIJSdXbhgqT6YURZ_gUY_Lt0sc
387	18.22103	−94.83827	Approximate	Mecayapan, Ver., Mexico	Mecayapan	ChIJo9Q4ZEju6YUReYZhNM66mZw
388	18.22961	−94.87189	Approximate	Soteapan, Ver., Mexico	Soteapan	ChIJr0Enpwzv6YUR2MJ_tzCDQ7s
389	17.95420	−94.64245	Approximate	Zaragoza, Ver., Mexico	Zaragoza	ChIJcTHGSjon6oURn5AaZ_RTKOw
390	20.19915	−97.70501	Approximate	Filomeno Mata, Ver., Mexico	Filomeno Mata	ChIJ73pzvDp82oUR3lLyUypXc1w
391	18.51799	−97.05437	Approximate	Tehuipango, Ver., Mexico	Tehuipango	ChIJt70p2_ZSxIURF31UztIjROI
392	20.80120	−88.19985	Approximate	Temozón, Yuc., Mexico	Temozón	ChIJC3rp_LZ1UY8RJ3cRXKfufQ4
393	21.02203	−88.17876	Approximate	Calotmul, Yuc., Mexico	Calotmul	ChIJ_0w2mm9_UY8RThwyKxZ8zqU
394	21.00886	−88.30606	Approximate	Espita, Yuc., Mexico	Espita	ChIJaf8B8pV8UY8RMDvi90OjGYw

(continued)

Table 2.A (continued)

ID	lat	lon	location_type	formatted_address	long_name	place_id
395	20.63426	−88.21946	Approximate	Chichimilá, Yuc., Mexico	Chichimilá	ChIJ3T8l_7gLUY8RTIjD8j−3p1M
396	21.19888	−86.82521	Geometric_Center	Yucatán, Gastronómicos, 77,528 Cancún, Q.R., Mexico	Yucatán	ChIJG1JaBSksTI8RKbu_kY7Ra6k
397	20.62243	−88.41457	Approximate	Kaua, Yuc., Mexico	Kaua	ChIJARnBkBAUUY8RSao68GGcxUM
398	20.56784	−88.51266	Approximate	Chankom, Yuc., Mexico	Chankom	ChIJJ−DFW6k9UY8RW3zv3D1wt5g
399	20.90099	−88.75130	Approximate	Tunkás, Yuc., Mexico	Tunkás	ChIJabXFUIBSUY8Rzy6rKd2ryIY
400	21.05086	−89.07388	Approximate	Teya, Yuc., Mexico	Teya	ChIJR_iklUmgVo8RIrLt1c-Nuxs
401	20.86390	−89.20083	Approximate	Hoctun, Yuc., Mexico	Hoctun	ChIJ9cHRkvqQVo8RlYzZWGCl3YU
402	20.93000	−89.02271	Approximate	Izamal, Yuc., Mexico	Izamal	ChIJPcsrG4GkVo8RNgEZfUMVVVI
403	20.81125	−89.51021	Approximate	Timucuy, Yuc., Mexico	Timucuy	ChIJB0Y_c−RlVo8RJD7NEQ2wIBo
404	20.64687	−89.68057	Approximate	Abalá, Yuc., Mexico	Abalá	ChIJt5dbw7hAVo8ROfsNFSqFRpE
405	20.64758	−89.90017	Approximate	Kopomá, Yuc., Mexico	Kopomá	ChIJYSWGmrsjVo8RinABTPAsUhs
406	20.55009	−89.85738	Approximate	Opichén, Yuc., Mexico	Opichén	ChIJNagg3zYlVo8Rs8dY-GqIjBQ
407	20.49600	−89.59020	Approximate	Sacalum, Yuc., Mexico	Sacalum	ChIJTxzBIwtPVo8RPL9L7vN2g7E

(continued)

Table 2.A (continued)

ID	lat	lon	location_type	formatted_address	long_name	place_id
408	20.45827	-89.45694	Approximate	Chapab, Yuc., Mexico	Chapab	ChIJWdCy98JWVo8RvDn0BYxqGr0
409	20.39307	−89.39176	Approximate	Maní, Yuc., Mexico	Maní	ChIJ5yklIUxVVo8RQjDjT5LJsfI
410	20.32784	−89.64407	Approximate	Santa Elena, Yuc., Mexico	Santa Elena	ChIJ9-fx7rK0V48RPNl4MdjzuiY
411	20.17143	−89.01784	Approximate	Chacsinkín, Yuc., Mexico	Chacsinkín	ChIJRWyNAS0lV48Ru0WD2vF312Y
412	20.83372	−89.18295	Approximate	Xocchel, Yuc., Mexico	Xocchel	ChIJzZhmiW2WVo8RAPji5-nx4jw

Table 2.B 319 municipalities classified with high vulnerability

ID	lat	lon	location_type	formatted_address	long_name	place_id
1	22.22414	−102.17380	Approximate	Tepezalá, Aguascalientes, Mexico	Tepezalá	ChIJ6aEYb9gDgoYRo_rJh5IAMNo
2	21.91211	−102.04884	Approximate	El Llano, Ags., Mexico	El Llano	ChIJ0cdlAMAdKoQRTFnPE5f5wuQ
3	31.88166	−116.62843	Approximate	Estado de Mexico, Ensenada, B.C., Mexico	Estado de Mexico	ChIJeTbfWZKS2IARVMniANujgX8
4	32.62454	−115.45226	Approximate	Mexicali, Baja California, Mexico	Mexicali	ChIJ0913qAxw14ARmvXN5aAzANQ
5	32.51495	−117.03825	Approximate	Tijuana, Baja California, Mexico	Tijuana	ChIJ03tYJgI52YARViTmpK9LchQ
6	26.07079	−111.84420	Approximate	Comondú, B.C.S., Mexico	Comondú	ChIJD4lUIzBWtIYRZezLGtonZnQ
7	26.89059	−111.98108	Approximate	Mulegé, Baja California Sur, Mexico	Mulegé	ChIJkbgLLop9tYYRN1SFhsfpZk0
8	24.14264	−110.31275	Approximate	La Paz, B.C.S., Mexico	La Paz	ChIJVxDa9d7Sr4YRtqPxwOjSdUg
9	20.37086	−90.05047	Approximate	Calkini, Campeche, Mexico	Calkini	ChIJn5iMeO6A-IURL1YejNysIms
10	19.83013	−90.53491	Approximate	Campeche, Camp., Mexico	Campeche	ChIJbRNrF5Yz-IURRGLylUyOPek
11	19.34716	−90.72002	Approximate	Champoton, Campeche, Mexico	Champoton	ChIJEWE_f1tw94URf–mVoJXErw

(continued)

Table 2.B (continued)

ID	lat	lon	location_type	formatted_address	long_name	place_id
12	20.18190	−90.13546	Approximate	Hecelchakán Municipality, Campeche, Mexico	Hecelchakán Municipality	ChIJTfWMNdt6-IURdCywt-60ORA
13	19.74724	−89.84246	Approximate	Hopelchén, Campeche, Mexico	Hopelchén	ChIJQ4diRhvwV48R6C_B2gx1kK4
14	18.25458	−92.09148	Approximate	Palizada, Camp., Mexico	Palizada	ChIJ54Z-50OS8YURCl2vCyfRAdc
15	20.04097	−90.22555	Approximate	Tenabo, Campeche, Mexico	Tenabo	ChIJ8WbrgYNu-IURO8JeEfXmEOM
16	18.61018	−90.73902	Approximate	Escárcega, Campeche, Mexico	Escárcega	ChIJsTfpKiE_9oURzDADsyc1obg
17	18.03830	−89.67389	Approximate	Calakmul, Camp., Mexico	Calakmul	ChIJvXZLTjA1X48R4wUe8g2Ij-o
18	18.18453	−91.04186	Approximate	Candelaria, Camp., Mexico	Candelaria	ChIJfx4HAHWl9oURx1EmlQ1FLNA
19	26.98656	−102.06369	Approximate	Cuatro Ciénegas, Coah., Mexico	Cuatro Ciénegas	ChIJaSTHviR3jIYRMPDRAVxDT54
20	25.77226	−103.26943	Approximate	Francisco I. Madero, Coahuila, Mexico	Francisco I. Madero	ChIJU9Mw7ZzMj4YRRmT3cGd7oYc
21	25.53853	−103.07060	Approximate	Hidalgo, Coah., Mexico	Hidalgo	ChIJR814iwW8j4YRtLdwL5lqbN4
22	25.52604	−103.22595	Approximate	Matamoros, Coahuila, Mexico	Matamoros	ChIJg8a6tSrBj4YRh7lkZj_TyB0

(continued)

Table 2.B (continued)

ID	lat	lon	location_type	formatted_address	long_name	place_id
23	25.44228	−102.16046	Geometric_Center	Coahuila, Col Federico Cárdenas, 27,987 Parras de la Fuente, Coah., Mexico	Coahuila	ChIJyZOe-P5Lj4YRbjB25FVkL7M
24	27.42802	−100.98778	Approximate	Progreso, Coah., Mexico	Progreso	ChIJiY2WWyReioYRLcGtFRDZIoo
25	25.54115	−100.94831	Approximate	Ramos Arizpe, Coah., Mexico	Ramos Arizpe	ChIJJRdMvxUTiIYRonnI_tJpPdA
26	25.42672	−100.99543	Approximate	Saltillo, Coah., Mexico	Saltillo	ChIJ7xnfeJANiIYRwDBHeUGSUak
27	27.29070	−103.70141	Approximate	Sierra Mojada, Coahuila, Mexico	Sierra Mojada	ChIJ30azDpqGkoYR4fWlDdXYTys
28	19.31906	−103.75498	Approximate	Comala, Col., Mexico	Comala	ChIJY4aVsZtEJYQRHaHemtVYDxc
29	18.99957	−103.73642	Approximate	Ixtlahuacán, Colima, Mexico	Ixtlahuacán	ChIJ26TWOguzOoQRrihqaGhF9Lk
30	19.38635	−104.04947	Approximate	Minatitlán, Colima, Mexico	Minatitlán	ChIJP2fP2icWJYQRArpjn8eA3Zk
31	15.27953	−92.69064	Approximate	30,580 Acapetahua, Chis., Mexico	Acapetahua	ChIJ_8FCQYERkoUR48tZx-3UBXA
32	14.99582	−92.16713	Approximate	Cacahoatán, Chis., Mexico	Cacahoatán	ChIJ43oSft0KjoURX3CS_tuK2F8
33	16.96345	−92.61645	Approximate	Chalchihuitán, Chis., Mexico	Chalchihuitán	ChIJgwBWeyBm7YURdTtUU8ZvoCY

(continued)

Table 2.B (continued)

ID	lat	lon	location_type	formatted_address	long_name	place_id
34	16.78694	−92.68759	Approximate	Chamula, Chis., Mexico	Chamula	ChIJFQRuFRpE7YURg-gX_Dhqk-k
35	17.10468	−92.27366	Approximate	Chilon, Chis., Mexico	Chilon	ChIJX6HYksWP8oURNiKwetLMNbo
36	15.32325	−92.65862	Approximate	Escuintla, Chis., Mexico	Escuintla	ChIJHZRPZLoTkoURX2L_pTFcuzo
37	15.01942	−92.38085	Approximate	Huehuetán, Chis., Mexico	Huehuetán	ChIJCYmjnAj-jYUR43R7_4DrmtI
38	16.25173	−92.02171	Approximate	La Independencia, Chis., Mexico	La Independencia	ChIJXXtHMno7jYURyggD65qpgxg
39	16.32244	−91.79106	Approximate	Chiapas, Chis., Mexico	Chiapas	ChIJjatjkszZjIUR_KgKeasZPEg
40	16.90872	−92.09437	Approximate	Ocosingo, Chis., Mexico	Ocosingo	ChIJlwTOu3Xq8oURArA-xrQP4IE
41	17.51098	−91.99305	Approximate	Palenque, Chis., Mexico	Palenque	ChIJKTvaAEZP8oUR8XOZc3PNatE
42	15.21272	−92.57623	Approximate	Villa Comaltitlán, Chis., Mexico	Villa Comaltitlán	ChIJwUH5mbgPkoURYjzRqbtRNYs
43	17.55625	−92.34311	Approximate	Salto de Agua, Chis., Mexico	Salto de Agua	ChIJacULQ35 × 8oURneWJZrVbT5o
44	17.14058	−92.71090	Approximate	Simojovel, Chis., Mexico	Simojovel	ChIJbWXtCs9z7YUREtVvx3s4HrU
45	17.02441	−92.30585	Approximate	Sitalá, Chis., Mexico	Sitalá	ChIJA7YLlHaa8oURvtUjAow84Qs

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Table 2.B (continued)

ID	lat	lon	location_type	formatted_address	long_name	place_id
46	14.90556	−92.26341	Approximate	Tapachula de Córdova y Ordoñez, Chis., Mexico	Tapachula de Córdova y Ordoñez	ChIJscFxXjkPjoURiyK4ALi5KF0
47	16.81898	−92.50580	Approximate	Tenejapa, Chis., Mexico	Tenejapa	ChIJzeh5-sRe7YURtoNAF0F4U-0
48	17.30232	−92.42334	Approximate	Tila, Chis., Mexico	Tila	ChIJQXPSz7V_8oURorySNrat4rE
49	17.27699	−92.31590	Approximate	Tumbalá, Chis., Mexico	Tumbalá	ChIJhZQRAx198oUR-Ndu94qCCgU
50	15.14660	−92.42211	Approximate	Tuzantán, Chis., Mexico	Tuzantán	ChIJxWbu_eL4jYURsCEl3M9du3g
51	16.75948	−92.72163	Approximate	Zinacantán, Chis., Mexico	Zinacantán	ChIJe9ACPYc47YUR_9-hUBzBKzk
52	16.89191	−92.37078	Approximate	San Juan Cancuc, Chis., Mexico	San Juan Cancuc	ChIJef1oRQ-i8oURzvgQ60f6IIQ
53	16.14097	−91.29272	Approximate	Maravilla Tenejapa, Chis., Mexico	Maravilla Tenejapa	ChIJVxkjirGYjIUR3W0wsTm1Ofw
54	16.94006	−92.71454	Approximate	Santiago el Pinar, Chis., Mexico	Santiago el Pinar	ChIJ-d1p0jRq7YUR5dSjaMG1f5s
55	28.70616	−106.13010	Geometric_Center	Paseo de Ahumada, Paseos de Chihuahua, 31,125 Chihuahua, Chih., Mexico	Paseo de Ahumada	ChIJvWDPPyNC6oYRXQyAnKivX-8
56	27.03039	−107.73623	Approximate	Batopilas, Chihuahua, Mexico	Batopilas	ChIJTU_Ljmg8v4YRKU6WKyB6AeQ

(continued)

Table 2.B (continued)

ID	lat	lon	location_type	formatted_address	long_name	place_id
57	27.84096	−107.58531	Approximate	Bocoyna Municipality, Chihuahua, Mexico	Bocoyna Municipality	ChIJKfxeW26RwIYRAqlnLql2I3c
58	27.91697	−107.05520	Approximate	Carichí, Chihuahua, Mexico	Carichí	ChIJIVhWNP5owIYR4CkEmFS-4mo
59	27.33621	−108.50085	Approximate	Chínipas de Almada, Chihuahua, Mexico	Chínipas de Almada	ChIJwUdU7rieuIYRaKc67_Y_8sE
60	26.82004	−107.06922	Approximate	Guachochi, Chihuahua, Mexico	Guachochi	ChIJh-YNFu1MvoYRX-IKYK3daR8
61	26.09098	−106.96264	Approximate	Guadalupe y Calvo Municipality, Chihuahua, Mexico	Guadalupe y Calvo Municipality	ChIJa6wH-fbevYYRMxQS-TftjtQ
62	27.37139	−108.28111	Approximate	Guazapares, Chih., Mexico	Guazapares	ChIJldbE7WCmuIYRVbwradxjZF0
63	27.05578	−106.18112	Approximate	Huejotitán, Chih., Mexico	Huejotitán	ChIJh2tNY5d0lYYR43Vhn38lxoE
64	31.69036	−106.42455	Approximate	Ciudad Juarez, Chihuahua, Mexico	Ciudad Juarez	ChIJnTILPcte54YRdHmcVABhGQs
65	27.85690	−107.99364	Approximate	Maguarichi, Chihuahua, Mexico	Maguarichi	ChIJD0qWiWTKwIYRmpdExwnV_dU
66	26.67146	−107.67703	Approximate	Morelos Municipality, Chihuahua, Mexico	Morelos Municipality	ChIJz55M_Y7dvoYRfVTiYV6Ux-c
67	27.47399	−106.73722	Approximate	Nonoava, Chihuahua, Mexico	Nonoava	ChIJqzaasBHwv4YRFYdW3otW-xY

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Table 2.B (continued)

ID	lat	lon	location_type	formatted_address	long_name	place_id
68	27.21207	−107.91401	Approximate	Urique, Chihuahua, Mexico	Urique	ChIJqZiSIC5Jv4YRKLSWHqaoze4
69	27.86660	−108.21539	Approximate	Uruachi Municipality, Chihuahua, Mexico	Uruachi Municipality	ChIJFwdpIHM3 × 4YR3-eDPkQdrhY
70	19.34208	−99.05322	Approximate	Iztapalapa, Federal District, Mexico	Iztapalapa	ChIJiQcnB4ICzoURqfhU7FCS5cE
71	19.36272	−99.17553	Geometric_Center	Alvaro Obregón, Ciudad de México, D.F., Mexico	Alvaro Obregón	ChIJ52CFWJL_0YURnS_CE84VZE8
72	25.93164	−105.95467	Approximate	Guanaceví, Durango, Mexico	Guanaceví	ChIJ1RWQDcRnloYRzL02AVQFT74
73	25.83371	−103.84874	Approximate	Mapimí, Durango, Mexico	Mapimí	ChIJyYLN_ujLkYYRrnP3_2eZmkQ
74	23.47464	−104.39397	Approximate	San Francisco del Mezquital, Durango, Mexico	San Francisco del Mezquital	ChIJ8TRIIqF-nIYRtfBsvVWjlWE
75	25.29347	−103.99841	Approximate	Gral Lázaro Cárdenas, Dgo., Mexico	General Lázaro Cárdenas	ChIJp2ne_uZrkIYRpYbq20gIeng
76	24.98261	−106.92020	Approximate	Tamazula de Victoria, Durango, Mexico	Tamazula de Victoria	ChIJqxFhTlw_vYYROcau2ed4Yck
77	20.91445	−100.74524	Approximate	San Miguel de Allende, Gto., Mexico	San Miguel de Allende	ChIJD7xxmK9RK4QRpLAHHQMBMWU

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Table 2.B (continued)

ID	lat	lon	location_type	formatted_address	long_name	place_id
78	20.46027	−100.62247	Approximate	Apaseo el Alto, Guanajuato, Mexico	Apaseo el Alto	ChIJ34sxrq20LIQRSx9ytqS2Nq8
79	20.54469	−100.68443	Approximate	Apaseo el Grande, Gto., Mexico	Apaseo el Grande	ChIJC48rhGmyLIQRUaovo8hUffw
80	21.26798	−99.71874	Approximate	Atarjea, Guanajuato, Mexico	Atarjea	ChIJH0LJgExD1IURGrkhucylHm8
81	20.71979	−100.75969	Approximate	Comonfort, Guanajuato, Mexico	Comonfort	ChIJCUkiOVOoLIQRURthV3Z4gV0
82	21.64815	−101.47828	Approximate	Ocampo, Guanajuato, Mexico	Ocampo	ChIJJTesO-JQKoQRcGecZ3hpAQQ
83	20.87089	−101.51686	Approximate	Romita, Guanajuato, Mexico	Romita	ChIJicdJh0SFK4QRvSZwvdl_vPY
84	21.46837	−100.87055	Approximate	San Diego de la Unión, Guanajuato, Mexico	San Diego de la Unión	ChIJ71ELcc0gK4QR_J3-K8gX3TQ
85	20.99867	−100.38629	Approximate	San José Iturbide, Guanajuato, Mexico	San José Iturbide	ChIJ9epazgS71IURctdVKLaMYEg
86	21.29340	−100.52399	Approximate	San Luis de la Paz, Guanajuato, Mexico	San Luis de la Paz	ChIJTfU5CYfM1IUReGNQqdl5djw
87	20.64232	−100.99256	Approximate	Santa Cruz de Juventino Rosas, Guanajuato, Mexico	Santa Cruz de Juventino Rosas	ChIJr4JHojhgK4QRoAeJt7UkCxI
88	21.29562	−100.05737	Approximate	Xichú, Guanajuato, Mexico	Xichú	ChIJfdkWdr_x1IUREUOxG-cQxUo

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Table 2.B (continued)

ID	lat	lon	location_type	formatted_address	long_name	place_id
89	17.71373	−98.93586	Approximate	Ahuacuotzingo, Gro., Mexico	Ahuacuotzingo	ChIJdYVpq9pOyYUR_rZwj1whXuw
90	17.56162	−98.93436	Approximate	Atlixtac, Gro., Mexico	Atlixtac	ChIJ9TutwY5ByYURZlIDPKLCIzg
91	16.96583	−99.09305	Approximate	Ayutla de los Libres, Gro., Mexico	Ayutla de los Libres	ChIJ1TJHsyOEyYURR7Cl_bcxh70
92	17.46235	−98.71333	Approximate	Copanatoyac, Gro., Mexico	Copanatoyac	ChIJkbUlO-c9yYURJvUex4wogus
93	17.00846	−100.08547	Approximate	Coyuca de Benítez, Guerrero, Mexico	Coyuca de Benítez	ChIJedCTtpP8yoURZsfsRaoa_m8
94	16.47113	−98.41519	Approximate	Cuajinicuilapa, Guerrero, Mexico	Cuajinicuilapa	ChIJ06sXduoryIURq7pf1rh_V2w
95	17.24527	−98.67184	Approximate	Malinaltepec, Gro., Mexico	Malinaltepec	ChIJtYVBWp0PyYURcX0wsKVeM20
96	17.57417	−99.39967	Geometric_Center	Mártir de Cuilapan, Vicente Guerrero, Tixtla de Guerrero, Gro., Mexico	Mártir de Cuilapan	ChIJqTkZDxDvy4URDhftlFaqzd4
97	16.69090	−98.41020	Approximate	Ometepec, Guerrero, Mexico	Ometepec	ChIJl8CL1Ck0yIURpeHHVjZdbk8
98	16.80707	−98.73501	Approximate	San Luis Acatlán, Gro., Mexico	San Luis Acatlán	ChIJZ1-a6UK5yYUR2dsxz4oaQxo
99	16.98657	−99.26049	Approximate	Tecoanapa, Gro., Mexico	Tecoanapa	ChIJzb-FveEryoURRL9zdeYXy9M

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Table 2.B (continued)

ID	lat	lon	location_type	formatted_address	long_name	place_id
100	17.46739	−98.60782	Approximate	Xalpatláhuac, Gro., Mexico	Xalpatláhuac	ChIJDbCbMoEYyYURDUg6TP2OCpo
101	16.79185	−98.24209	Approximate	Xochistlahuaca, Guerrero, Mexico	Xochistlahuaca	ChIJE63YNiBHyIURqxnDQ6RAl9w
102	18.47784	−100.99040	Approximate	Zirándaro, Gro., Mexico	Zirándaro	ChIJTQbZHvsfM4QRp1HNoAxl1mE
103	19.43877	−99.12529	Geometric_Center	José Joaquín Herrera, Ciudad de México, D.F., Mexico	José Joaquín Herrera	ChIJk876MjT50YUR4LpEy25RtWg
104	21.01695	−98.34444	Approximate	Atlapexco, Hgo., Mexico	Atlapexco	ChIJ-d-j380v14URdDXbTKqfCws
105	21.15843	−98.90384	Approximate	Chapulhuacán, Hidalgo, Mexico	Chapulhuacán	ChIJCY4T_7e-1oUR-Y2QKPUghlQ
106	21.03170	−98.28686	Approximate	Huautla, Hidalgo, Mexico	Huautla	ChIJ2_wH0bUx14UROfT51UuyVaE
107	20.97859	−98.50689	Approximate	Huazalingo, Hgo., Mexico	Huazalingo	ChIJJSoE3HTW1oUR7hUp6oPVuqM
108	20.46049	−98.07516	Approximate	Huehuetla, Hgo., Mexico	Huehuetla	ChIJ1YbIf0SU0IURSzaSqihfPiY
109	21.13672	−98.41222	Approximate	Huejutla de Reyes, Hidalgo, Mexico	Huejutla de Reyes	ChIJRU5tfJMm14URWYiA1msxQ0k
110	21.13299	−98.53777	Approximate	Jaltocan, Hidalgo, Mexico	Jaltocan	ChIJY7oPZDzZ1oURoablyjL0S_4
111	21.16907	−98.61332	Approximate	Orizatlán, Hidalgo, Mexico	Orizatlán	ChIJKReZAS3c1oURDE4cHRDv2NE

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Table 2.B (continued)

ID	lat	lon	location_type	formatted_address	long_name	place_id
112	21.19437	−99.00599	Approximate	Pisaflores, Hidalgo, Mexico	Pisaflores	ChIJLQKtcim91oURuSpJeo-CMNI
113	20.40138	−98.20079	Approximate	San Bartolo Tutotepec, Hidalgo, Mexico	San Bartolo Tutotepec	ChIJ59l7xFST0IUR8oGUnxUus3A
114	20.33672	−98.22403	Approximate	Tenango de Doria, Hidalgo, Mexico	Tenango de Doria	ChIJ_46SCwbu0IURMFnDxtAOmMw
115	21.01403	−98.84041	Approximate	Tepehuacán de Guerrero, Hidalgo, Mexico	Tepehuacán de Guerrero	ChIJD47Xvda31oURfJsqZINy6qs
116	20.98947	−98.65731	Approximate	Tlanchinol, Hgo., Mexico	Tlanchinol	ChIJNXTHz-HR1oURmQ3QvhXqUPI
117	20.83427	−98.28490	Approximate	Xochiatipan, Hidalgo, Mexico	Xochiatipan	ChIJpbLxJ6PN0IURXbMHyc8Amc4
118	20.95327	−98.38052	Approximate	Yahualica, Hidalgo, Mexico	Yahualica	ChIJa1l2jWot14URUZ7Kp–1EK8
119	20.55024	−102.50812	Approximate	Atotonilco El Alto, Jalisco, Mexico	Atotonilco El Alto	ChIJTwQysNDLLoQRzkYnKpc1FQU
120	20.29066	−102.54582	Approximate	La Barca, Jalisco, Mexico	La Barca	ChIJN3X-TjvCLoQRNXdM2RIRplk
121	20.31836	−105.32158	Approximate	Cabo Corrientes, Jalisco, Mexico	Cabo Corrientes	ChIJ32f63CPeI4QRXw0LQ0pIuxA
122	19.45080	−104.35954	Approximate	Cuautitlán de García Barragán, Jalisco, Mexico	Cuautitlán de García Barragán	ChIJzTpft0PhJIQRIKZZCXBFwK4

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Table 2.B (continued)

ID	lat	lon	location_type	formatted_address	long_name	place_id
123	20.44890	−102.13183	Approximate	Degollado, Jalisco, Mexico	Degollado	ChIJYcMrzw6mLoQRUHWcZ3hpAQQ
124	20.28301	−103.42517	Approximate	Jocotepec, Jal., Mexico	Jocotepec	ChIJJQXgnAtcL4QR_WyIg2kBIRs
125	22.38945	−103.72632	Approximate	Mezquitic, Jal., Mexico	Mezquitic	ChIJhZtpvQpInYYRNo38dzfrxWg
126	20.37934	−102.92618	Approximate	Poncitlán, Jal., Mexico	Poncitlán	ChIJ_yLdhwglL4QRlVcbKLO29bI
127	20.76133	−104.85281	Approximate	San Sebastián del Oeste, Jal., Mexico	San Sebastián del Oeste	ChIJ6_SunGS3JoQRX2hCj0vAFtk
128	19.93445	−105.25166	Approximate	Tomatlán, Jal., Mexico	Tomatlán	ChIJbV3reQuJI4QRgHmcZ3hpAQQ
129	20.54457	−102.78753	Approximate	Tototlán, Jalisco, Mexico	Tototlán	ChIJi_06Ze3VLoQRIav6yJMvfHc
130	19.54821	−103.81235	Approximate	Zapotitlán de Vadillo, Jalisco, Mexico	Zapotitlán de Vadillo	ChIJ0S9l8itmJYQRD6tfFzXM058
131	20.46609	−102.92477	Approximate	Zapotlán del Rey, Jalisco, Mexico	Zapotlán del Rey	ChIJcUFVPeEuL4QR8HqcZ3hpAQQ
132	18.68623	−100.18784	Approximate	Amatepec, Méx., Mexico	Amatepec	ChIJGfz9z4QZzYURzo_C_QuAZdI
133	18.92450	−99.76863	Approximate	Coatepec Harinas, Méx., Mexico	Coatepec Harinas	ChIJN-2skJyizYURBN04pIh_iSY
134	19.26244	−98.89694	Approximate	Chalco de Díaz Covarrubias, State of Mexico, Mexico	Chalco de Díaz Covarrubias	ChIJDcgeOsgezoUROPRs4F3AIhY

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Table 2.B (continued)

ID	lat	lon	location_type	formatted_address	long_name	place_id
135	19.43040	−98.95766	Approximate	Chimalhuacán, State of Mexico, Mexico	Chimalhuacán	ChIJmdc6XHDj0YUR94fvy-Tt4Ok
136	19.30879	−100.14404	Approximate	Donato Guerra, State of Mexico, Mexico	Donato Guerra	ChIJH8CaaX6e0oUREl3mu8Xq-1Q
137	19.60184	−99.05067	Approximate	Ecatepec, State of Mexico, Mexico	Ecatepec	ChIJoXf3chzy0YURgGayQgpU1Ew
138	19.56959	−99.76647	Approximate	Ixtlahuaca, Ixtlahuaca de Rayón, Méx., Mexico	Ixtlahuaca	ChIJH3bbRstl0oURWmVYzO4xmtI
139	19.68333	−99.66667	Approximate	Morelos, Méx., Mexico	Morelos	ChIJ74hS7tlp0oURTL_vhuAJEhM
140	19.71300	−99.95155	Approximate	San Felipe del Progreso, Méx., Mexico	San Felipe del Progreso	ChIJdVLys_P00oURbGbRmTYyFGs
141	18.90622	−100.15072	Approximate	Tejupilco, Tejupilco de Hidalgo, State of Mexico, Mexico	Tejupilco	ChIJa0XKe0oTzYURHrGtMVEkCgo
142	19.04366	−100.04197	Approximate	Temascaltepec de González, State of Mexico, Mexico	Temascaltepec de González	ChIJz76th69xzYURNTYmSmF5fXo
143	19.46539	−99.59404	Approximate	Temoaya, State of Mexico, Mexico	Temoaya	ChIJG247Okty0oURXWLe3-BPvKY
144	18.96134	−99.59107	Approximate	Tenancingo, State of Mexico, Mexico	Tenancingo	ChIJvQNB36KVzYURNg7Tc_ECsWw

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Table 2.B (continued)

ID	lat	lon	location_type	formatted_address	long_name	place_id
145	18.61585	−100.20827	Approximate	Tlatlaya, State of Mexico, Mexico	Tlatlaya	ChIJwSo7ItEezYUR7fy2vzrOhlk
146	19.37356	−100.14720	Approximate	San José Villa de Allende, State of Mexico, Mexico	San José Villa de Allende	ChIJNUb9aLyc0oUR84-viAixHXY
147	18.96311	−99.63692	Approximate	Villa Guerrero, State of Mexico, Mexico	Villa Guerrero	ChIJhfHqNwmWzYUR1yo5coUUngg
148	19.43767	−99.99542	Approximate	Villa Victoria, State of Mexico, Mexico	Villa Victoria	ChIJKabU9NSF0oURN7LgSjxD5jk
149	18.92010	−100.29788	Approximate	Luvianos, State of Mexico, Mexico	Luvianos	ChIJpfptRMJAzYURylIfB-5dDPM
150	19.66127	−100.15706	Approximate	San José del Rincón, Méx., Mexico	San José del Rincón	ChIJ81ZdzbLs0oURE4wukjNrHYs
151	19.65528	−101.91484	Approximate	Nahuatzen, Mich., Mexico	Nahuatzen	ChIJX2KJzGXbLYQRw_D0UMvJqEI
152	19.58320	−100.33960	Approximate	Ocampo, Mich., Mexico	Ocampo	ChIJDR6e08e-0oURHBpNNyp8VWE
153	18.58894	−100.78590	Approximate	San Lucas, Michoacán, Mexico	San Lucas	ChIJB702-8fZMoQRi0H7wqw6AhM
154	19.40643	−101.63970	Approximate	Santa Clara del Cobre, Michoacán, Mexico	Santa Clara del Cobre	ChIJ16jLgWCMLYQRaUC10DIofX4
155	19.22581	−101.45740	Approximate	61,650 Tacambaro, Mich., Mexico	Tacambaro	ChIJ6wO5GmqHLYQR3tUq_N4gQLE

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Table 2.B (continued)

ID	lat	lon	location_type	formatted_address	long_name	place_id
156	19.40531	−102.04184	Approximate	México, Uruapan, Mich., Mexico	México	ChIJaYwz9FjiLYQRgIdt19e-YH8
157	19.33451	−101.91824	Approximate	Taretan, Michoacán, Mexico	Taretan	ChIJLd_a__H6LYQRxR_xAfmXbCg
158	18.90052	−100.73728	Approximate	Tiquicheo, Michoacán, Mexico	Tiquicheo	ChIJWdt5ZEe2MoQRwfggc_hqZDg
159	19.05299	−101.41863	Approximate	Turicato, Michoacán, Mexico	Turicato	ChIJwcSuPpF8MoQRRaASmzl9RII
160	19.20667	−100.57538	Approximate	Tuzantla, Michoacán, Mexico	Tuzantla	ChIJCyrGL1ZUzYUROR_sJ2_knzo
161	19.40645	−102.04305	Approximate	Uruapan, Michoacán, Mexico	Uruapan	ChIJUUj-wljiLYQRNJ8jH-KbflM
162	19.99018	−102.28341	Approximate	Zamora, Michoacán, Mexico	Zamora	ChIJDc6O2K2ILoQRKz8GfoKXiKU
163	19.86006	−100.82726	Approximate	Zinapecuaro de Figueroa, Mich., Mexico	Zinapecuaro de Figueroa	ChIJ3WY7l8kjLYQRYlFZBkkemV0
164	19.41637	−101.91025	Approximate	Ziracuaretiro, Mich., Mexico	Ziracuaretiro	ChIJAXABEbjlLYQRiISUN31GNaI
165	18.76061	−98.98251	Approximate	Ciudad Ayala, Morelos, Mexico	Ciudad Ayala	ChIJBbxPVGtlzoURs6uY-qUV0fA
166	18.87766	−98.77393	Approximate	Ocuituco, Morelos, Mexico	Ocuituco	ChIJyVarRtxDzoURn4VT8ar9EyE
167	18.61469	−99.32015	Approximate	Puente de Ixtla, Mor., Mexico	Puente de Ixtla	ChIJg15atQHTzYURIr53ChAE36k

(continued)

Table 2.B (continued)

ID	lat	lon	location_type	formatted_address	long_name	place_id
168	19.00949	−98.99825	Approximate	Tlalnepantla, Morelos, Mexico	Tlalnepantla	ChIJK1r9mn4NzoURxV5pEFsznII
169	18.87828	−98.86109	Approximate	Yecapixtla, Mor., Mexico	Yecapixtla	ChIJZyU-vQ9qzoURlpE9chq_u_k
170	21.23793	−104.90076	Approximate	Compostela, Nay., Mexico	Compostela	ChIJAcJh7dApJ4QRdBUZuwaSvYE
171	22.63906	−105.31951	Approximate	Huajicori, Nay., Mexico	Huajicori	ChIJFSzeLgeKnoYRybnC9R7E2l8
172	23.98756	−104.67373	Geometric_Center	Nayarit, Mexico	Nayarit	ChIJX16cdO_Hm4YRajYqAhGqQec
173	22.12203	−105.20552	Approximate	Rosamorada, Nay., Mexico	Rosamorada	ChIJj9_GAsUPnoYRizl2qoD188A
174	21.95056	−105.14344	Approximate	Ruiz, Nay., Mexico	Ruiz	ChIJA_gUkzMCnoYRMaXtX7LeeKs
175	21.54130	−105.28472	Approximate	San Blas, Nay., Mexico	San Blas	ChIJo0obSje4IIQR9c24KtR0IX0
176	21.33279	−104.58811	Approximate	Santa María del Oro, Nayarit, Mexico	Santa María del Oro	ChIJ3TFXHP0YJ4QRi8nioS8r7hk
177	21.81319	−105.20433	Approximate	Santiago Ixcuintla, Nayarit, Mexico	Santiago Ixcuintla	ChIJQ5hKgrKoIIQR2iswU9ASIcI
178	22.39658	−105.45953	Approximate	Tecuala, Nay., Mexico	Tecuala	ChIJb7VdqANDnoYRWOnCpvoFnoM
179	21.94465	−105.29848	Approximate	Tuxpan, Nay., Mexico	Tuxpan	ChIJsZyCwzIcnoYRPd-wFs8JV8Q
180	24.10074	−99.81793	Approximate	67,940 Aramberri, N.L., Mexico	Aramberri	ChIJYX7aqvwzfIYR0s-SKwIzR48

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Table 2.B (continued)

ID	lat	lon	location_type	formatted_address	long_name	place_id
181	23.67733	−100.18283	Approximate	Doctor Arroyo, N.L., Mexico	Doctor Arroyo	ChIJefrlHsRzfoYRYUP00B3qxpA
182	23.42506	−100.11712	Approximate	Mier y Noriega, N.L., Mexico	Mier y Noriega	ChIJRVB–IJCfoYR9_WEb_x5_a8
183	17.67284	−96.12877	Approximate	Ayotzintepec, Oax., Mexico	Ayotzintepec	ChIJ2Q8GvV9BwYURFJR3QSstgIw
184	18.10169	−96.79893	Approximate	Huautepec, Oaxaca, Mexico	Huautepec	ChIJL6ZFdOAixIUR9MZejPqrsIM
185	17.23555	−97.55045	Approximate	Magdalena Peñasco, Oaxaca, Mexico	Magdalena Peñasco	ChIJVRjYQdwzxoUR7XL9L6vAT3g
186	18.03120	−96.67221	Approximate	San Bartolomé Ayautla, Oaxaca, Mexico	San Bartolomé Ayautla	ChIJTTG9VlIZxIURI40ybj4AXN8
187	18.15169	−96.71863	Approximate	San José Tenango, Oax., Mexico	San José Tenango	ChIJya7hQ6MXxIURXUU-pPSU564
188	17.33649	−95.97731	Approximate	San Juan Comaltepec, Oaxaca, Mexico	San Juan Comaltepec	ChIJnQL-QE0awYURbbAn3QhDtd4
189	17.46835	−96.03596	Approximate	San Juan Petlapa, Oaxaca, Mexico	San Juan Petlapa	ChIJe8orfGUWwYURj6FDGgsHlQM
190	18.05878	−96.39430	Approximate	San Lucas Ojitlán, Oaxaca, Mexico	San Lucas Ojitlán	ChIJ1yCZjLj5w4URj_i4tfJ2GlI
191	18.14173	−96.86785	Approximate	San Mateo Yoloxochitlán, Oaxaca, Mexico	San Mateo Yoloxochitlán	ChIJUx9fXOI6xIURUU_9asP_4pI

(continued)

Table 2.B (continued)

ID	lat	lon	location_type	formatted_address	long_name	place_id
192	16.48802	−97.98711	Approximate	San Pedro Atoyac, Oaxaca, Mexico	San Pedro Atoyac	ChIJk92V-WUbyIUR1NmMDulCgLY
193	18.14438	−96.51017	Approximate	San Pedro Ixcatlán, Oaxaca, Mexico	San Pedro Ixcatlán	ChIJoXOiO-sFxIURCt0LocDglug
194	17.82616	−96.66379	Approximate	San Pedro Sochiapam, Oaxaca, Mexico	San Pedro Sochiapam	ChIJp7B9IAikxoUR65Opc7sCEek
195	16.18538	−96.61801	Approximate	Santa Lucía Miahuatlán, Oaxaca, Mexico	Santa Lucía Miahuatlán	ChIJDROCZui6uIURsnVgVZAqcbQ
196	18.10807	−96.81940	Approximate	Santa María la Asunción, Oax., Mexico	Santa María la Asunción	ChIJ68uNtEgjxIURStHStTvedVU
197	18.23322	−96.82965	Approximate	Santa María Chilchotla, Oaxaca, Mexico	Santa María Chilchotla	ChIJ8Z9LWfE7xIURb7sj0ewvZfA
198	17.86021	−96.20990	Approximate	Santa María Jacatepec, Oaxaca, Mexico	Santa María Jacatepec	ChIJ1y3WIIlQwYURZWT3z1Iwh9Y
199	16.16307	−97.19565	Approximate	Santa María Temaxcaltepec, Oaxaca, Mexico	Santa María Temaxcaltepec	ChIJK9El1mhkuIURSaDowCzQheI
200	17.53556	−95.94417	Approximate	Santiago Jocotepec, Oax., Mexico	Santiago Jocotepec	ChIJGcdW5-MSwYUR8tNygEpIUp8

(continued)

Table 2.B (continued)

ID	lat	lon	location_type	formatted_address	long_name	place_id
201	17.33423	−95.69827	Approximate	Santiago Yaveo, Oaxaca, Mexico	Santiago Yaveo	ChIJIwRxraSpwYURkjC14YjK2jE
202	20.03749	−97.75661	Approximate	Camocuautla, Pue., Mexico	Camocuautla	ChIJ5-OG90qC2oURbrMf2NwZKq0
203	18.49843	−96.95470	Approximate	Eloxochitlán, Pue., Mexico	Eloxochitlán	ChIJDcGLCy9QxIURFuSBZdiSXlo
204	20.46049	−98.07516	Approximate	Huehuetla, Hgo., Mexico	Huehuetla	ChIJ1YbIf0SU0IURSzaSqihfPiY
205	18.88600	−98.69088	Approximate	Hueyapan, Morelos, Mexico	Hueyapan	ChIJhYFEAMVFzoURjVbDt-tWoJ0
206	20.01297	−97.62392	Approximate	Atlequizayan, Pue., Mexico	Atlequizayan	ChIJHR6oPnCF2oURkpGjjmwsGH8
207	20.02436	−97.64559	Approximate	Ixtepec, Puebla, Mexico	Ixtepec	ChIJn2TDQKiF2oURw_rAp3Ahbu0
208	18.39762	−96.84766	Approximate	Tlacotepec de Díaz, Pue., Mexico	Tlacotepec de Díaz	ChIJKe_MThxExIURlKWVEE367ic
209	20.13642	−97.92130	Approximate	Tlaola, Puebla, Mexico	Tlaola	ChIJ84QONXF90IURWhTJhhvxaTU
210	18.33632	−97.02019	Approximate	Zoquitlán, Pue., Mexico	Zoquitlán	ChIJ86_0VzBKxIURBPCCLVb9nN4
211	21.13545	−99.62557	Approximate	Pinal de Amoles, Qro., Mexico	Pinal de Amoles	ChIJqQEuedtr1IURWMeHh-wDe0w
212	20.78128	−100.05097	Approximate	Colón, Qro., Mexico	Colón	ChIJgSp4TWd904URKcg1mpqCl_8

(continued)

Table 2.B (continued)

ID	lat	lon	location_type	formatted_address	long_name	place_id
213	20.58879	−100.38989	Approximate	Santiago de Querétaro, Qro., Mexico	Santiago de Querétaro	ChIJVZJb3I9b04URL4MbVqqUsJc
214	20.91649	−99.56499	Approximate	San Joaquín, Qro., Mexico	San Joaquín	ChIJtVRrYqZ01IURDq0tQRMQnio
215	19.58033	−88.04410	Approximate	Felipe Carrillo Puerto, Q.R., Mexico	Felipe Carrillo Puerto	ChIJF8Ygl013UI8RgI8HZOPxLsw
216	19.74857	−88.70608	Approximate	José María Morelos, Quintana Roo, Mexico	José María Morelos	ChIJp_RXdSOuUI8RedAFYXdJiDU
217	32.46774	−115.08085	Geometric_Center	Lázaro Cárdenas, Batáquez, B.C., Mexico	Lázaro Cárdenas	ChIJz3BNVHyv14ARGYA0_85fvX0
218	21.62490	−99.01974	Approximate	Aquismón, San Luis Potosí, Mexico	Aquismón	ChIJg89OFU591oURLeBMWOk_Fa4
219	21.59752	−98.96663	Approximate	Tancanhuitz de Santos, San Luis Potosí, Mexico	Tancanhuitz de Santos	ChIJ6QKQRsuJ1oURrv_IILo9u3U
220	22.15647	−100.98554	Approximate	San Luis Potosi, San Luis Potosí, Mexico	San Luis Potosi	ChIJefusBQCiKoQRV4Lhrynu0g4
221	21.36953	−98.66126	Approximate	San Martín Chalchicuautla, San Luis Potosí, Mexico	San Martín Chalchicuautla	ChIJVZh36V_v1oURYI896M8Hy94
222	21.25939	−98.78815	Approximate	Tamazunchale, San Luis Potosí, Mexico	Tamazunchale	ChIJEcIhlWLq1oURz2JYOFhpcQE

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Table 2.B (continued)

ID	lat	lon	location_type	formatted_address	long_name	place_id
223	21.40069	−98.73190	Approximate	Tampacan, San Luis Potosí, Mexico	Tampacan	ChIJbYqF3mXu1oURPLQ_BLyowXY
224	21.43934	−98.87212	Approximate	Axtla de Terrazas, San Luis Potosí, Mexico	Axtla de Terrazas	ChIJy8ShbXaN1oURZQkc4-rQiN8
225	21.38417	−98.99217	Approximate	Xilitla, S.L.P., Mexico	Xilitla	ChIJUaqjGX6a1oUROaR81kTtL2w
226	21.38417	−98.99217	Approximate	Xilitla, S.L.P., Mexico	Xilitla	ChIJUaqjGX6a1oUROaR81kTtL2w
227	21.33716	−98.82767	Approximate	Matlapa, San Luis Potosí, Mexico	Matlapa	ChIJjY7hIT2T1oUR9AoT8fl-MfI
228	23.28869	−106.06696	Approximate	Concordia, Sinaloa, Mexico	Concordia	ChIJO34U4pc0n4YRWYFZgd_DjiI
229	24.80906	−107.39401	Approximate	Culiacán Rosales, Sin., Mexico	Culiacán Rosales	ChIJj_lHd8fWvIYRzCMt6_Dr2Y0
230	26.70877	−108.32455	Approximate	Choix, Sinaloa, Mexico	Choix	ChIJwRwNMVYnuYYR-wRFYA9R9Hg
231	23.96957	−106.71166	Approximate	Elota, Sin., Mexico	Elota	ChIJdU68iV19ooYR7cqZCwACigI
232	22.84561	−105.90130	Approximate	Escuinapa, Sin., Mexico	Escuinapa	ChIJFSiENN0bn4YRW2bcWKaPbU0
233	26.41763	−108.61459	Approximate	El Fuerte, Sin., Mexico	El Fuerte	ChIJrxqdvR0OuYYRykAmVkVL3Xw
234	23.24941	−106.41114	Approximate	Mazatlán, Sin., Mexico	Mazatlán	ChIJwTcYaEFTn4YRsnI88arEpGI

(continued)

Table 2.B (continued)

ID	lat	lon	location_type	formatted_address	long_name	place_id
235	25.48135	−107.92059	Approximate	Mocorito, Sin., Mexico	Mocorito	ChIJKxbRQTN2vIYR-26-_sPV97M
236	26.94486	−108.46201	Approximate	Rosario, Sin., Mexico	Rosario	ChIJ6WvAa5fpuIYR_0uAFmPBsQ4
237	25.82570	−108.21430	Approximate	Sinaloa, Sin., Mexico	Sinaloa	ChIJc5HCY736u4YR4mlso-1a-g8
238	24.76378	−107.70145	Approximate	Navolato, Sinaloa, Mexico	Navolato	ChIJN0UjGJe3vIYR8Dctft9pwUQ
239	27.02549	−108.94131	Approximate	Alamos, Son., Mexico	Alamos	ChIJA7DHGwVnuIYR6967xyskDlw
240	27.55288	−110.08216	Approximate	Bácum, Sonora, Mexico	Bácum	ChIJ6SoPQntHyIYRjvh5hKXkP9k
241	30.69697	−112.18848	Approximate	Caborca, Son., Mexico	Caborca	ChIJHYJ2aoYU04YRjNVSgK-O3tY
242	26.91110	−109.62661	Approximate	Etchojoa, Sonora, Mexico	Etchojoa	ChIJS5Nb0tz0t4YRPUzj4C2CTEM
243	27.91787	−110.90894	Approximate	Guaymas, Sonora, Mexico	Guaymas	ChIJ7 × 3QuPQVyYYRhPkF6AJU2ZY
244	27.52145	−109.25464	Approximate	Quiriego, Son., Mexico	Quiriego	ChIJ4SJiO7rtx4YRuWJPLYtRfpQ
245	32.45189	−114.77171	Approximate	San Luis Río Colorado, Son., Mexico	San Luis Río Colorado	ChIJrZlmMP8F1oARedtdfaKfS4Q
246	18.00121	−93.37323	Approximate	Cárdenas, Tabasco, Mexico	Cárdenas	ChIJR7ud4ZEg7IURj-YUWSAnTkk

(continued)

Table 2.B (continued)

ID	lat	lon	location_type	formatted_address	long_name	place_id
247	18.53339	−92.64606	Approximate	Frontera, Tab., Mexico	Frontera	ChIJBXbyxxQ77oURCJ_xE5mLalQ
248	21.86479	−102.91621	Approximate	Centro, Tabasco, Zac., Mexico	Centro	ChIJwd3HrncxKIQRxAW9V8nExbs
249	18.26116	−93.22169	Approximate	Comalcalco, Tabasco, Mexico	Comalcalco	ChIJrSTYmcCI7oUR-QotOQFjEkA
250	18.07215	−93.17125	Approximate	Cunduacán, Tab., Mexico	Cunduacán	ChIJw9Sjx36B7oURrzfGSgSH-S4
251	17.83204	−93.39181	Approximate	Huimanguillo, Tab., Mexico	Huimanguillo	ChIJ4ej1Q3Aj7IUR3G1zbCN3-44
252	17.71928	−92.81119	Approximate	Jalapa, Tab., Mexico	Jalapa	ChIJcUm_caLB7YUR7BlT7ICEsn4
253	18.09108	−92.13643	Approximate	Jonuta, Tab., Mexico	Jonuta	ChIJf2f7ZiSL8YURjAKXyv1ODD0
254	17.76070	−92.59361	Approximate	Macuspana, Tabasco, Mexico	Macuspana	ChIJ_-C6sS_y7YURFdMV-A_3dIg
255	17.59698	−92.82655	Approximate	Tacotalpa, Tabasco, Mexico	Tacotalpa	ChIJF3rbFPu-7YURL-iw8xjVQng
256	17.56711	−92.95006	Approximate	Teapa, Tab., Mexico	Teapa	ChIJlzB__0u37YURwXJ-eHNIOgs
257	17.47723	−91.43109	Approximate	Tenosique, Tab., Mexico	Tenosique	ChIJsYACeKKQ84URSjIGfhuvBpQ
258	22.40775	−97.92116	Approximate	Altamira, Tamaulipas, Mexico	Altamira	ChIJLfeZYBf914UR3PZ0PvgDlPk
259	22.55107	−99.08452	Approximate	Antiguo Morelos Municipality, Tamaulipas, Mexico	Antiguo Morelos Municipality	ChIJ201dKMOxeIYRNhoVVOlktGU

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Table 2.B (continued)

ID	lat	lon	location_type	formatted_address	long_name	place_id
260	22.82831	−98.43213	Approximate	González, Tamps., Mexico	González	ChIJY-8MDVleeIYRgBN6ktD-t7o
261	22.74219	−98.97466	Approximate	Ciudad Mante, Tamaulipas, Mexico	Ciudad Mante	ChIJszTB92K4eIYRr6LUs9QuecU
262	25.86903	−97.50274	Approximate	Matamoros, Tamaulipas, Mexico	Matamoros	ChIJhwDRk8eUb4YRXsoTOXB4IXM
263	24.84192	−98.15024	Approximate	San Fernando, Tamaulipas, Mexico	San Fernando	ChIJsRWsHKPyeoYR8_oxfk9J4wc
264	23.76802	−98.20763	Approximate	Soto la Marina, Tamaulipas, Mexico	Soto la Marina	ChIJa8rRrcWNeYYRBpFowmWy04o
265	19.31815	−98.23751	Approximate	Tlaxcala, Tlaxcala, Mexico	Tlaxcala	ChIJPSiCS0DZz4URkjFMAaQ8riU
266	19.32458	−97.65165	Approximate	90,570 Tequexquitla, Tlax., Mexico	Tequexquitla	ChIJX7WWb0RSxYURwDh6 × 1wtUGA
267	19.29908	−97.77155	Approximate	Cuapiaxtla, Tlax., Mexico	Cuapiaxtla	ChIJR7W8AApWxYURL5XHe8uiMNI
268	19.31815	−98.23751	Approximate	Tlaxcala, Tlaxcala, Mexico	Tlaxcala	ChIJPSiCS0DZz4URkjFMAaQ8riU
269	19.33225	−98.16117	Approximate	Contla, Tlax., Mexico	Contla	ChIJ4RhwYEXez4URWaVePbl_gPQ
270	19.49197	−98.53705	Approximate	90,280 Nanacamilpa, Tlax., Mexico	Nanacamilpa	ChIJ-fKwvRfS0YURGZQr8pZxXgY

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Table 2.B (continued)

ID	lat	lon	location_type	formatted_address	long_name	place_id
271	19.31451	−98.23730	Geometric_Center	Trinidad Sánchez Santos, Centro, 90,000 Tlaxcala de Xicohténcatl, Tlax., Mexico	Trinidad Sánchez Santos	ChIJ_yYrLDnZz4URURNWXuZd6HY
272	19.26093	−98.17210	Approximate	San Francisco Tetlanohcan, Tlaxcala, Mexico	San Francisco Tetlanohcan	ChIJESLzSZrdz4UR1EdjHX2A9mU
273	19.33678	−98.06317	Approximate	San José Teacalco, Tlaxcala, Mexico	San José Teacalco	ChIJ3QTZAHThz4URUbzNYbtN6xM
274	19.78695	−97.24282	Approximate	Atzalán, Ver., Mexico	Atzalán	ChIJLwxcLkLd2oURRvO6J_Rmrxg
275	18.42126	−95.11297	Approximate	Catemaco, Ver., Mexico	Catemaco	ChIJwdRIvo8LwoURAWZXoSLxwwk
276	18.13448	−94.45899	Approximate	Coatzacoalcos, Ver., Mexico	Coatzacoalcos	ChIJy7PhrlCB6YURpKXNqVlhN-M
277	18.88389	−96.92378	Approximate	Córdoba, Ver., Mexico	Córdoba	ChIJs1cSfwqNxIURMn6DEmxACLs
278	20.19915	−97.70501	Approximate	Filomeno Mata, Ver., Mexico	Filomeno Mata	ChIJ73pzvDp82oUR3lLyUypXc1w
279	18.14900	−95.14341	Approximate	Hueyapan de Ocampo, Ver., Mexico	Hueyapan de Ocampo	ChIJiS391uEFwoURYFg4ur0apks
280	20.78068	−98.44379	Approximate	Ilamatlán, Ver., Mexico	Ilamatlán	ChIJc5-7mn3W0IURu_7tT94-e9I

(continued)

Table 2.B (continued)

ID	lat	lon	location_type	formatted_address	long_name	place_id
281	19.05094	−96.98417	Approximate	Ixhuatlán del Café, Ver., Mexico	Ixhuatlán del Café	ChIJkX1mgEznxIURnID3zgbrxq4
282	20.68525	−98.01243	Approximate	Ixhuatlán de Madero, Ver., Mexico	Ixhuatlán de Madero	ChIJ79wewVy60IURo7ek3pUCMyU
283	20.21039	−97.68125	Approximate	Mecatlán, Ver., Mexico	Mecatlán	ChIJGcOCUst92oUR6wO_jmBONOo
284	18.74561	−96.78554	Approximate	Omealca, Ver., Mexico	Omealca	ChIJ4Uebs9f0xIURdgXtbIFD9O4
285	18.26237	−94.69213	Approximate	Pajapan, Ver., Mexico	Pajapan	ChIJSdXbhgqT6YURZ_gUY_Lt0sc
286	18.44412	−95.21303	Approximate	San Andrés Tuxtla, Ver., Mexico	San Andrés Tuxtla	ChIJlds5_wETwoURl7I0xt8_WWg
287	18.51799	−97.05437	Approximate	Tehuipango, Ver., Mexico	Tehuipango	ChIJt70p2_ZSxIURF31UztIjROI
288	20.58501	−98.36430	Approximate	Texcatepec, Ver., Mexico	Texcatepec	ChIJhY65g2jc0IURThMm1l-FWl4
289	18.60217	−96.68720	Approximate	Tezonapa, Ver., Mexico	Tezonapa	ChIJMcg9AjZhxIURj9Ng1v34DtU
290	19.96094	−97.21406	Approximate	Tlapacoyan, Ver., Mexico	Tlapacoyan	ChIJGTItKcLk2oUR0cJU0FW99kc
291	18.66685	−97.00012	Approximate	Zongolica, Ver., Mexico	Zongolica	ChIJF1WCOvdVxIURb1uHxeq0cvs
292	20.14001	−97.57502	Approximate	Zozocolco de Hidalgo, Ver., Mexico	Zozocolco de Hidalgo	ChIJUaRjFEmI2oURD3KPVloBlNA

(continued)

Table 2.B (continued)

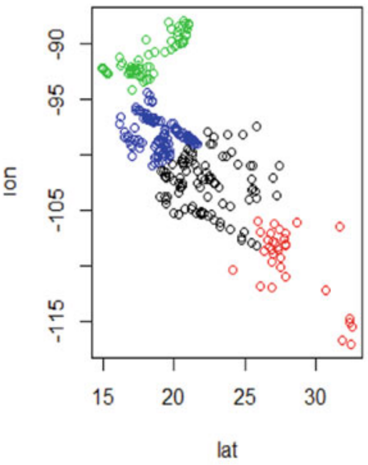
ID	lat	lon	location_type	formatted_address	long_name	place_id
293	17.06038	−94.15306	Approximate	Uxpanapa, Oax., Mexico	Uxpanapa	ChIJszxeRwAO64URAfJt7sr274I
294	20.64687	−89.68057	Approximate	Abalá, Yuc., Mexico	Abalá	ChIJt5dbw7hAVo8ROfsNFSqFRpE
295	20.26342	−89.34753	Approximate	Akil, Yuc., Mexico	Akil	ChIJ70PSwWUAV48R7Lqxc0qQgLw
296	21.02203	−88.17876	Approximate	Calotmul, Yuc., Mexico	Calotmul	ChIJ_0w2mm9_UY8RThwyKxZ8zqU
297	20.65645	−87.93603	Approximate	Chemax, Yucatán, Mexico	Chemax	ChIJ-zXzQtS9UY8RX16qCUb3R78
298	20.33469	−88.48736	Approximate	Chikindzonot, Yuc., Mexico	Chikindzonot	ChIJk-lEpbDeUI8RGMEap0xtWlg
299	21.00886	−88.30606	Approximate	Espita, Yuc., Mexico	Espita	ChIJaf8B8pV8UY8RMDvi90OjGYw
300	20.81403	−89.24695	Approximate	Hocabá, Yuc., Mexico	Hocabá	ChIJzUtfRiGOVo8RosRej-DUXDM
301	20.86390	−89.20083	Approximate	Hoctun, Yuc., Mexico	Hoctun	ChIJ9cHRkvqQVo8RlYzZWGCl3YU
302	20.62243	−88.41457	Approximate	Kaua, Yuc., Mexico	Kaua	ChIJARnBkBAUUY8RSao68GGcxUM
303	20.64758	−89.90017	Approximate	Kopomá, Yuc., Mexico	Kopomá	ChIJYSWGmrsjVo8RinABTPAsUhs
304	20.55009	−89.85738	Approximate	Opichén, Yuc., Mexico	Opichén	ChIJNagg3zYlVo8Rs8dY-GqIjBQ
305	20.32784	−89.64407	Approximate	Santa Elena, Yuc., Mexico	Santa Elena	ChIJ9-fx7rK0V48RPNl4MdjzuiY
306	20.20113	−88.94258	Approximate	Tahdziú, Yuc., Mexico	Tahdziú	ChIJm62d7TwnV48RKaro9eEBEAs

(continued)

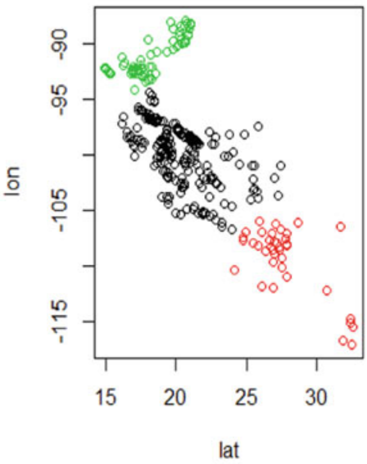
Table 2.B (continued)

ID	lat	lon	location_type	formatted_address	long_name	place_id
307	20.80120	−88.19985	Approximate	Temozón, Yuc., Mexico	Temozón	ChIJC3rp_LZ1UY8RJ3cRXKfufQ4
308	20.90099	−88.75130	Approximate	Tunkás, Yuc., Mexico	Tunkás	ChIJabXFUIBSUY8Rzy6rKd2ryIY
309	20.83372	−89.18295	Approximate	Xocchel, Yuc., Mexico	Xocchel	ChIJzZhmiW2WVo8RAPji5-nx4jw
310	23.17776	−102.86874	Approximate	Fresnillo, Zacatecas, Mexico	Fresnillo	ChIJIdCtv7EIg4YRK1rB-fgC0KQ
311	22.66268	−102.11040	Approximate	Gral Pánfilo Natera, Zac., Mexico	General Pánfilo Natera	ChIJwz2lwL8lgoYRtoAZd9yTkZQ
312	22.43391	−102.24621	Approximate	Luis Moya, Zac., Mexico	Luis Moya	ChIJfTsjcgEagoYROi5tCIt-IJ8
313	22.44208	−101.90782	Approximate	Noria de Ángeles, Zac., Mexico	Noria de Ángeles	ChIJ-4CktevxgYYReQ0XCpjp-AU
314	22.57060	−102.25467	Approximate	Ojocaliente, Zac., Mexico	Ojocaliente	ChIJD_P5Rys9goYReZPC3LZZ0_Q
315	22.87731	−102.54081	Approximate	Pánuco, Zac., Mexico	Pánuco	ChIJG5VZQVNLgoYRuef9yKw39JU
316	22.29728	−101.57472	Approximate	Pinos, Zac., Mexico	Pinos	ChIJkR2N0L3ZgYYRIOqcZ3hpAQQ
317	24.52020	−100.86710	Approximate	El Salvador, Zac., Mexico	El Salvador	ChIJY3RoMI2dh4YR2-ByKAe9Fd8
318	22.77092	– 102.58325	Approximate	Zacatecas, Zac., Mexico	Zacatecas	ChIJVzPDP3pOgoYRwRNCCV-rA8w
319	21.67694	−102.58918	Approximate	Villa Hidalgo, Jalisco, Mexico	Villa Hidalgo	ChIJP4rlSZq5KYQRwI0n2QQCy5I

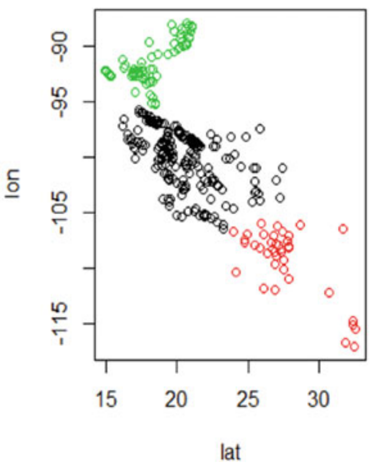
Instance INECC (1)



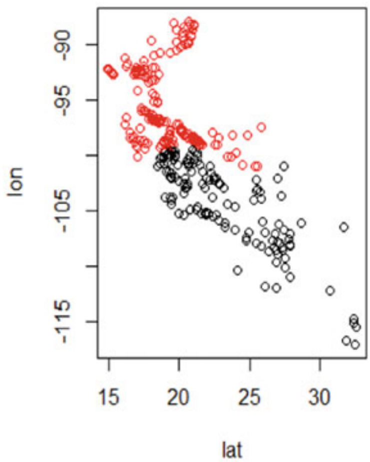
Method ward.D



Method ward.D2

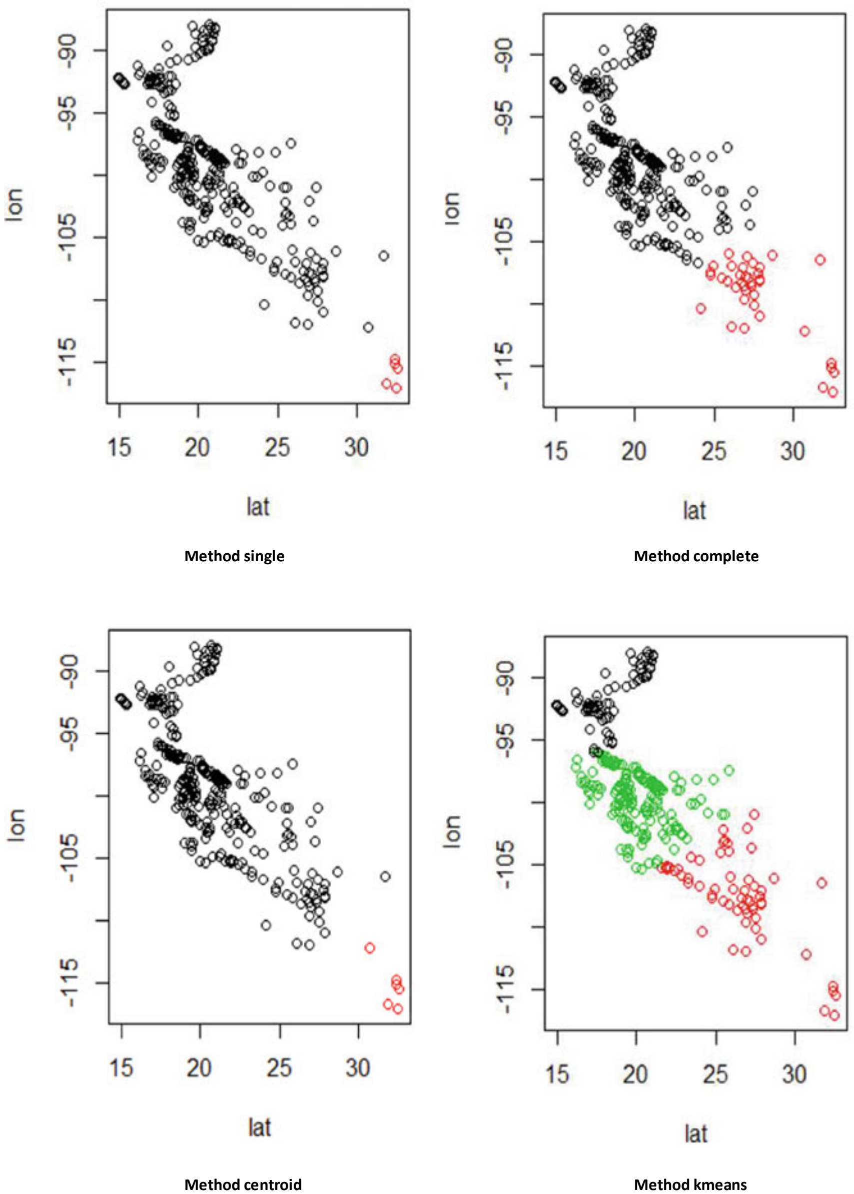


Method mcquitty

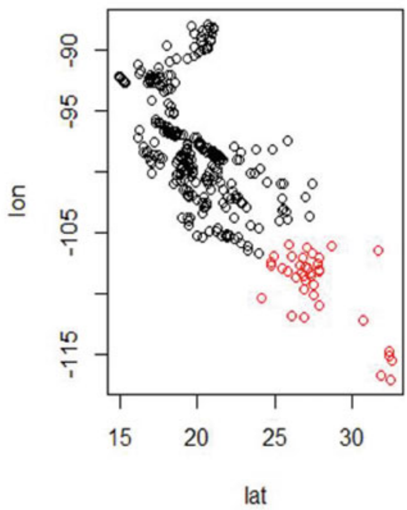


Method median

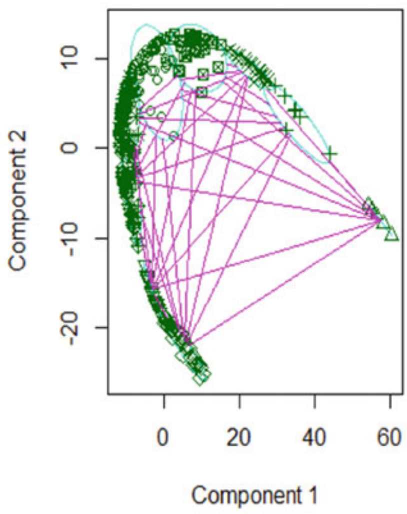
Instance INECC (1)



Instance INECC (1)

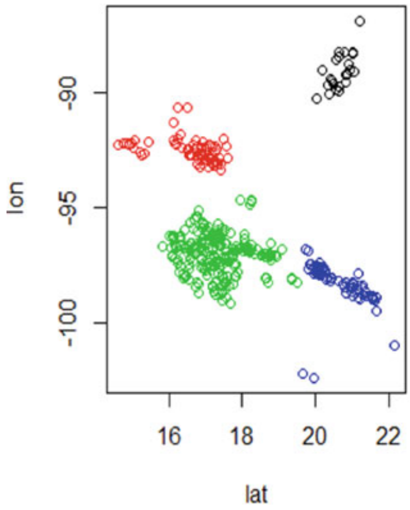


Method average

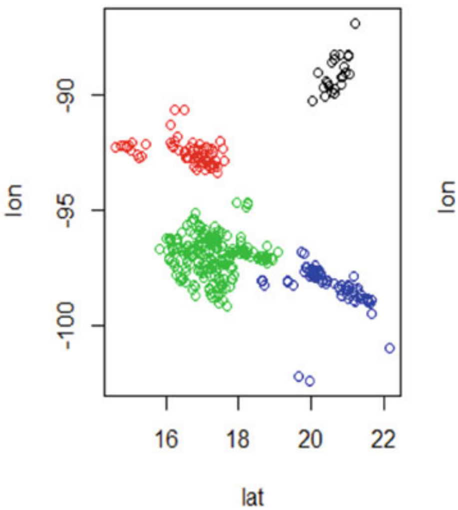


Method gaussian mixture

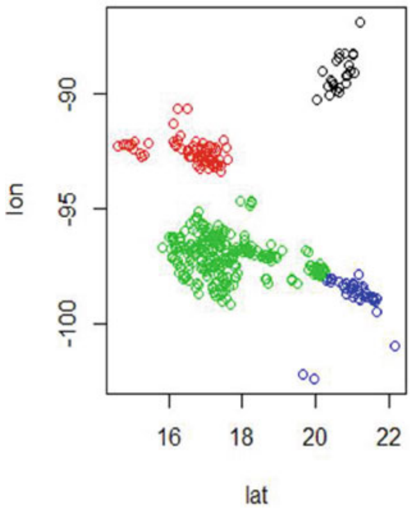
Instance Virtual Interactive Atlas (2)



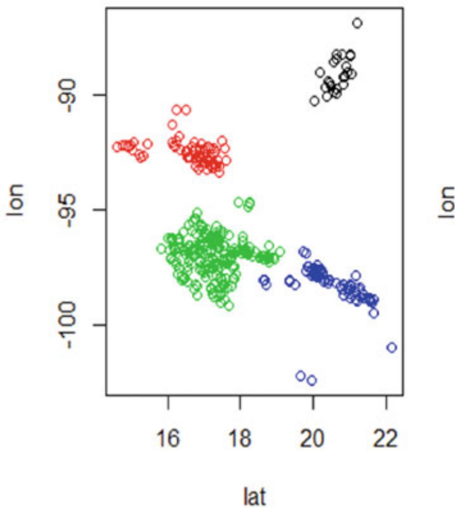
Method ward.D



Method ward.D2

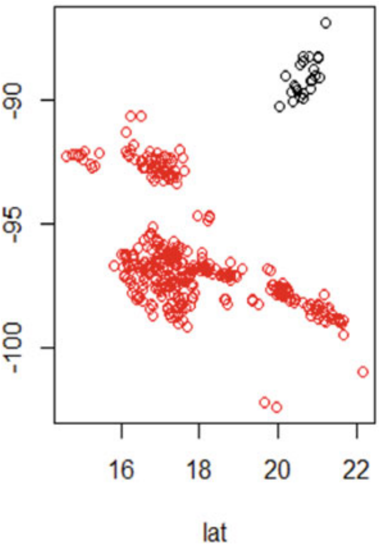


Method mcquitty

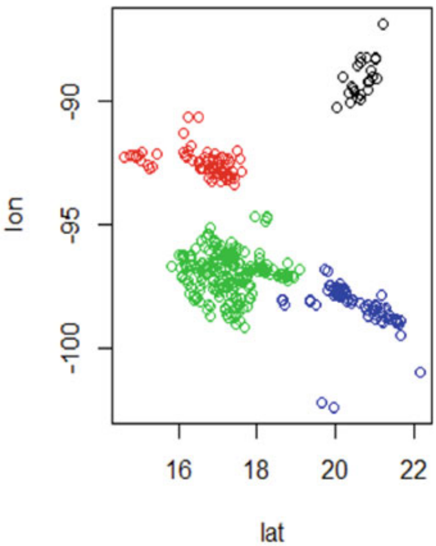


Method median

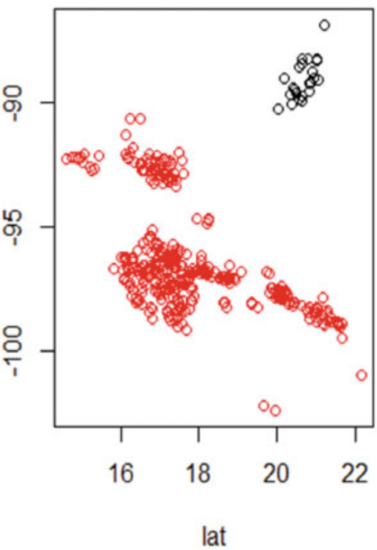
Instance Virtual Interactive Atlas (2)



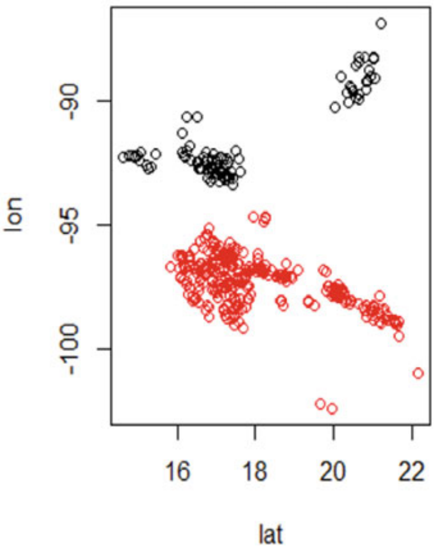
Method single



Method complete

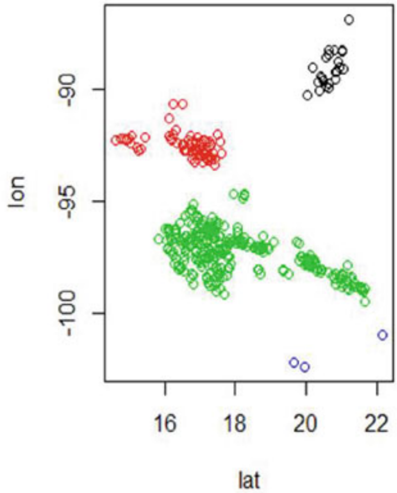


Method centroid

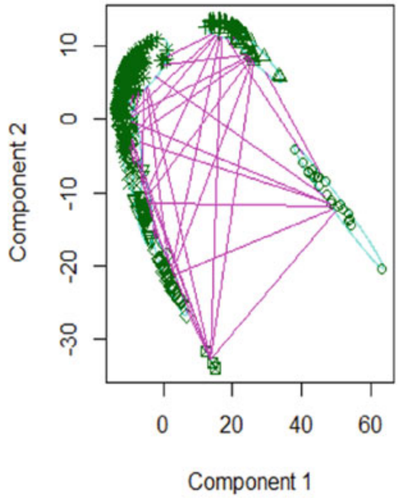


Method kmeans

Instance Virtual Interactive Atlas (2)



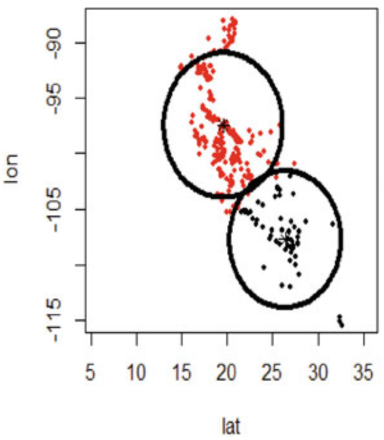
Method average



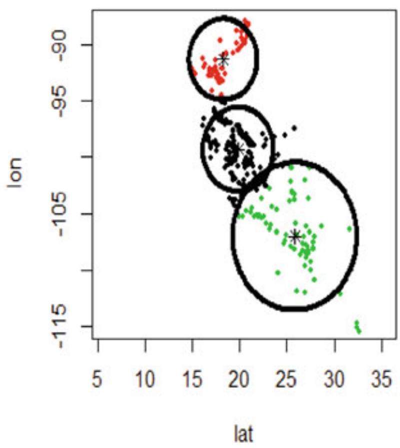
Method gaussian mixture

Appendix 2.G

Visualization of clusters by CEC method, for instance one—INECC and two—Virtual Interactive Atlas Map.

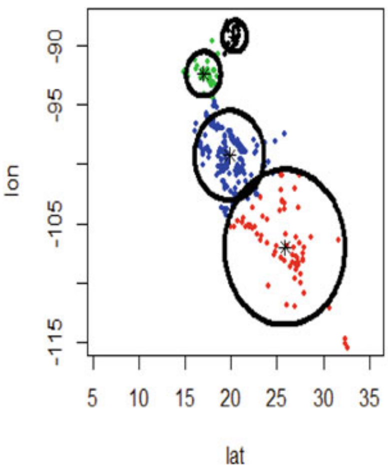


2 Clusters

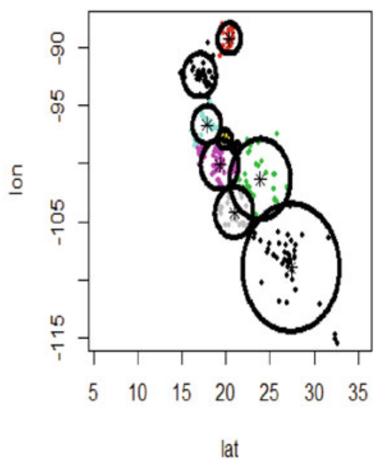


3 Clusters

Instance INECC (1)
CEC Method

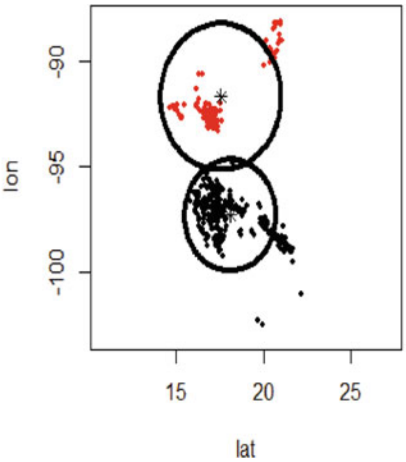


4 Clusters

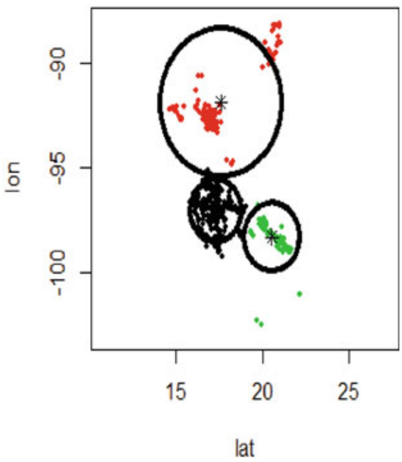


13 Clusters

Instance Virtual Interactive Atlas (2)
CEC Method

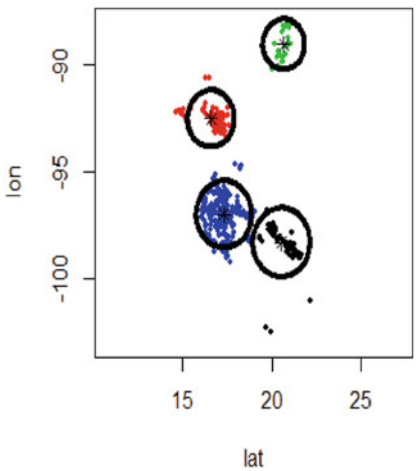


2 Clusters



3 Clusters

Instance Virtual Interactive Atlas (2)
CEC Method



4 Clusters

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Chapter 3
Strategies that Improve the Performance of the Humanitarian Supply Chain

Patricia Cano-Olivos, Diana Sánchez-Partida, Santiago-Omar Caballero-Morales, and José-Luis Martínez-Flores

Abstract Disasters are not a novel phenomenon; however, they have demonstrated the need to implement coordinated action by international organizations, governments, and humanitarian actors to meet the different challenges they pose in recent decades. In this sense, there are numerous plans and protocols for steps in prevention and response. However, beyond the socio-economic consequences of disasters, the same humanitarian supply chains are affected, so those responsible must prepare a rapid and effective response to possible future events. Logistics planning allows the flow of humanitarian products and services, demolition, and reconstruction of physical infrastructure, but should be incorporated as a strategic activity to prepare a National Emergency Plan which depends on the government. The strategies proposed in this research can develop the ability to respond more quickly to the disaster so that its effect decreases, and assistance operations are facilitated. It should be noted that, before the disaster, a reconstruction strategy must be carefully formulated so that post-disaster implementation is implemented with minimal change if required. Hence, reconstruction is longer than the previous ones and requires more economic resources. In general, all strategies (planning, information flow, evaluation, coordination supplying, warehousing, transportation, distribution, and reconstruction) necessary for the deployment of logistics flows during an emergency must prepare, known, tested, and validated in advance by all government offices. It is vital to arrive in the exact place, at the required opportunity, in the necessary quantities and with a high level of service. Logistics strategies must be structured and agreed upon by all parties involved; otherwise, the implementation may not function properly. Therefore, logistics strategies take on extreme relevance in processes for future preventive operations.

Keywords Humanitarian logistic · Supply chain · Earthquake 2017 · Mexico · Strategies

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3.1 Introduction

Logistics in the humanitarian supply chain is defined as effective and efficient planning, implementation, and control of the flows of products, materials, and information from donors to affected people to meet survival needs. According to Wassenhove (2006), the planning strategy includes five critical elements: (a) human resources deployment; selection and training of people coordinating and in intervention in the event of a disaster, (b) knowledge management; store, code, and use information about previous events to improve prevention and support strategies, (c) operations management; location of collection centers and shelters, distribution routes for support resources and evacuation routes under various scenarios, (d) financial resources; allocation of monetary resources to deploy aid operations, and (e) collaboration; identify the various actors (government, private institutions, NGOs and the community) in the event of a disaster and coordinate the humanitarian logistics effort among the participants.

However, humanitarian (HL) and commercial logistics are radically different, but so far, most analytical formulations fail to capture the full complexity of HL (Holguin-Veras et al. 2007). In Mexico, the earthquakes of September 7th and 19th, 2017, left a latent pre-occupation due to the mismanagement and disorganization of humanitarian aid; these events evidenced the unlearned lessons of September 19th, 1985. The contingency and evacuation plans always have variations and eventualities typical of each disaster that was not predicted, so HL must be flexible enough to adapt quickly to needs. On the other hand, corruption in government increases property damage and the death of people, derived from the diversion of resources and the poor application of laws for the construction of real estate, roads, bridges, among others. Thus, HL is an integrated process associated with the management of different flows (capital, goods, and services, people) and whose development impacts the performance of the humanitarian supply chain, favoring both response times and early recovery.

Preparing for a disaster is complex, but there are more likely areas to achieve better results when implementing strategies. A comprehensive humanitarian supply chain requires ideal strategies to improve its performance, i.e., reducing the impact of disasters. This research has identified nine strategies, which are: (1) planning, (2) information flow, (3) evaluation, (4) coordination, (5) supplying, (6) warehousing, (7) transportation, (8) distribution, y (9) reconstruction. These strategies should be directly correlated and continually reviewed before and after the disaster for updating.

3.2 Literature Review

Humanitarian logistics provides emergency supplies quickly to reduce deaths and human suffering. (Balcik and Beamon 2008; Hasanzadeh and Bashiri 2016; Krishnamurthy et al. 2013). However, coordination in humanitarian logistics is one of the most important aspects for both the preparation phase and the response phase (Nikbakhsh and Farahani 2011). Therefore, it is necessary to recognize that disaster response should not be an impromptu outcome; on the contrary, the successful response depends on the response and collaboration capabilities demonstrated by the local government (Van-Wassenhove 2006). According to Yadav and Barve (2015), strategic planning of humanitarian logistics should include resource provision, development of response plans, and analysis of requirements, and define coordination strategies among humanitarian agencies.

Various research mention that humanitarian logistics management implements commercial logistics strategies, such as inventory management (Balcik and Beamon 2008; Chakravarty 2014; Kunz et al. 2014), location of logistics and emergency centers (Najafi et al. 2015; Salman and Yücel 2015; Tuzkaya et al. 2015), and routing to distribute humanitarian aid and evacuate people (Vargas-Florez et al. 2015; Zhen et al. 2015). However, implementing commercial logistics strategies is not fully transferable due to the inherent characteristics of humanitarian logistics (Pettit and Beresford 2009). Complexity increases because disaster preparedness and response operations are related to the diversity and number of involved actors (Kumar and Havey 2013; Ergun et al. 2014), such as local, regional, and international organizations (Yadav and Barve 2015), which do not always work together, and many do not have sufficient experience to carry out their operations (Van-Wassenhove 2006; Kovács and Spens 2007). Table 3.1 shows the main differences between commercial and humanitarian logistics.

Table 3.1 Differences between commercial and humanitarian logistics (Holguín-Veras et al. 2012)

Characteristics	Commercial logistics	Humanitarian logistics
Objective	Minimizing logistical costs	Minimizing social costs (human suffering due to lack of goods or services + logistics costs)
Source of supply flow	Autonomous	Impacted by the arrival of large quantities of supplies in the disaster zone
Demand	Known with some certainty	Unknown and dynamic, lack of information and access to the site
Structure for decision-making	Structured and controlled interactions by few decision-makers	Unstructured interactions with thousands of decision-makers
Periodicity/volume of logistics activities	Repetitive, relatively stable flows, large volumes	Once in a lifetime, great unexpected impulse, small volumes
Communication, social media, etc	Normal, as usual	Severely impacted, in continuous change
Support systems (e.g., transport)	Stable and functional	Impacted and dynamically changed

On the other hand, a disaster is mainly characterized by the level of uncertainty, the variability of demand, and the scarcity of resources and supplies (Day et al. 2012), making the planning process of the humanitarian supply chain more complex (Tofighi et al. 2016). Humanitarian supply chain actors can minimize logistical complexity through the systematic organization, allocation and understanding of specific functions, and identification of barriers (Heaslip et al. 2012; Kabra et al. 2015). Thus, the generation and consolidation of inter-organizational coordination of logistics operations (Tatham and Spens 2011) facilitate the division and organization of responsibilities, competencies, and resources; Actors need to know that their roles can change according to the stages of the disaster, capacities, and access to resources (Jensen and Hertz 2016).

Whereas logistics processes represent 80% of the total costs in disaster care (Van-Wassenhove 2006; Rodríguez-Espíndola and Gaytán 2015), logistics coordination becomes a critical factor in the performance of humanitarian logistics (Balcik et al. 2010). It is important to note that coordination enhances efficiency and effectiveness indicators in operational costs, delivery times, coverage levels, and beneficiaries' satisfaction (Balcik et al. 2010; Jahre and Jensen 2010; Akhtar et al. 2012). Supply chain management requires coordinated execution of operations for satisfactory results when chain members are focused on achieving global optimal (Nikbakhsh and Farahani 2011). Thus, effective relationships between organizations improve process management and overall chain performance in agility and adaptability (Cozzolino 2012; Makepeace et al. 2017). The humanitarian supply chain must integrate all actors to react and coordinate their different links (Ganguly and Rai 2016). Figure 3.1 shows the various actors involved in the humanitarian distribution network.

As the number of actors involved in disasters grows, the complexity of the network becomes difficult (Balcik et al. 2010; Bharosa et al. 2010), and at the same time, donor pressure for transparency in the use of resources grows (Cozzolino et al. 2012). It should be noted that, in the disaster zone, there are also exogenous situational

Fig. 3.1 Actors in the humanitarian aid distribution network

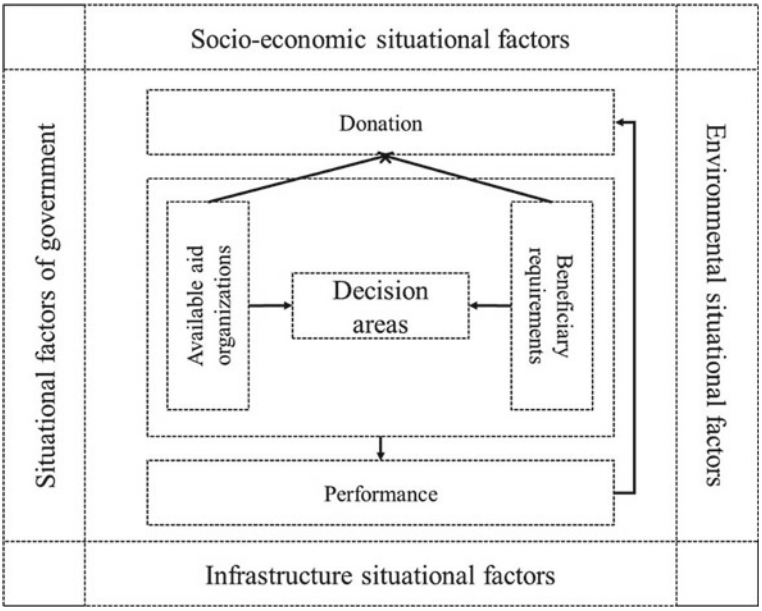

Fig. 3.2 Situational factors in the disaster zone

factors or contextual variables (Fig. 3.2), which have a direct impact on the performance of humanitarian logistics (Kunz and Reiner 2012). Aid organizations do not control these factors or variables, but the effect can be reduced based on the skills organizations have in managing them.

Some of the challenges in humanitarian supply chains after a disaster are (Day et al. 2012):

1. *Management and control problems.* Recognition of government's role at all levels, as international agencies, cannot take any action if local government does not request it.
2. *Life or death.* The effectiveness of humanitarian supply chains is represented by the number of victims alive or killed in the disaster.
3. *Supply chain formation.* The specific group of organizations assembled by a disaster depends on the location, nature, and severity of the disaster, availability of potential units for a response, expected needs, and official procedures.
4. *The independence of donors.* The effort to help after a disaster often depends on donor organizations to provide the necessary goods and services.
5. *High levels of uncertainty.* After a disaster, humanitarian supply chains operate with high levels of uncertainty about the location and distribution of the disaster, victims' needs, donor contributions, the composition of infrastructure, and aid groups.
6. *Dynamic general priorities.* Although speed can significantly reduce the loss of human life and suffering, it is difficult to achieve it at a time of high demand

uncertainty. As a result, aid organizations frequently "push" available supplies into the disaster area as quickly as possible. Simultaneously, response efforts focus on demand, using the information on damage and needs to "pull" supplies to victims.

7. *Dynamic operational needs.* Local conditions are highly dynamic, requiring different responses, resources, and capabilities.
8. *Participants with their initiative.* It is common for individuals, groups, or organizations to want to help. It is essential to recognize that participants with their initiative have social capital and relationships, increasing aid capacity when required and not. They can also smooth out potential conflicts between organizations resulting from differences in culture, religion, gender, and race or ethnicity. However, good intentions become problems as (a) they demand logistical capacity, coordination, communication, and livelihood like everyone else, and (b) generally disrupt or complicate the efforts of others. Sometimes, the donation of materials or other goods creates turbulence that complicates the supply chain's management.
9. *A large number of actors.* It increases the problems related to coordination activities and the information-sharing process.
10. *Advertising and press.* The press always accompanies a disaster, but it generates costs and benefits. For example, the press can direct attention to problems in supply chain performance. On the other hand, publicity derived from the coverage of a charitable organization at the disaster site can help generate donations.
11. *Advertising and press.* The press always accompanies a disaster, but it generates costs and benefits. For example, the press can direct attention to problems in supply chain performance. On the other hand, publicity derived from the coverage of a charitable organization at the disaster site can help generate donations.

3.3 Case Study: Earthquake in Mexico September 19th, 2017

On September 19th, 2017, the National Seismological Service (SSN) reported an earthquake with magnitude 7.1 located on the state boundary between Puebla and Morelos, 12 km southeast of Axochiapan, Morelos, and 120 km from Mexico City. The quake, which occurred at 1:14:40 p.m., was strongly felt in the center of the country. The epicenter coordinates are 18.40 latitude N and −98.72 longitude W, and the depth is 57 km (Fig. 3.3).

The earthquakes in Mexico in September 2017 showed the fragility and vulnerability of the cities and towns of the country (Fig. 3.4). These events exacerbated the current fragile situation that the government did not attend to in the past. However, government deficiencies in infrastructure and education were discovered, and the scarcity of supply chain professionals reduces the efficiency and effectiveness of

Fig. 3.3 The epicenter of the earthquake

Fig. 3.4 Damages in Juchitan, Oaxaca

humanitarian aid in the most affected places. Therefore, humanitarian logistics is essential to improve response procedures in Mexico in recurrent catastrophic events.

The National Coordination of Civil Protection of the Ministry of the Interior, through its four General Directorates: Civil Protection (DGPC); Linking, Innovation and Normativity (DGVIN); Risk Management (DGGR); and the National Center for Disaster Prevention (CENAPRED), implement the following actions: (a) the MX

Plan was activated and through the DGPC the National Emergency Committee was installed, this was responsible for coordinating support for the federation entities concerned, (b) the DGPC established permanent communication with the authorities of the federal entities where theism was perceived, as well as the Federal Units to integrate a preliminary damage assessment, through the National Communication and Operations Centre (Cenacom), (c) national search and rescue teams, (d) were activated and convened, (d) a link was established in the Crisis Room and the CDMX C5 Emergency Operations Centre, (e) a Command Post (CNAR) was established, where the operational base was installed to coordinate the actions of national and international search and rescue teams.

On the other hand, the Ministry of Foreign Affairs and the Governments of the Federal Entities will carry out the channeling and logistics of supplies of international aid to reach each affected population. The tremendous damage to the earthquake was in Chiapas, Oaxaca, Morelos, Puebla, and Mexico City. The houses suffered a partial or total injury, which has historically been one of the most neglected areas of public policy (Puebla 2002; Schteingart 2018), being more critical municipalities and localities with less population than in the big cities as interference of the housing policy is minimal. Under the assumption that the effect of the earthquake in Juchitán is linked to social and housing vulnerability. It is known that in Mexico City, 60 buildings collapsed, 22 thousand 182 buildings suffered less severe affectations, Fig. 3.5 is enormous, and there was undoubtedly no capacity to verify it immediately.

Although CENAPRED had designed a protocol and network to review real estate security after theism, the formats neither the criteria nor the expertise were standardized in transparent processes. Databases were not approved or concentrated. To date, they are a cause for uncertainty, as the lack of official opinions that many people lack is a problem in the reconstruction process. Currently, a final death toll of 369 people is confirmed: 228 death in Mexico City, 74 in Morelos, 45 in Puebla, 15 in the State of Mexico, 6 in Guerrero, and 1 in Oaxaca; and more than 14,000 families affected in Mexico City alone. However, the lack of transparency of government

Fig. 3.5 Damage in Mexico City, Mexico

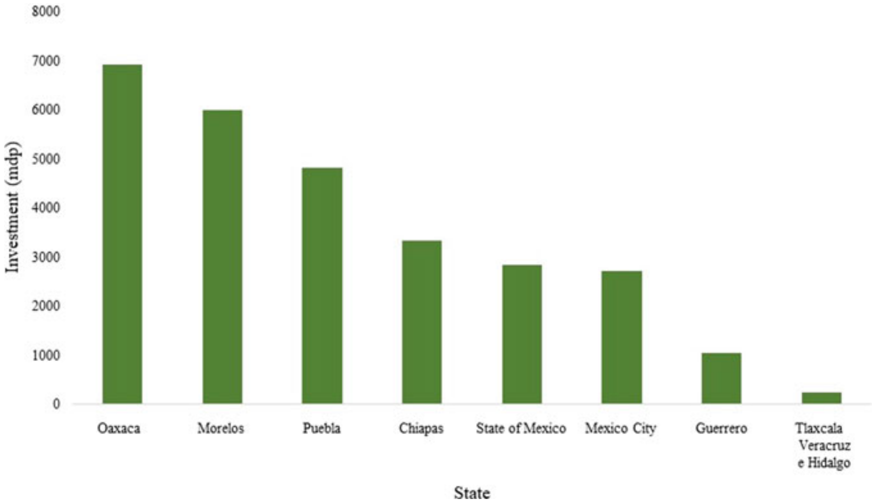

Fig. 3.6 Investment to rebuild the entity

programs and donations has limited the reconstruction of the damage. However, at the morning presidential conference (March 2021), it was mentioned that 9% of the actions to rebuilding homes, hospitals, schools, and real estate of cultural heritage are still pending, i.e., the progress to date is 91%.

Oaxaca is the entity with the highest investment (millions of Mexican pesos) with $6,916; followed by Morelos with $5,985; Puebla with $4,821; Chiapas with $3,335; the State of Mexico with $2,842; Mexico City with $2,717, and Guerrero with $1,029; in Tlaxcala, Veracruz and Hidalgo approximately $225 have been allocated (Fig. 3.6). Of the total resources, 15.2% of the National Natural Disaster Fund (FONDEN), one of the funds disappeared on the initiative of the current federal administration. In contrast, from the Multi-Contribution Fund (FAM), 12%, 32.4%, were raised from the Federation's Egress Budget, and 19% through insurance.

The Committee on Reconstruction has not achieved coordination between units; there is no single file for victim or property; it is the neighbors who seek the different secretariats to deliver the same documents for similar procedures. The dispersion of the budget and formalities between the units have also resulted in a weak commission that cannot impact public spending or sanction officials who do not provide information. The earthquakes of September 2017 showed the country's lack of disaster prevention and preparedness. Despite updating technical standards and regulations, the government does not have an inventory, measures, or funds to strengthen or renovate buildings.

On the other hand, we do not know whether we live in areas of greater risk, nor the precise recommendations for maintaining our workspaces, housing, or study centers. The earthquake also made clear the lack of qualified professionals to assess damages and recommend measures. Finally, the authorities cannot coordinate professionals and trade unions, which has led to a lack of accurate and timely diagnoses. The

Fig. 3.7 DN-III-E Plan and health brigades in Chiapas and Oaxaca

absence of professionalization of civil protection at the different levels of government and the C5 operations center did not coordinate institutional efforts. The DNIII Plan (Fig. 3.7) was actually (if not ignored) by the social solidarity used by current technology and social capital networks, including hundreds of chats, data, collaborative maps, and volunteer chains mobilizing resources.

3.4 Humanitarian Supply Chain Strategies

Efficient and effective supply chain management allows humanitarian organizations to make the best use of resources to address high-priority needs in the shortest possible time, under the restriction of limited funds. However, humanitarian logistics are highly dynamic, often informal or improvised, and far from unification. Under these conditions, it is essential to identify the main strategies that will improve the performance of the humanitarian supply chain (Fig. 3.8).

3.4.1 Planning

Planning is a crucial strategy at any stage of humanitarian logistics; that is, the government must prepare and continuously revise the National Emergency Plan and constantly update it before the disaster, which is essential for its proper post-disaster functioning. Planning before the tragedy demands a significant investment of efforts but helps to improve knowledge of possible areas of operation, identify both weaknesses and needs, as well as solutions and alternatives. Planning should be based on the geographical, social, political, and physical context of the areas where managers will carry out logistical activities. Government and society should dismiss

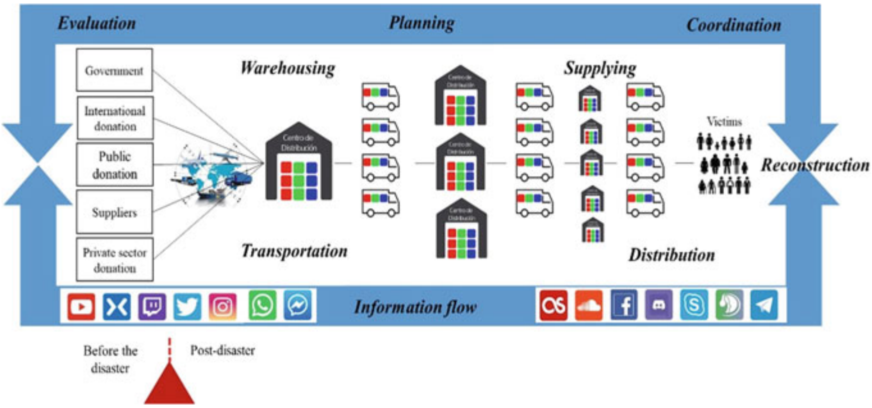

Fig. 3.8 Humanitarian supply chain strategies

the misconception that logistics is improvised at the time of disaster since the catastrophes to which society is exposed as the needs they generate are predictable. The National Emergency Plan should be directly related to infrastructure vulnerability and resource analysis and the particular plans of organizations involved in disasters (Fig. 3.9).

Infrastructure vulnerability analysis should identify the strengths and weaknesses of the country or region's strategic real estate works and resources under study and provide alternative actions in the event of a collapse of the infrastructure available. To do this, government and humanitarian associations must:

- Systematically map and review critical elements of the national transport infrastructure, such as strategic route capabilities and difficulties, potential bottlenecks,

Fig. 3.9 National Emergency Strategic Plan

availability of communications resources, risks, and blockages due to the impact of an event.

- Analyze annual climate records to determine the impact of the weather on the capacity of the transportation system at different times of the year.
- Regularly monitor major modifications or constructions that could lead to bottlenecks or different temporary routes.
- The availability of strategic resources for logistics support is dynamic, so periodic reviews must be up-to-date. This resource review includes both the private sector, the public sector, and the non-governmental sector, both domestic and international. This way, it will have:
- Inventory of sources and location of different types of supplies, including delivery times to provide critical resources that victims might need in an emergency, such as medical and rescue equipment, food, clothing, fuel, among others.
- Inventory of transport modes for the mobilization of persons and provisions, with specific information of transport capacity, such as fleet size, type, and capacity, location, rates, availability, etc.
- List of places for the logistics operation, depot and fuel supply centers, including public and private facilities, ample storage complexes, factories, and other facilities to adapt it.
- Identified the locations and capabilities of ports and airports to handle emergency supplies under different scenarios.
- List of feasible routes in emergencies.

Review government policies, plans, and preparations; the government is primarily responsible for assistance and coordination between the different actors in the humanitarian supply chain. Actors should reach mutual collaboration agreements to facilitating emergency activities, such as tax exemption for humanitarian supplies, priority treatment in customs formalities, etc. Effective planning can significantly prevent loss of life.

3.4.2 Information Flow

It is essential to maintain the information flow with all potential identified actors in the humanitarian supply chain for creating an effective response and recovery plans from lessons learned from other disasters. The information flow integrates technology, actors in the humanitarian supply chain and affected community; however, to improve the quality of information, there are three basic principles (ONU-OCHA 2012):

- Information is a basic need.
- Everyone can generate valuable information (disaster victims, society, and supply chain actors).
- Information creates more value when it is widely and freely shared.

The community can contribute helpful information even when the Internet is not available. Free applications developed on mobile devices allow it to send messages between mobile devices without an Internet connection or the cellular network. Therefore, people are the sensors: people collecting and sharing information to help in the recovery process (Laituri and Kodrich 2008). So, a person is considered a mobile smart sensor if who has interpretation and integration skills, which vary according to the experiences. Users can improve skills through mobile phones with integrated GPS, digital cameras, and tracking devices (Manfré et al. 2012).

Strengthen information systems to provide real-time, up-to-date, and integrated information to expeditiously develop and execute reality-adjusted recovery plans and needs in each territory. The standardization of collaborative technology platforms allows verification and systematizing large amounts of data in real-time. So, citizens locate family members and neighbors and alert rescuers to disaster points by supporting the changing needs in a coordinated way. In addition, the availability of a logistics information system in a disaster situation helps in the efficient management of assistance.

3.4.3 Evaluation

The evaluation will identify an approximation of the logistical and supply needs of the inhabitants, the capacities available locally, and the restrictions and facilitation in the disaster zone (Fig. 3.10). This assessment should be comprehensive in determining the type and extent of damage and the most urgent areas of intervention. The speed and quality of this assessment are crucial, as requests for supplies will be made based

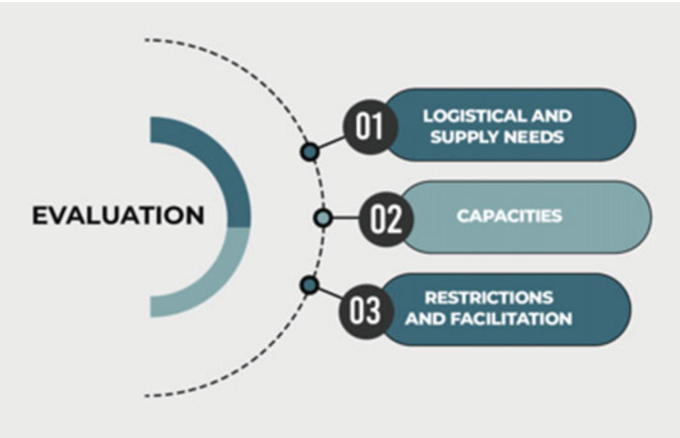

Fig. 3.10 Actions evaluation

on the identified situation. However, evaluation should not be a paralyzing activity; evaluators can initiate the most urgent actions even if the rescue is not complete.

It is essential to know the logistical needs to perform the functions correctly in the emergency context. When planning is effective, the determination of available and missing resources is simplified. On the other hand, supply needs are often dynamic and changing, so the assessment should identify the needs of the current situation and anticipate future needs. Disasters should not be typified; the generated requirements depend on the type of event, socio-economic characteristics, and other specific aspects (socio-environmental and cultural) of the affected region or country. As evaluations continue, preliminarily, it is possible to determine what type of assistance will likely be needed and initiate response activities. As evaluations continue in the short term, they will reveal more specific aspects of the required care. Generally, the possible basic survival needs are:

- Health
- Water
- Food
- Shelter
- Sanitation

Assessing capacities involves knowing the resources available in operations and the local aspects that could facilitate or complicate supply management. For example, disasters often affect lifelines, including communication routes and infrastructure in general, so rapid verification of the availability or operationality of sites and means for the mobilization and arrival of supplies, such as:

- Ways and means of communication for the delivery of supplies
- Sites for storage of supplies
- Availability of means of transport

Restriction or facilitation measures for the entry of foreign organizations, in addition to the regulation for mobilization in the affected areas, religious, political, or health reasons sometimes restrict the access into the country of any product or material. On the other hand, some Governments take exceptional measures to facilitate the tasks of organizations involved in the aid of victims and allow for more flexible procedures for the entry of humanitarian assistance. The evaluation must mention restrictions and/or facilities in the displacement of work equipment and supplies.

3.4.4 Coordination

The coordination of logistics systems must be transparent; humanitarian supplies must be beneficial to populations in crisis. The various actors that assist the affected people are of different origins, mandates, and working methods. Although all have the same will for help, lack of coordination, poor information flow, and minor teamwork cause delays in victim care, duplication of effort, and waste of resources. Assistance tasks require a coordination effort to minimize difficulties and maximize resources. Coordination should be initiated with a cross-sectoral, inter-agency, and interdisciplinary vision before emergencies occur and strengthened immediately after the disaster.

There are permanent and temporary structures for humanitarian aid in each country; Civil Protection for Mexico, which is responsible for coordinating aspects related to national emergencies, is generally a permanent structure. Minor emergencies are addressed by national agencies and sometimes by some international organization, and when they are significant events, they are addressed by various actors, both national and international such as:

- Local population
- Neighboring communities or regions
- National or local government
- Foreign governments
- Multilateral agencies
- National and international non-governmental organizations
- The private and commercial sector
- Specialized institutions
- Military forces

Agreements must be concrete and feasible, not generate expectations of non-compliance; the effort must be geared toward cooperation and mutual support that allow for rapid and diversified assistance. On the other hand, when the effects of the disaster exceed the country's available capacity to respond adequately, the federal government will request humanitarian aid to the international community, usually channeled through the United Nations and diplomatic representations abroad. Similarly, the national subsidiaries of some international organizations will make applications to their respective headquarters or other counterparties in the region.

3.4.5 Supplying

Once the requisitions of the affected area are known, it is also necessary to identify sources and forms of acquisition, indicate the conditions of preparation and shipment, and the shipping procedures (Fig. 3.11).

Requisitions need to be clear and concrete so that supplies are available as quickly and accurately as possible. Order forms can avoid requisition errors, which must specify the details of the articles, priority, volume, frequency. Emergency supplies come from various sources, whether organizations purchase them directly, are donated by the national and international community, or provided by collaborators. In a disaster, all these modalities are combined. However, it is not always able to choose among them the most appropriate. Managers must decide based on technical criteria to minimize response times.

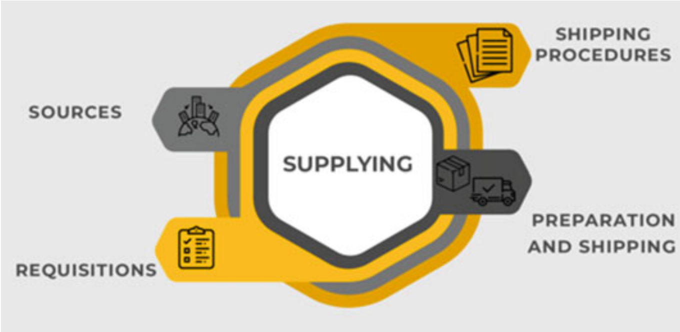

Fig. 3.11 Supply functions

The preparation of shipments plays a vital role in humanitarian logistics. Ideally, the shipped supplies are separated and classified because it would facilitate the delivery of humanitarian aid in the affected area. Do not ship products whose quality or condition is not safe. Avoid the shipment of products whose expiration date is very close except in early use or distribution cases. Many international organizations use symbols and colors to identify content. For example:

- Green for medicines and medical equipment;
- Red for food;
- Blue for clothing and household goods; and
- Yellow for equipment and tools, among others

The shipment of supplies must follow a procedure to ensure that everything is correct and transparent, as inquiries are not suitable in an emergency operation.

3.4.6 Warehousing

During emergencies, collection centers (courtyards, offices, garages, among others) are often set up to receive donations. However, it is complicated to organize a storage system in these sites, mainly because of the lack of space. However, collection centers can separate and classify donations and send only those considered helpful products to warehouses. On the other hand, warehouses must safeguard supplies until distribution or use. Still, it is a matter of having a space to store and an organized system that allows knowing the type, quantity, and location of the existing provisions. The organization of a warehouse must have the necessary standards for the optimal care of supplies. However, in the reality of emergencies, most of the time, it is necessary to improvise the available spaces (schools, communal centers, gyms, etc.), which have not been designed for storage. Nevertheless, even under these circumstances, warehouses should consider effective and efficient operations (Fig. 3.12).

Fig. 3.12 Important aspects of warehouses

3.4.7 Transportation

The various routes and means of transport have different characteristics and requirements that reflect advantages and disadvantages according to the particular situation of the operation and ranging from its costs to its capabilities. Nevertheless, in deciding the transport type, other variables are involved in the identified needs and the specific and accessible possibilities (Fig. 3.13). Managers will not always have the necessary resources to pay for the ideal transport, i.e., perfect transportation will not always be available. Furthermore, the conditions of access to the area will not allow the use of a specific type of transport even if it is available. For this reason, the challenge is not only to determine needs but also to real possibilities and alternatives. For each planned means of transport, there should be an alternative plan for the case where circumstances make it impossible to use.

Fig. 3.13 Considerations for transporting supplies

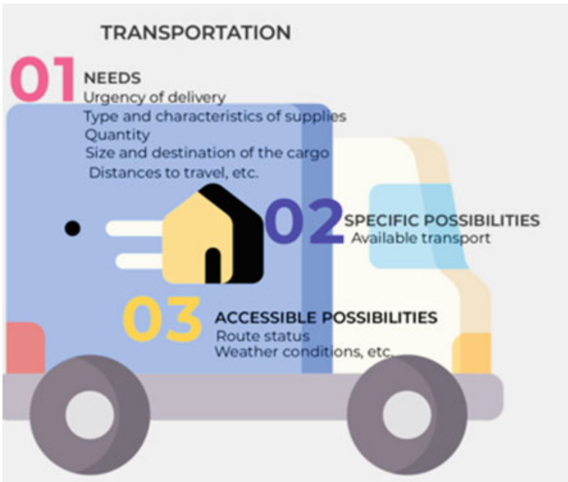

Fig. 3.14 Scopes of distribution

3.4.8 Distribution

Distribution cannot be a generalized and indiscriminate action but must instead be proportional and controlled (Fig. 3.14). While each organization has policies and motivations regarding disaster assistance, some criteria must transcend the individuality of organizations and be applied as basic principles for more equitable and effective distribution. On the other hand, it is necessary to control and monitor the revenues, the dispatches, and outputs of products of the warehouses, and the proof of distribution to have continuously updated inventories. The revision of documents is not sufficient and should therefore be supplemented by physical verification at distribution sites, not only for accounting reasons but also for observing and determining the adequacy of the procedures used, identifying needs, correcting problems, etc.

3.4.9 Reconstruction

It is focused on restoring the normality of life, so it is essential to reactivate services to the community and its sanitation. Activities should focus on rehabilitation, demolition, enablement, repair, reconstruction, construction, etc. Reconstruction is often conceptualized and designed to return to normal development conditions, which were enjoyed before the disaster. Often leads to the reconstruction of existing risk conditions before the disaster, preparing for future disasters, and possibly contributing to the country's debt levels increase thanks to loans for reconstruction.

Similarly, people begin to recover spontaneously, rebuilding and reproducing even conditions riskier than those that existed before the disaster occurred. Thus, when providing appropriate technical support for recovery efforts early, it is possible to consider risk management and reduction considerations within initiatives from the outset, avoiding risk reconstruction and addressing underlying causes.

3.5 Discussion

Logistics operations in the humanitarian supply chain are much more complex than those in business logistics, not only because there is a need to respond immediately to unpredictable situations in terms of demand (how much) and because there is uncertainty when, where, and how will provide aid. For example, even in places prone to natural disasters, where contingency and evacuation plans are available, there are always variations and eventualities which were not foreseen. In addition to uncertainty, donations that are not needed add complexity, causing saturation in humanitarian organizations' warehouses. Not to mention the problem of local policies (e.g., customs) that cause bottlenecks and minimize the flow of resources required to satisfy the basic needs for the survival of the affected people.

While it is challenging to prepare for a disaster, more disaster-prone areas can achieve better results by implementing a planning strategy than distributing aid once the disaster has occurred. Planning allows the anticipation and preparation of national, regional, and local institutions and citizens. Unfortunately, humanitarian supply chain operations are highly complex, as there is a need to respond immediately to unpredictable situations, implying high flexibility. Therefore, strategies must provide the essential components from planning as a crucial and determining element. In general terms, the guiding principles of action are:

- Speed, coordination, and coherence
- Recovering the destroyed by improving the quality of services
- Rebuild with respect and protection of the characteristics of the natural environment and local customs

All information and activities carried out in the planning should be accessible and timely for all national, local, and international actors involved in a disaster. Providing for early policies, mechanisms, and instruments and formulating guidance allows for an adequate articulation between emergency care and recovery and for it to be sustainable and not to reproduce risk. Needs assessment is the basis of disaster impact decision-making to provide a solid foundation for a recovery process. On the other hand, it is necessary to improve coordination between governmental, intergovernmental, and non-governmental risk management actors to create institutional and operational capacities and better prepare strategic areas subject to hazards and vulnerabilities. Finally, the recovery tends to be the longest lasting and the most economically resource-efficient.

3.6 Concluding Remarks

LH should optimize financial resources (considering there are no demand planning processes) and certify suppliers who produce and market products suitable for survival. It cannot buy everything at any price, although the costs are not definitive at the time of purchase.

Each disaster situation is unique, and the inherent difficulties determine the level of challenge to face to bring provisions and resources to the affected regions. Therefore, the application of knowledge and skills, plus the mobilization of people and materials, is essential for the rapid and effective care of the affected population.

Frequently, disaster sites are flooded with tons of supplies, many of which do not satisfy the needs of the affected population, which is a significant problem for relief workers. However, disasters offer unique (albeit transitional) opportunities for change.

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Chapter 4
Water Resources in Mexico and Their Implications in the Phenomenon of Drought

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Abstract Drought is a hydrometeorological phenomenon with systemic implications that currently affect large territorial extensions in the world. Its direct effects and causes are contextualized through the action of multiple factors related to each other at different levels. The greenhouse effect, the increase in global temperatures, natural phenomena such as "el niño" and "la niña", contamination of the primary sources of fresh water, and the overexploitation of aquifer deposits are examples. This research aims to better understand the construction of the reality of drought by characterizing the hydrological resources available in Mexico. For this, the research is supported by a qualitative methodology developed through a descriptive and exploratory analysis of the current conditions of hydrological resources in Mexico through the SINA (National Water System) records and the reports of CENAPRED (National Center for Disaster Prevention).

Keywords Drought problems · Water resources · Implications and trends · Drought types · RHA (Administrative Hydrological Regions)

4.1 Introduction

Since time immemorial, drought has been a threat to the survival of humanity (Ortega-Gaucin 2013); this is one of the most complex phenomena and perhaps the least understood of all-natural hazards (Ortega-Gaucin 2018). Civilization has always depended on both surface and groundwater for its survival. Furthermore, this is essential for the planet; its conservation determines the continuity and balance of life on Earth. Of all the resources on Earth, water is paramount. The scarcity of freshwater and the consequent degradation of the soil, as well as the loss of biological diversity, expressed in desertification, constitute the most implacable and silent threat to humanity (Diéguez et al. 2014). Its main effects translate into hunger, thirst, and

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the death of animals and plants, or even human beings (National Center for Disaster Prevention 2007). Therefore, the absence of water is a latent threat to the survival of humanity and has frequently become the cause of mass migrations, famines, and wars and alter the course of history itself (Ortega-Gaucin 2013).

It should be noted that there are studies that relate the fall of the great cultures with the fact of having suffered prolonged droughts (Domínguez 2016). It is the case of several ancient societies, such as the Indus civilization in India, the Khmer society in current Cambodia, or the ancient Mayan civilization of Central America, where drought is believed to have contributed to its collapse (Kuil et al. 2019) during the period known as “great warming,” which occurred between the tenth and fifteenth centuries, which represented an increase of an average degree centigrade on the planet (Cisneros et al. 2010).

On the other hand, human impacts on the terrestrial hydrosphere have been so significant and widespread that it is currently challenging to find a hydrographic basin that does not reflect the interaction between human activities and natural hydrological processes (Tu et al. 2018). Besides, the effects of global warming will also produce far-reaching impacts on water resources, human societies, and ecosystems (Cisneros et al. 2010), so that some forecasts for the future are certainly not encouraging. It is estimated that around half of the world’s population in 2025 will live in conditions of water scarcity (Bifulco and Ranieri 2017), on the other hand, and according to some data, in 2050, water stress will be double the current. This fact will also directly affect food security, which will give one more reason for population displacement (Rua 2013).

However, the fundamental difference between droughts and other extreme climatic events such as floods and hurricanes lie in the fact that drought occurs for much more extended time (Hao and AghaKouchak 2013). Due to this slow temporal development and its comprehensive spatial coverage, it is difficult to determine the onset, duration, and extension while it occurs. It is also worth noting how complicated it is to define mitigation measures for the severe impacts that are generated (Vilchis Francés et al. 2018) due to droughts, making it easier to assume that they are cumulative, chronicles (Esparza 2014), short and long term. Thus, for example, in the case of short-term droughts, with less than six months, the effects are perceived in agriculture and pasture land, while in the long term, more than six months, the effects are reflected in the hydrology and ecology (Reddy and Singh 2014) of the place.

Drought can be seen as an unspectacular phenomenon depending on its progress and impact in the short term, and perhaps because of this, it did not attract much attention tending to underestimate it, belittling its presence, hoping that it is somewhat short duration and without significant incidents. Nevertheless, although it seems of little relevance, the drought describes a wide range of situations whose common factor is the presence of water in less than average amounts (Gutiérrez et al. 2005) and sometimes with a poor quality of it. As mentioned above, drought is somewhat worrying because it affects the lives of human beings, destroying essential food sources and causing disorders in social and political life (Domínguez 2016). Historically, droughts affect more people worldwide than any other extreme climatic event (Hao and AghaKouchak 2013) even if flood and landslide impacts are considered.

The conditions that are currently maintained throughout the world have been modified for the most part by man. The state of the deposits and water flows has become a relationship dependent on the conditions that exist between human and natural processes. Likewise, water deficits (or droughts) result from a complex interaction between meteorological anomalies, the processes of the Earth's surface, and the inflows, outflows, and changes in storage by humans (Bierkens 2016).

Regarding the significant changes in the physical and biological systems, it must be taken into account that they occur on all continents and in most of the oceans, significantly affecting the availability and quality of resources such as water and soil (Diéguez et al. 2014). As the global climate increases, so does the concern that it influences the flow of water in streams and rivers, which are the primary source of freshwater and sustenance for human, animal, and plant life, as well as the processes fluvial and ecosystem functions; thus, a change in it, would bring possible risks that would lead to an increasingly probable hydrological drought (Austin and Nelms 2017). It is crucial to consider the increasing human influence on the hydrological system and the greater dependence of society on the water availability, which, when combined with significant population growth, and climate change, increases the possibility of hydro phenomena. -extreme weather conditions (Bierkens 2016). Finally, it is essential to further highlight the relationship between climate change and extreme climatic phenomena such as drought, considering the climatic phenomenon of this nature with a hydrometeorological character (Greenpeace Spain 2017) repercussions on different aspects of life on the planet.

However, one of the conditions that have aggravated the effects of droughts in the last 100 years is the idea that water is an abundant resource (Esparza 2014). Because of this, the drought maintains a series of significant consequences for the environment, agriculture, the economy, health, and society (Greenpeace Spain 2017), which have been well defined and explored in the meteorological, hydrogeological, agricultural context. Moreover, economics, leaving aside the impact on our health so that we may not be adequately prepared to face its short and long-term consequences in this regard. Currently, with the availability of water taken for granted in western and industrialized countries, it is possible to consider drought as a severe problem for living standards in a third world country (Bifulco and Ranieri 2017).

In urban areas, the shortage of rain is causing the exacerbation of chronic disorders of the respiratory tract, so it is not surprising that in China, where drought is becoming a severe emergency, respiratory diseases are more easily spread. Besides the aspects above, the loss of quality of life among the population, the reduction of jobs, school dropout in rural areas, deterioration of public health indicators, reduced hygiene conditions, and the conditions of hygiene between groups in poverty (Vargas et al. 2014).

In this sense, in the face of the increasingly recurrent and severe drought problems (Gutiérrez et al. 2005) that are occurring with higher frequency, all over the world, water could become, shortly, a resource that could lead to international and national disputes for owning it (National Center for Disaster Prevention 2007). The fight will be for water and not for land (Rua 2013).

Due to all those above, the last summers in Europe are getting hotter and drier, experiencing a new big problem, drought, associated with suffocation, and insufficient rainfall in winter and spring that do not allow the restoration of reserves water (Bifulco and Ranieri 2017). For its part, low rainfall in Africa, Southeast Asia, eastern Australia, and southern Europe are the leading cause of the drought trend in these regions and forest fires. The most common source of episodic droughts worldwide is the *El Niño*/Southern Oscillation (ENSO) phenomenon, causing major droughts to occur in Australia, Indonesia, Southeast Asia, parts of Africa, and the Northeast Brazil (Li et al. 2017).

In Mexico, the conditions are not very different from those mentioned above, according to demographic effects and according to the Falkenmark water stress criterion, by 2030, most of the Mexican territory will be in water stress conditions (1000 to 1700 m^3/inhab/year), shortage (500 to 1000 m^3/inhab/year) or absolute scarcity (<500 m^3/inhab/year) (Martínez Austria et al. 2019).

It is worth mentioning that drought is a climatic phenomenon that occurs with certain periodicity in the country and occurs cyclically following a specific pattern (Domínguez 2016). Although in part of the national territory there are abundant rains, there are regions that do not have the vital liquid in the quantities required, such as the northern and central states: Durango, Baja California, Chihuahua, Coahuila, Nuevo León, San Luis Potosí, Aguascalientes and Zacatecas (National Center for Disaster Prevention 2007).

Currently, the country's rivers and streams constitute a hydrographic network of 6.33 × 105 km, in which 51 main rivers stand out, through which 87% of the annual wring flows and whose basins occupy 65% of the national territory. Also, highlighting the basins of the Bravo and Balsas rivers and their length the Bravo and Usumacinta rivers (Martínez Austria et al. 2019).

Today more than ever, there is an evident need to improve the economic, political, and social understanding of drought through more consistent methodologies that can reflect significant changes in the degree of vulnerability and its associated costs (National Water Commission 2018) concerning this type of climatic and social phenomenon of broad impact.

To continue building a response to the needs and problems already mentioned, this research focuses on the descriptive analysis of the current situation of water resources in Mexico through a generalized framework. The framework comprises all those variables participating directly and indirectly in the effects and causes of drought among the different hydrological country's regions to help strengthen and consolidate information that facilitates the development of efficient and effective strategies focused on the phenomenon of drought.

The article consists of five sections without grouping the developed introduction. The theoretical section exposes the foundations corresponding to the construct of drought to consistently contextualize the analysis of the variables that configure its effect in Mexico.

The materials and methods are presented with a detailed approach to analyze the variables and the available resources that would contribute to understanding the current situation of the drought in Mexico.

Finally, the sections of results, discussion, and conclusions summarize the findings and the statistical measures of the data of each one of the variables analyzed. It is in these sections that the critical aspects regarding the research carried out are concentrated.

4.2 Literature Review

4.2.1 Drought and Its Characteristics

Droughts are frequent climatic extremes that often extend across broad spatial and temporal scales (Hao and AghaKouchak 2013). These are defined as a prolonged period of shortage of water resources below normal levels, causing adverse effects on resource production systems (Francés et al. 2018). The impact of the drought effects has been the subject of numerous scientific studies; on the other hand, the diversity of Climatic typologies existing on the planet makes it almost impossible to use the same rainfall deficit threshold in two different places (Valiente 2001). As it is a complex phenomenon, it is difficult to give it a generic approach, which considers all its aspects and meets all expectations, since it is instead a particularity of the climate and the environment, which has multiple facets (Gutiérrez et al. 2005).

Now, insufficiency of the usual volume in the supply points can bring a smaller amount of rain to fill these, which derives from a delay in the rain or a combination of both natural causes (National Water Commission 2018). It should be noted that drought and scarcity may seem the same, but they are concepts that represent different phenomena, while drought is a natural phenomenon that ends (in all its manifestations) when the rains arrive and the average level of the bodies of water recovers. The shortage can persist with or without rains and without a drought occurring. This phenomenon is due to human action and consists of extracting and consuming more water than can be recharged and in existence and disposal (Esparza 2014). Therefore, drought and water scarcity are critical words for managing the regions with water stress (Li et al. 2017). In general, it is difficult to affirm if, in a given condition of absence of rain, it is a drought or a simple delay. Thus, indicating with certainty when a drought begins is highly uncertain since the phenomenon is recognized more for the effects than for itself (Gutiérrez et al. 2005). Because of this, the drought severity is a variable concerning space–time since it can cover large areas of territory and lasting months or years. Its effects can be catastrophic in communities that are not sufficiently prepared (National Center for Disaster Prevention 2007) for these purposes. Thus, the most significant difficulty in predicting the impact of drought depends on the fact that it may take many months before water supplies are consumed, but it may take as long or even longer to restore them (Bifulco and Ranieri 2017).

The drought severity depends on the magnitude of the reduction of rain, its duration, the area affected by its effects, and the demand for water from ecosystems and human activities (Vargas et al. 2014). It suggests that the drought will largely depend on the approach from which its repercussions are appreciated and measured (Gutiérrez et al. 2005).

Droughts can have severe consequences in the use of water in various sectors such as agriculture, the supply of drinking water, and the production of hydroelectric energy, in addition to causing problems in ecosystems (Bierkens 2016). The latter is the legitimate and prominent concern in the mapping and controlling water resources, core in the study of meteorological, agricultural and hydrological droughts (Ayantobo et al. 2019). Therefore, when discussing droughts, one must differentiate between meteorological, hydrological, agricultural, or social. The first corresponds to a rain deficit, while the others may well occur even without meteorological drought since they involve a certain degree of water management (Rueda and Neri 2012). On the other hand, the first three types of droughts are related to a physical phenomenon, unlike the socio-economic drought that is associated with the local water supply, which is carried out through monitoring of demand through socio-economic systems (Tu et al. 2018), so it departs from the first two names.

The different droughts can focus on any of the following classifications according to their characteristics (a) Meteorological drought, (b) Agricultural drought, (c) Hydrological drought, and (d) Socioeconomic drought. Its appearance is not particular to a specific region and a particular case since for a sufficiently long time, and under progressive deterioration circumstances, all of them can arise.

It is necessary to emphasize that the differences in the concept of drought are derived from its impact. Because of this, the definitions are diverse, whether they allude to the identification of the limits of the beginning and end of the phenomenon or its severity and frequency (Vargas et al. 2014). Table 4.1 summarizes the critical data that identifies the characteristics of drought types according to their connotations, such as duration, affectations, description, and other details that could help quickly locate the eventualities that arise or combine the developing conditions. Given the above, the differences between the droughts can be contrasted based on criteria such as soil moisture, precipitation, and the characteristics of current flows for each case, in a particular situation (Austin and Nelms 2017).

Also, other essential elements should not be neglected, as in the case of subtle differences in the phenomenon appreciation according to the environment in which it is lived and its relationship with water. For example, these differences, between rural and urban inhabitants contribute to the complexity of understanding drought (Gutiérrez et al. 2005) and its scope.

In the specific case of domestic water consumption, the situation will depend mainly on population growth, while irrigation consumption will depend mainly on the area planted, the water requirements of the crops, and the ambient temperature. Urban water uses can be divided into domestic, commercial (or service), and industrial use. The first will depend substantially on the demographic growth in the city (by the relationship between births and deaths, or by immigration/emigration), and the other two, on the differentiated economic growth rates (growth in services and industrial growth) (Martínez-Austria and Vargas-Hidalgo 2016).

Table 4.1 Drought types prepared by the authors based on (Cisneros et al. 2010; Domínguez 2016; National Water Commission, 2018; Hao and AghaKouchak 2013)

Types of drought	Description	Affectations	Duration	Other data
Meteorological drought 	It is identified by the lack of precipitation as the leading indicator (Hao and AghaKouchak 2013); it is a decrease in precipitation for a certain threshold during a specific period (Cisneros et al. 2010)	Its impact is reflected in the recharge of aquifers, lakes, dams (National Water Commission 2018)	This is a long-term impact, while agricultural drought has an immediate effect on crops, hydrological drought can affect agricultural production of several years, hydroelectric production, or the groundwater extraction (National Water Commission 2018)	It is based on climatic data. It expresses the deviation of the precipitation for the average during a determined time
Agricultural drought 	It is related to the total deficit of soil moisture (Hao and AghaKouchak 2013). Agricultural drought occurs when there is not enough moisture in the soil to develop a particular crop in any of its growth phases. (Cisneros et al. 2010)	This type of drought is one of the most sensitive. It affects the vulnerable sectors since the opportunity of the rain can mean an entire year without agricultural production, both commercial and self-consumption, which translates into the consequent social and economic problems of the population dependent on this sector (Domínguez 2016)	This drought can be classified as the medium or medium-term (Domínguez 2016)	The specificity of the crop is also considered in terms of its moisture requirements. It depends on the growth stage and biology of the plant (National Water Commission 2018)

(continued)

Table 4.1 (continued)

Types of drought	Description	Affectations	Duration	Other data
Hydrological drought 	It is characterized by the shortage of streamflow and water supplies underground (Hao and AghaKouchak 2013)	It causes severe damage to the population, affecting the most developed social and economic sectors, mainly those that have made significant investments in dams and reservoirs, which in turn remain idle and deteriorate without remedy (Domínguez 2016)	Its effects and recovery are long terms (Domínguez 2016)	The management of water resources means that hydrological drought does not depend exclusively on the volume of water existing in natural or artificial deposits, but how water is used is also decisive (Cisneros et al. 2010)
Socio-economic drought 	It can be considered a combination of decreased precipitation, the growth of the needs of the population or productive activities, efficiency in water, and available technology (Domínguez 2016)	The loss of human lives, the material losses of the population in the area affected by the scarcity of rains will acquire more significant or lesser relevance and will even go so far as to configure situations in which drought is considered a catastrophe (Cisneros et al. 2010)	It is directly affected by the degree of dependence on the resource in time and volume. The minimum needs to be satisfied, its importance as an input in production processes, etc. (Cisneros et al. 2010)	It occurs when the availability of water decreases to the point of causing damage (economic or personal) (Cisneros et al. 2010)

4.2.2 *The Effects of Drought and Climate Change*

The climatic variations that the Earth will experience in this century are a tangible example that allows us to recognize ourselves as part of a process that is and will affect our lives (Rua 2013). In addition to the magnitude of the climatic threat, there is also the combination of the systems (regions) vulnerability and the increasing risk and producing a disaster. From a climatological point of view, drought is framed among the most critical processes of natural variability of the climate (Rueda and Neri 2012), with adverse effects such as the promotion of crops exportation, food importations, loss of food self-sufficiency, and aridity in various regions of the planet. As can be seen, these kinds of considerations are generating a significant impact in reducing agricultural potential, reducing essential services such as drinking water, fertile soil (Ochoa Lupián and Ayvar Campos 2015), and increasing the number of climate migrants displaced by the conflicts produced by the scarcity of the exact climate change (Rua 2013).

For their part, natural disasters in the context of industrialized countries also constitute a serious obstacle that usually causes economic losses, but their population maintains high availability of economic resources, which facilitates their recovery more quickly. On the other hand, for developing countries, this type of situation entails the loss of human lives and livelihoods, poverty generally makes people more vulnerable to the impact of dangers (Post-natural disaster intervention (Higher Technical School of Architecture (ETSAM), 2017; Caballero-Morales et al. 2018), which places them in a delicate and vulnerable situation.

Climate change has also intensified the frequency and intensity of extreme meteorological phenomena (Ochoa Lupián and Ayvar Campos 2015). It has significantly altered the periods of rain and drought to reduce the period of rain to a few months, increasing drought and water shortages (Rua 2013). Once the effects of drought and scarcity are combined, a social catastrophe occurs because, with drought, scarcity ends up collapsing in society in many of its main aspects (Esparza 2014).

4.2.3 *Drought in Mexico*

The works on the history of drought and how it has been studied in Mexico show that, with few exceptions, scientists in our country have seen a drought as a recent phenomenon generally associated with climate change. The situation is mainly due to ignorance of the consultation bases since it has always been thought that the place that concentrates the information is the National Meteorological Service (SMN), therefore, what is not there, only does not exists (Servín 2005), and there is no way of knowing more about it.

In 2009, the first episode of drought with considerable impacts was reported. Although in 2011 and 2012, the rainy season turned out to be insufficient for the northern and central states of the country affected by a severe drought event that impacted 1,213 municipalities in 19 states (National Water Commission 2018).

The National Water Program 2014–2018, which was developed around water security against droughts and floods, recognized Mexico as a country highly vulnerable to drought, mainly in the northern states, such as Chihuahua, Coahuila, Nuevo León, Durango, and Zacatecas, where the impact of this phenomenon can have consequences ranging from mild to catastrophic.

Despite having elaborated the national program, the implementation of a National Program against Droughts (PRONACOSE) was also constituted, which was made up of two components: programs of measures to prevent and face drought at the basin level with its 26 tips; and, secondly, to carry out actions to mitigate droughts (National Water Commission 2018; Domínguez 2016).

It should be emphasized that the main extreme hydrometeorological events in Mexico are floods and droughts (Barojas-Payán et al. 2019; Cisneros et al. 2010) both occupy a significant proportion concerning the total number of disasters registered. As a consequence, it is expected that the increase in these two categories in the future would force the various public management organizations (among which is the health sector) to be prepared (Abeldaño Zúñiga and González Villoria 2018) before such hydrometeorological phenomena.

In particular, Mexico is a country where agriculture represents an essential source of employment and economic income, and due to this, the high dependence on agricultural activities, both irrigation and seasonal. The vulnerability of this sector implies a high risk in the presence of the droughts that have devastated large areas and caused severe imbalances to the regional and national economy. The most recent droughts that have arisen have been of meteorological, hydrological, agricultural origin, and even social (Ortega-Gaucin 2013). The drought in Mexico tends to occur with higher frequency and intensity in the center-north of the country (Servín 2005) and not in the southeast regions.

4.2.4 Efforts to Decrease Drought

Regarding the efficiency of water use to reduce drought, it is essential to develop a management of water resources that anticipates droughts, allowing mitigation of adverse, ecological, and socio-economic effects, guaranteeing the human right of the entire population to water, but generating the minimum environmental impact (Greenpeace Spain 2017).

Given the current and future panorama, decision-makers in the planning of water services in municipalities and cities require methods and tools that allow them to explore various solutions and their impacts over time and the different possible scenarios (Martínez-Austria and Vargas-Hidalgo 2016).

On the other hand, during the drought, it is essential to carry out an adequate control of the available water, through a strategic plan that adequately manages the use of all the hydrological, technical, governmental, technological, cultural and human resources available for this purpose (Gutiérrez et al. 2005).

Nevertheless, although long-term planning is developed with the best tools and information, it sometimes presents a high degree of uncertainty, because the expected or foreseeable changes may be more drastic and unpredictable than expected. That is why it is more convenient to plan in the medium term so the reviews and updates can be more accurate and with a more significant impact on the issue of water (Austin and Nelms 2017) and the implications of drought. It should also be borne in mind that for planning and the allocation process, the importance of the central function of seasonal supply and demand is vital in addition to other factors such as instability, time, and intensity of the demand above. This seasonality will largely depend on random factors, including meteorological (Gutiérrez et al. 2005).

It is important to note that the diagnosis represents the starting point for adaptation and prevention actions since the process of understanding the impact of climate change on social and economic systems must be continuous through adaptation at the local level. Therefore, it is essential to consider in more detail the regional conditions and impacts to involve states and municipalities in the development of local adaptation plans, taking into account the priorities, needs, knowledge, and local capacities that link people to plan and do to face the effects of climate change and the repercussions of drought (Ochoa Lupián and Ayvar Campos 2015).

On the other hand, and speaking more extensively and correctly about mitigation measures, the use of reservoirs represents a widely used condition for mitigation of drought, which is so widely used.

At the end of the last century, approximately 20% of the world's total annual river discharge was controlled by artificial reservoirs, and 70% of global freshwater withdrawals came from these reservoirs, indicating the importance of the reservoirs to provide resilience for human use of water worldwide (Tu et al. 2018). Although the transfers that connect to the reservoirs are also not an adequate measure to manage scarcity or droughts, since they increase vulnerability in the affected basins, as has been demonstrated repeatedly (Greenpeace Spain 2017) where said elements created adverse effects on the basins.

It is considering the possible degradation of groundwater quality that currently occurs at the national level, and how this can be prevented or controlled, as long as the processes involved are understood and integrated into diagnostic projects on water availability. It is possible to formulate planning plans and public policies for the sustainable management of resources, which would imply the design of strategies to optimize the extraction of aquifers, one of the primary sources of water for many regions (Diéguez et al. 2014) of the country. All this makes it necessary not only to try to reduce drought but also to improve control measures and use of water resources in order to guide efforts in two directions: on the one hand, increasing the supply of water by increasing hydraulic infrastructure, and on the other, reduce or limit the demand for it for its different uses. Therefore, due to their nature, these mitigation measures are also known as structural and non-structural. The non-structural ones, in turn, can also be classified as reactive and preventive or prospective (National Center for Disaster Prevention 2007).

4.2.4.1 Structural Measures

These refer to those constructions and engineering works that help control, store, extract, and distribute water, in order to optimize the use of the vital resource in times of drought. These engineering works include dams, storage tanks, drinking water supply systems, sewage treatment plants, well drilling, lined canals, and irrigation systems. It should be mentioned that a double drainage system, a sanitary one (sewage), and another pluvial (rainwater), is the most recommended since a good percentage of the water that goes down the drain is rainwater. It does not need treatment as complicated as that of sewage to purify it. Moreover, sometimes without treatment, they could be injected into the subsoil to recharge the aquifers. These refer to those constructions and engineering works that help control, store, extract, and distribute water, in order to optimize the use of the vital resource in times of drought. These engineering works include dams, storage tanks, drinking water supply systems, sewage treatment plants, well drilling, lined canals, and irrigation systems. It should be mentioned that a double drainage system, a sanitary one (sewage), and another pluvial (rainwater), is the most recommended since a good percentage of the water that goes down the drain is rainwater. Moreover, it does not need treatment as complicated as that of sewage to purify it, which is more, sometimes without treatment, they could be injected underground to recharge the aquifers.

In general, all engineering works to mitigate droughts are expensive and by themselves are not a solution to prevent droughts, rather they are the complement of other measures that together help to counteract the negative effects of this phenomenon.

4.2.4.2 Non-structural Measures

Non-structural or institutional measures are those actions taken before and during the drought to lessen its adverse effects, without involving the construction of any work. These measures are socio-economic, legal, planning, and refer mainly to regulations on water use. Institutional measures can be classified in turn into two main branches, which are: reactive and preventive, preventive, or prospective.

Reactive Measures

They include those adopted measures during the event and involve the community acting by doing something about it. For example, there are limit the provision of water to the population and agriculture, implementation of emergency programs that help farmers and ranchers to reduce economic losses within their activities, redistribution water among the different economic activities giving priority to those of greater importance, bearing in mind that, in the ranking of importance, the use of water for domestic consumption of the population must come first.

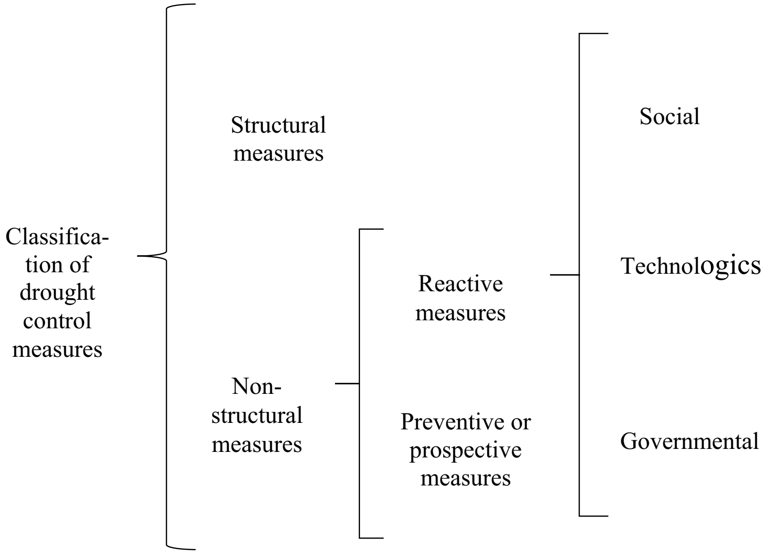


Fig. 4.1 Classification of drought control measures according to (National Center for Disaster Prevention, 2007) and what is proposed by (Ortega-Gaucin 2018)

Preventive or Prospective Measures

These measures are established long before a drought occurs. They create a culture among the population for the care of water. For example, recommend that basic-level schools teach classes on the proper use of natural resources, distribute leaflets in markets, on the street, in workplaces, in recreational places, etc., that talk about the proper use of water. Other measures are the implementation of irrigation techniques to reduce the amount of water in agriculture; introduction into the field some type of livestock or crop that is better adapted to the climate; implementation of continuous monitoring programs in industries so that they do not dump waste into rivers and take care that they are not contaminated; among others (National Center for Disaster Prevention 2007). In summary, Fig. 4.1 summarizes the classification of the drought control measures presented above in detail.

Furthermore, Fig. 4.1 indicates an additional subdivision where it explains how said measures can be analyzed from three approaches such as:

- **Social measures**. They are those that have been carried out independently or organized by members of civil society to try to prevent or lessen the effects of drought on social life.
- **Technological measures**. They refer to those that have been based on the design and use of various types of techniques, methods, works, and devices to capture, store and make better use of water in times of scarcity and drought.

- **Government measures**. They are the actions, regulations, and public policies that have been instituted by state or national authorities to prevent and mitigate the effects of drought on the economy and society (Ortega-Gaucin 2018).

In very general terms, when discussing about the differences regarding measures against drought, we could also mention the focus of the actions carried out by developed and undeveloped countries. In the former, the solutions are more focused on material conditions, while in developing countries, the solutions are, above all, social mechanisms (Post-natural disaster intervention—Escuela Técnica Superior de Arquitectura (ETSAM) 2017).

For example, the Ministry of Water and Agriculture of Saudi Arabia, a country known for its high oil revenues, began to carry out studies to assess the availability of water in each of the country's regions in order to strategically determine where and how many desalination plants were built to supply the population, agriculture, and industry. The collected information resulted in the ambitious and costly Saudi desalination program, which involved building a large number of plants of various sizes along the Red Sea and Persian Gulf coasts (Esparza 2014).

Despite all this, in most parts of the planet, only impacts are addressed, rather than prevented. Thus, meteorological drought frequently ends up becoming a disaster, that is, an agricultural, hydrological, or socio-economic drought (Magaña-Rueda et al. 2018).

Currently, Mexico has a considerable extension of territories close to the sea, which suggests the possibility of developing a water corridor, installing a large number of desalination plants in the Pacific and the Atlantic that supply the states and cities that today suffer from drought or water deficit (Esparza 2014). It could become an alternative to the growing need for scarce water resources at the national level.

On the other hand, although currently there are signed agreements and programs implemented in Mexico, policies to address migration, climate change, and drought continue to be mainly reactive rather than preventive (Ochoa Lupián and Ayvar Campos 2015). This, due to that most of the actions are triggered once the development of the phenomenon and its effects in the country's different sectors have been identified.

4.3 Materials and Methods

The research presented in this chapter is qualitative, given the characteristics of the analysis carried out on the different types of hydrological resources identified at the national level through the data available in the SINA (National Water Information System (SINA)|National Water Commission|Government|gob.mx, na). It is worth mentioning that these were conceptualized as variables for the development of the investigation to complete a scope based on the exploratory and descriptive approach. It allows us to form an approach to reality through an explanation of the phenomenon of drought based on the resources identified to the national level, as well as its characteristics, descriptions, and effects. This phenomenon is so incomprehensible at first sight that it requires a detailed analysis of its components to understand its impact and relationship with the environments: social, meteorological, agricultural, and hydrological in Mexico.

Regarding the development of the analysis of the information up to the point of the explanation of the observed elements, a series of stages were established through which it was possible to identify, describe and explain a substantial part of the conditions that currently keep water resources in Mexico as well as the effects of drought based on data provided by CENAPRED (National Center for Disaster Prevention) on the platform (Open Data from Mexico—Socioeconomic Impact of Disasters from 2000 to 2015, nd). The following steps represent the methodological proposal for the structure of the results, which in turn are divided into the following stages.

4.3.1 Stage 1. Search for Information for Data Concerning the Status of Water Resources and Drought in Mexico

The search for data concerning the current status of water resources and the effects of drought in Mexico was carried out from two primary sources. The first was the SINA (National Water Information System) page, where detailed information regarding the quantity, quality, use, conservation of water, and relevant statistical and geographic information on the subject of water in Mexico (National Water Information System (SINA)|National Water Commission|Government|gob. mx, na) was found.

The site is divided into ten sections. Each one establishes different elements concerning water in the country, such as its implications and characteristics. The sections or consultation tabs are distributed as a national information system on quantity, quality, use and conservation of water, geographic and socio-economic context, the situation of water resources, water uses, hydraulic infrastructure, instruments for water management, water, health and the environment, future scenarios, water in the world, and statistical and geographical publications.

On the other hand, the most current records corresponding to the drought were obtained from the platform Open Data from Mexico (Open Data from Mexico-Socio-economic impact of disasters from 2000 to 2015, na). The file contains the record of the information corresponding to a period of 15 years with regarding different types of disasters that have occurred in the country based on data collected by CENAPRED.

4.3.2 Stage 2. Structure and Evaluation of the Data Obtained

The data obtained from the SINA page and the natural disaster file recovered on the open data platform in Mexico were ordered and prioritized according to the needs of the investigation, such as most of the conditions provided in the SINA records. They had to be standardized according to the 13 administrative hydrological regions into which the country is divided for their correct interpretation and analysis, for their part, in the case of drought affectations obtained from CENAPRED records. The data was generally found in the same file after the category "anthropogenic disasters" to those of the "natural" type. Thus, the data were screened and organized according to the drought implications and the subsequent ones, i.e., high temperatures and forest fires.

4.3.3 Stage 3. Analysis of Conditions Based on Different Categories Adapted to Contain the Information and Translate It into Drought Variables and Hydrological Conditions

Once the information was organized by region, the categories were considered to order the variables corresponding to each of them and develop the corresponding description of the same.

4.3.4 Stage 4. Particular Descriptions on Impact Variables to Build Understanding of Drought and Its Relationship with Water Resources

At this stage, those variables that most directly interact with the drought phases and the social, hydrological, and agricultural implications of the same were analyzed in greater detail.

4.4 Results and Discussion

4.4.1 The Analysis of the Elements that Make up the 13 Hydrological Regions of Mexico

According to the national water administration goal, on July 7th, 2016, the availability of the 757 hydrological basins, into which our country is divided, has been published. The basins are grouped into 37 hydrological regions. These turn into 13 hydrological-administrative regions (RHA) (National Water Information System (SINA)|National Water Commission|Government|gob.mx, na). This generalization of water resources proposed by SINA and CONAGUA (National Water Commission) based on 13 RHA was the benchmark for ordering all the variables from the analysis of the data provided by the different information bases consulted.

Therefore, once the available data were extracted from the ten sections of the SINA, they were grouped in 13 RHAs that constitute the basin organizations at the national level. It was contextualizing all the states of the Republic and their hydrological characteristics, considering each of their expressions from pluvial precipitation, population quantity, and rivers, without having to analyze from time-to-time state by state of the Republic.

It is worth mentioning that to categorize the nature of the variables analyzed further, a classification, according to the proposed topics and orient the nature of each variable according to its affinity to the analyzed problem, was used, as shown in Fig. 4.2.

Now, a total of 36 variables were validated for each Administrative Hydrological Region (RHA) except for region 12, which is represented by the Peninsula of Yucatan, where there are no records of dams or containment of storm bodies on the surface. For that reason, this region only has 33 variables; three less were analyzed than in all

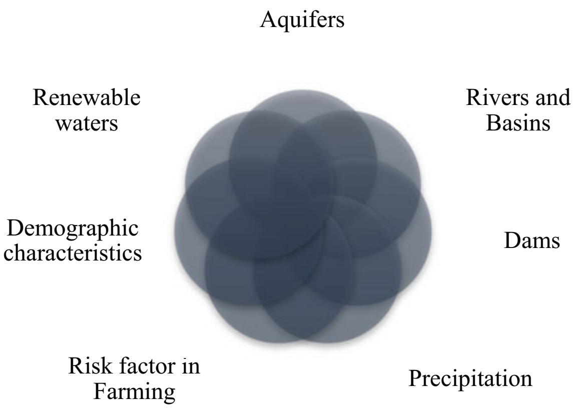


Fig. 4.2 Topics used to order the variables analyzed in the 13 RHAs. Own elaboration

Fig. 4.3 Map of the administrative hydrological regions taken from (Galaviz-villa 2019) and prepared by García-González (2017) page 9, Chapter 1 Physiographic and Demographic Aspects of the Lower Basin of the Usumacinta River

the others. The hydrological basins are divided into (I) Baja California Peninsula, (II) Northwest, (III) North Pacific, (IV) Balsas, (V) South Pacific, (VI) Bravo River, (VII) North Central Basins, (VIII) Lerma Santiago Pacific, (IX) North Gulf, (X) Central Gulf, (XI) Southern Border, (XII) Peninsula of Yucatan, and (XIII) Waters of the Valley of Mexico. Figure 4.3 shows in detail the geographical distribution of the 13 RHAs, showing the magnitude and dimensions of each of the regions concerning the national geographic context.

On the other hand, Table 4.2 also summarizes data of interest regarding the states of the RHA's primary influence.

Once the variables considered were compiled and ordered within the context of the information collected, it was possible to determine a set of metrics that would help understand the nature of the statistical data obtained in more detail. For its part, it is necessary to emphasize that the data series cover a range of analysis from 2004 to 2018. During this time, it was possible to collect the most abundant amount of information regarding the analyzed variables and obtain complete series; this gave as a result that the maximum number of data available by variables ranged between 15 and 0 due to the present conditions. The average value of measurements obtained by RHA was 12 observations without considering that there is a significant dispersion among them because some variables contain very few elements due to the absence of the condition or the relevant records.

Table 4.2 The administrative hydrological regions and the central states that make up each of them

Hydrological Region Administrative (RHA)	States of influence in the RHA
I Baja California Peninsula	B. California Norte y B. California Sur
II Northwest	Sonora y Chihuahua
III North Pacific	Sinaloa, Chihuahua, Nayarit, Durango y Zacatecas
IV Balsas	Puebla, Tlaxcala, Morelos, Edo. de México, Michoacán, Jalisco, Guerrero. Oaxaca e Hidalgo
V South Pacific	Guerrero y Oaxaca
VI Bravo River	Chihuahua, Coahuila, Nuevo León, Tamaulipas y Durango
VII North Central Basins	Durango, Coahuila, Zacatecas, San Luis Potosí y Tamaulipas
VIII Lerma Santiago Pacific	Nayarit, Jalisco, Colima, Michoacán, Aguascalientes, Zacatecas, Guanajuato, Edo. de México y Querétaro
IX North Gulf	Tamaulipas, Veracruz, San Luis Potosí, Querétaro, Hidalgo y Edo. de México
X Central Gulf	Veracruz, Puebla y Oaxaca
XI Southern Border	Chiapas, Tabasco y parte de Campeche
XII Peninsula of Yucatán	Campeche, Yucatán y Quintana Roo
XIII Waters of the Valley of Mexico	Mexico City

Once the details of the observed measures were established, the averages of each of the 36 analyzed variables were determined for most regions except for the RHA of the Peninsula of Yucatan, where the treatment was for 33 variables due to the absence of records of dams. The averages calculation was intended to establish a general comparison between them concerning the results observed during the range of analysis established between the years 2004–2018. It must be emphasized that the average was the descriptive measure used because of the discontinuity in the number of observations that significantly affected the standard deviation making it irrelevant due to the considerable variability presented. The mean was considered a central point estimate concerning the data series and was used to efficiently analyze the contrasted variables' behavior providing relevant questions about their conditions.

Tables 4.3, 4.4, 4.5, 4.6, 4.7, 4.8, 4.9, 4.10, 4.11, 4.12, 4.13, 4.14 and 4.15 summarize the characteristics of the identified variables and the averages for each of the RHA. The information contains the most relevant aspects and constitutes a profile based on the topics proposed by Fig. 4.2 together with the 36 variables analyzed.

The data contained in the Tables 4.3, 4.4, 4.5, 4.6, 4.7, 4.8, 4.9, 4.10, 4.11, 4.12, 4.13, 4.14 and 4.15 are a fundamental part of the investigation since, with them, it was possible to confirm and point out some patterns and behaviors related to the analyzed variables, their general and particular situation by hydrological region. Also, these behavioral patterns detected in the measures confirm that in Mexico, water stress has long reached very high levels that would have a more significant impact on the

Table 4.3 Characteristics of RHA I, own elaboration based on SINA records and (Naturales 2018) page 229 RHA and federal entities

RHA- I Baja California Peninsula

Analysis topics	Measurements obtained from the analysis of the variables
Aquifers	*Availability (hm^3) = **106.46,** *Precipitation per year (mm) = **192.16,** *Deficit (hm^3) = **647.91,** * Medium recharge (hm^3) = **1,519.29**, *Extraction (hm^3) = **1,588.04,** *Area (km^2) = **149,668.56,** *Total of aquifers =**88,** * Overexploited =**15,** * With marine intrusion =**11,** *Salinization =**5**
Renewable waters	Total renewable water (hm^3/year) = **4,938.23**, renewable water per capita (m^3/population/year) = **1,095.83**, Total surface average natural wring (hm^3/year) = **3,294.57**, Renewable water per capita at 2030 (hm^3/year) **= 873.93**
Demographic characteristics	*Population = **4,050,049.77,** *Continental surface (km^2) = **473,868.36,** * Population density (population/km^2) = **26.56**
Risk factors. Farming	*Harvested area (ha) = **54,560.19,** *Total irrigated area (ha) = **220,095.21,** * Number of users = **17,942.00,** *Production (thousands of tons) = **1,219.46,** *Performance (ton ha) = **23.20**

(continued)

Table 4.3 (continued)

Precipitation	*Precipitation per year (mm) = **192.16**, *Average Precipitation mm = **16.01**
Dams	*Capacity NAMO (hm^3) = **115.13**, *Volume storage (hm^3) = **36.13**, *Number of dams = **2.73**
Rivers and Basins	*Volume of natural annual wring (hm3) = **1,464.54,** *Volume of extraction (hm3) = **2,051.88,** *Average annual availability (hm3) = **1,267.81,** *Area (km2) = **145,113.66**

Colorado, Bravo, and Lerma-Balsas River Basins, as well as on the Baja California Peninsula, the Valley of Mexico, and the lagoon region. It would be alarming since the conditions could resemble those prevailing in North Africa and the Middle East (Gutiérrez et al. 2005). On the other hand, the tables characterize a behavioral profile for each RHA that could help make future inquiries regarding the behavior of these variables concerning each other and their long-term effects.

4.4.2 Comparative Analysis Between the Variables of the Different RHA

After summarizing the SINA information in the Tables 4.3– 4.15 corresponding to the different RHAs, a set of graphs was developed with the calculated average data for each series and specified variable. It is necessary to mention that given the number of graphs developed, only the most important have been considered to expand the discussion of this research.

For example, in the graph in Fig. 4.4, where the percentage distribution of rainfall is shown, the results corresponding to the regions such as Southern Border, Central Gulf, and Peninsula of Yucatan stand out. The trend of the factor's availability, deficit, average recharge, and extraction of aquifers were contrasted to determine the projections between them and establish the behavior by RHA. The highest recharge levels were located between the Peninsula of Yucatan, Southern Border, Lerma Santiago Pacific, Bravo River, and Balsas. At the same time, the most significant availabilities were determined in the Southern Border; high extraction volumes are more evident in the Lerma Pacific and Bravo River Region.

Regarding the current state of the aquifers, salinization, overexploitation, saline intrusion, and the number of such cases by RHA stand out. In particular, the most significant number of aquifers are located between the Bravo River region and the Baja California Peninsula, while the region with the lowest number of aquifers in the North Pacific. Besides, the most overexploited basins are the Northern Central Basins, Southern Border, and Peninsula of Yucatan, and therefore those less exploited

Table 4.4 Characteristics of RHA II, own elaboration based on SINA records and (Naturales 2018) page 229 RHA and federal entities

RHA- II Northwest

Analysis topics	Measurements obtained from the analysis of the variables
Aquifers	*Availability (hm³) = **435.18,** *Precipitation per year (mm) = **424.59,** *Deficit (hm³) = **416.21,** * Medium recharge (hm³) = **3,169.71**, *Extraction (hm³) = **2,447.13,** *Area (km²) = **198,773.45,** *Total of aquifers =**62,** * Overexploited =**10,** * With marine intrusion =**5,** *Salinization =**0**
Renewable waters	Total renewable water (hm³/year) = **8,268.40**, renewable water per capita (m³/population/year) = **2,819.53**, Total surface average natural wring (hm³/year) = **5,103.57**, Renewable water per capita at 2030 (hm³/year) **= 2,463.21**
Demographic characteristics	*Population = **2,715,994.27,** *Continental surface (km²) = **200,136.86,** * Population density (population/km²) = **13.50**
Risk factors. Farming	*Harvested area (ha) = **173,530.54,** *Total irrigated area (ha) = **391,420.43,** * Number of users = **36,282.14,** *Production (thousands of tons) = **2,576.75,** *Performance (ton ha) = **14.99**
Precipitation	*Precipitation per year (mm) = **424.59**, *Average Precipitation mm = **35.38**

(continued)

Table 4.4 (continued)

Dams	*Capacity NAMO (hm^3) = **7,907.20**, *Volume storage (hm^3) = **5,849.00**, *Number of dams = **8.93**
Rivers and Basins	*Volume of natural annual wring (hm3) = **4,369.43,** *Volume of extraction (hm3) = **8,373.36,** *Average annual availability (hm3) = **558.18,** *Area (km2) = **99,737.09**

regions are those that have the least number of aquifers; this is the specific case of the North Pacific Region.

For their part, those with the most significant impact from marine intrusion are the Baja California Peninsula, the Peninsula of Yucatan, and the Southern Border. Among those with greater salinization are the Baja California Peninsula, the Bravo River, the North Central Basins, and with a minimal but existing magnitude, the Peninsula of Yucatan.

Renewable water is the water that can be exploited annually in a region according to the projections of organisms in charge of water management in Mexico. According to the comparison made between the variables total renewable water, which in turn are made up of total medium surface natural wring and renewable water per capita for 2030, the evaluation of regions such as the Southern Border stands out (projections for 2030, total water and wring). In this case, they are the highest among all the analyzed regions, while the other regions maintain a very similar performance without significant changes in the analyzed data. For its part, the region with the highest proportion of water per capita is the southern border, followed by the Central Gulf and the Peninsula of Yucatan with significant percentages concerning the total of all other regions.

It should be noted that another relevant aspect that is embedded in the variables that emerge from each region are the demographic characteristics that directly infer in the conditions that shape and directly impact the state of water resources at the national level.

In the case of population density, the regions with the highest proportions are located between Lerma Santiago Pacific, Waters of the Valley of Mexico, and the Bravo River, which contrasts with the regions with the largest continental areas such as the California Peninsula, Rio Bravo River, and the Northeast, likewise the most significant population density of all is that of the Valley of Mexico.

The behavior of water use and agricultural factors is a priority issue since the costs of climate variability are increasing, and the dependence of the agricultural sector on imports is increasing (Rueda and Neri 2012). Therefore, this effect makes the nature of the comparison between harvested and irrigated surface of the graph that corresponds to Fig. 4.5 even more noticeable. This specific irrisible situation is presented, such as the regions where there is a higher quantity of irrigated area but is not equivalent to the harvested. For example, the particular case of the Baja California Peninsula, Northeast, and North Pacific, or where inverse conditions are

Table 4.5 Characteristics of RHA III, own elaboration based on SINA records and (Naturales 2018) page 229 RHA and federal entities

RHA- III North pacific

Analysis topics	Measurements obtained from the analysis of the variables
Aquifers	*Availability (hm³) = **495.60,** *Precipitation per year (mm) = **742.16,** *Deficit (hm³) = **82.53,** * Medium recharge (hm³) = **3,175.29**, *Extraction (hm³) = **1,413.65,** *Area (km²) = **154,077.08,** *Total of aquifers =**24,** * Overexploited =**3,** * With marine intrusion =**0,** *Salinization =**0**
Renewable waters	Total renewable water (hm³/year) = **25,905.14**, renewable water per capita (m³/population/year) = **5,620.96**, Total surface average natural wring (hm³/year) = **22,730.21**, Renewable water per capita at 2030 (hm³/year) **= 5,122.71**
Demographic characteristics	*Population = **4,287,251.67,** *Continental surface (km²) = **152,009.57,** * Population density (population/km²) = **28.04**
Risk factors. Farming	*Harvested area (ha) = **275,891.85,** *Total irrigated area (ha) = **752 377.57,** * Number of users = **89,155.07,** *Production (thousands of tons) = **3,995.04,** *Performance (ton ha) = **14.77**
Precipitation	*Precipitation per year (mm) = **742.16**, *Average Precipitation mm = **61.85**

(continued)

Table 4.5 (continued)

Dams	*Capacity NAMO (hm³) = **15,862.07**, *Volume storage (hm³) = **10,712.93**, *Number of dams = **16.47**
Rivers and Basins	*Volume of natural annual wring (hm3) = **22,167.72,** *Volume of extraction (hm3) = **22,983.55,** *Average annual availability (hm3) = **17,905.59,** *Area (km2) = **135,101.10**

present, such as the harvested area is larger than the irrigated, which is the particular case of the Balsas, Bravo River, and Lerma Santiago Pacific Regions. Finally, both become almost similar as in the North Central basins. The other regions adjust to the trends described above, but less clearly in the graph in Fig. 4.5.

Agricultural production maintains its highest results in the South Pacific and Lerma Santiago Pacific, maintaining incrementally from the Baja California Peninsula to the seventh region in the North Central Basins with a downward trend from the North Gulf to the Valley of Mexico, bone from region 9 to 13. In turn, crop yield maintains an incremental trend among all regions except the Peninsula of Yucatan, North Pacific, and Bravo River.

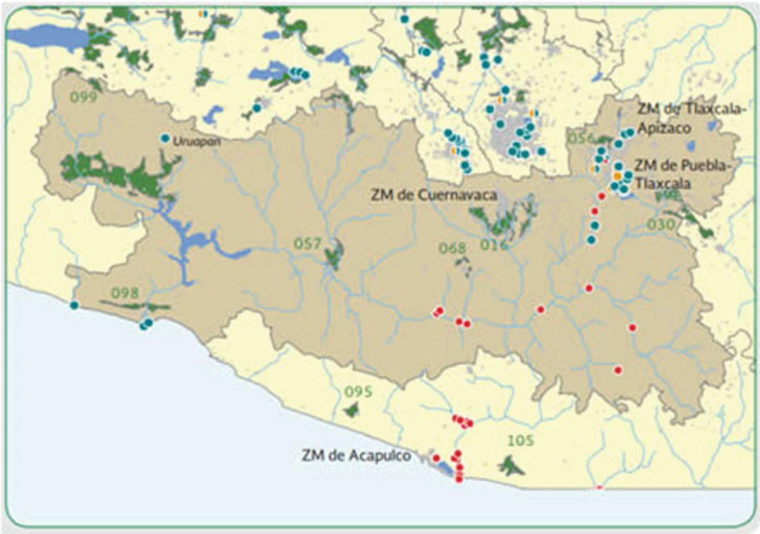
Among the regions with the highest proportion of water users for agriculture are the regions of the North Pacific, North Gulf, and Waters of the Valley of Mexico City, followed closely by the Balsas Region. The smallest number of users are in the Southern Border and the Peninsula of Yucatan. These types of results are essential due to the importance of the agricultural sector in solving drought problems. What makes it convenient to remember that irrigated agriculture is the most demanding water sector in the world, accounting for 87% of consumptive uses (Calvo et al. 2005).

Factors such as the installed capacity of the dam, the average volume registered by region, and the quantity in the proportion of dams by RHA were considered. According to this comparison, it was possible to visualize that most dams maintain a storage level very close to their capacity. For their part, the dams with the highest capacities and, therefore, with the highest storage volumes are located in the North Pacific, Balsas, Bravo River, Lerma Santiago Pacific, Central Gulf, and Southern Border, in the case of the Peninsula of Yucatan. There are records of dams because this region maintains an abundant amount of underground water deposits, so that storage by physical, structural means is not necessary so far. Those with the lowest capacities and with the lowest average volume are found among those of the Valley of Mexico, the Baja California Peninsula, and the North Central Basins. Finally, the regions with the highest proportion of dams nationwide are Lerma Santiago Pacific, Bravo River, and Balsas.

The variables volume of natural wring, the volume of extraction, and mean availability were compared for the basins and rivers. This comparison is shown in the graph in Fig. 4.6. According to what was observed, the highest mean annual avail-

Table 4.6 Characteristics of RHA IV, own elaboration based on SINA records and (Naturales, 2018) page 229 RHA and federal entities

RHA- IV Balsas



Analysis topics	Measurements obtained from the analysis of the variables
Aquifers	*Availability (hm³) = **810.93,** *Precipitation per year (mm) = **917.35,** *Deficit (hm³) = **84.15,** * Medium recharge (hm³) = **5,029.71**, *Extraction (hm³) = **2,022.875,** *Area (km²) = **122,096.34,** *Total of aquifers =**45,** * Overexploited =**2,** * With marine intrusion =**0,** *Salinization =**0**
Renewable waters	Total renewable water (hm³/year) = **22,439.91**, renewable water per capita (m³/population/year) = **1,807.95**, Total surface average natural wring (hm³/year) = **17,528.86**, Renewable water per capita at 2030 (hm³/year) **= 1,685.36**
Demographic characteristics	*Population = **11,259,535.00,** *Continental surface (km²) = **117,642.86,** * Population density (population/km²) = **95.23**

(continued)

Table 4.6 (continued)

Risk factors. Farming	*Harvested area (ha) = **368,995.72,** *Total irrigated area (ha) = **153 990.14,** * Number of users = **56,621.21,** *Production (thousands of tons) = **8,820.53,** *Performance (ton ha) = **23.92**
Precipitation	*Precipitation per year (mm) = **917.35**, *Average Precipitation mm = **76.45**
Dams	*Capacity NAMO (hm^3) = **14,022.93**, *Volume storage (hm^3) = **11,939.87**, *Number of dams = **20.87**
Rivers and Basins	*Volume of natural annual wring (hm3) = **1,328.17,** *Volume of extraction (hm3) = **15 283.71,** *Average annual availability (hm3) = **9,123.52,** *Area (km2) = **12,561.82**

ability is located in the South Pacific, Central Gulf, and North Pacific in the same way the volumes of natural wring coincide with the same regions and the extraction, unlike in this category, Lerma Santiago is considered Pacific. The regions with the highest proportion of area are Southern Border, Baja California Peninsula, and North Pacific.

On the other hand, the condition of Mexico City is highlighted, where the extraction of water from the aquifers is carried out with increasing depth, which has generated subsidence and cracking in much of the city. In turn, the natural surface currents are mostly polluted and require treatment processes to be used in order to increase the supply of good quality water CENAPRED (National Center for Disaster Prevention, 2007).

4.4.3 The Uses of Water by Sector (Self-Supplied Industry, Electric Energy Excluding Hydroelectricity, Agriculture and Public Supply)

The water maintains different uses; the characterization of its use was developed at a national level since the data corresponding to these conditions is not available for evaluation by RHA. The classification of the use of water maintained by the SINA is classified according to four aspects: self-supplied industry, electric energy excluding hydroelectricity, agriculture, and public supply. These were evaluated between 2006 and 2018 except 2011, which does not present records corresponding to any of the items mentioned above.

Table 4.7 Characteristics of RHA V, own elaboration based on SINA records and (Naturales, 2018) page 229 RHA and federal entities

RHA- V South Pacific

Analysis topics	Measurements obtained from the analysis of the variables
Aquifers	*Availability (hm^3) = **625.06,** *Precipitation per year (mm) = **1,186.29,** *Deficit (hm^3) = **11.73,** * Medium recharge (hm^3) = **1,810.71**, *Extraction (hm^3) = **442.19,** *Area (km^2) = **79,133.10,** *Total of aquifers =**36,** * Overexploited =**0,** * With marine intrusion =**0,** *Salinization =**0**
Renewable waters	Total renewable water (hm^3/year) = **31,893.26**, renewable water per capita (m^3/population/year) = **6,315.85**, Total surface average natural wring (hm^3/year) = **30,082.71**, Renewable water per capita at 2030 (hm^3/year) **= 5,906.43**
Demographic characteristics	*Population = **4,667,266.27,** *Continental surface (km^2) = **80,525.00,** * Population density (population/km^2) = **57.42**
Risk factors. Farming	*Harvested area (ha) = **88,790.77,** *Total irrigated area (ha) = **116,974.81,** * Number of users = **18,707.07,** *Production (thousands of tons) = **1,243.11,** *Performance (ton ha) = **14.10**
Precipitation	*Precipitation per year (mm) = **1,186.29**, *Average Precipitation mm = **98.86**

(continued)

Table 4.7 (continued)

Dams	*Capacity NAMO (hm^3) = **1,091.00**, *Volume storage (hm^3) = **878.73**, *Number of dams = **2.00**
Rivers and Basins	*Volume of natural annual wring (hm3) = **29,782.06,** *Volume of extraction (hm3) = **7,937.82,** *Average annual availability (hm3) = **58,544.01,** *Area (km2) = **78,825.60**

Therefore, according to the graph in Fig. 4.7 that shows the behavior of water consumption by sector, it can be seen in detail that the sectors that use the most volumes of water are agriculture and public supply, both maintain a trend in as for consumption of the vital liquid in an incremental way as shown in the dotted trend line of the graph in Fig. 4.7.

Something similar occurs when water uses are analyzed according to their origin of extraction, total volume, and the percentages thereof, the agricultural sector continues to be the one that consumes the most water of any type from which it is extracted, on the other hand. Determined percentage concerning the total of the analyzed cycle comes to consider an average of 76% of agricultural consumption, followed by 14% in the use of public supply.

4.4.4 The Quality of Water and Wastewater

BOD stands for Biochemical Oxygen Demand, the amount of oxygen used in the biochemical oxidation of organic matter for five days at 20ºC (68ºF). The Chemical Oxygen Demand (COD) is a parameter that measures the number of substances that can be oxidized by chemical means that are dissolved or in suspension in a liquid sample. It is used to measure the degree of contamination and is expressed in milligrams of diatomic oxygen per liter (mg O2/l). On the other hand, the total suspended solids or the non-filterable residue of a sample of natural or industrial or domestic wastewater, defined as the portion of solids retained by a filter, these three indicators are mostly the main measurement elements to determine water quality at the national level. They individually refer to the different physical and chemical conditions that are analyzed at the sampling points by region at the national level.

In order to examine the quality of water, the previously established conditions were evaluated concerning these three indicators based on the period 2006–2017. Figures 4.8, 4.9, 4.10 summarize the graphs of the performance of each variable measured that evaluates the quality of the water at the national level.

Table 4.8 Characteristics of RHA VI, own elaboration based on SINA records and (Naturales, 2018) page 229 RHA and federal entities

RHA- VI Bravo River

Analysis topics	Measurements obtained from the analysis of the variables
Aquifers	*Availability (hm³) = **1,123.48,** *Precipitation per year (mm) = **477.24,** *Deficit (hm³) = **1,589.60,** * Medium recharge (hm³) = **1,810.71**, *Extraction (hm³) = **442.19,** *Area (km²) = **5,731.00,** *Total of aquifers =**1026,** * Overexploited =**18,** * With marine intrusion =**0,** *Salinization =**8**
Renewable waters	Total renewable water (hm³/year) = **12,472.76**, renewable water per capita (m³/population/year) = **992.34**, Total surface average natural wring (hm³/year) = **6,741.79**, Renewable water per capita at 2030 (hm³/year) **= 868.07**
Demographic characteristics	*Population = **11,580,473.80,** *Continental surface (km²) = **385,773.71,** * Population density (population/km²) = **29.78**
Risk factors. Farming	*Harvested area (ha) = **616,678.71,** *Total irrigated area (ha) = **30,865.14,** * Number of users = **9,147.93,** *Production (thousands of tons) = **7,454.70,** *Performance (ton ha) = **12.08**

(continued)

Table 4.8 (continued)

Precipitation	*Precipitation per year (mm) = **477.24**, *Average Precipitation mm = **39.77**
Dams	*Capacity NAMO (hm^3) = **15,120.33**, *Volume storage (hm^3) = **10,438.33**, *Number of dams = **20**
Rivers and Basins	*Volume of natural annual wring (hm3) = **1,447.2,** *Volume of extraction (hm3) = **195.4,** *Average annual availability (hm3) = **1,356.83,** *Area (km2) = **72,333.72**

However, the results found from the descriptive analysis carried out on these three variables of water quality show that, in most cases, the sampled sites maintain excellent water quality based on outstanding performance in each of the three indicators (i.e., DB05, COD, and SST). On the other hand, it is essential to emphasize that the samplings are carried out at different points. These, in turn, are classified as excellent quality, good quality, acceptable, contaminated, and heavily contaminated. In addition to this, it highlights that only contamination conditions and acceptable water quality were presented during two periods, in the years 2013 and 2014 in the COD indicator. This suggests that the amounts of oxygen in the water for the basins during that period were not entirely satisfactory. It is essential to mention that the described results are generalized for the whole country and not for a particular basin.

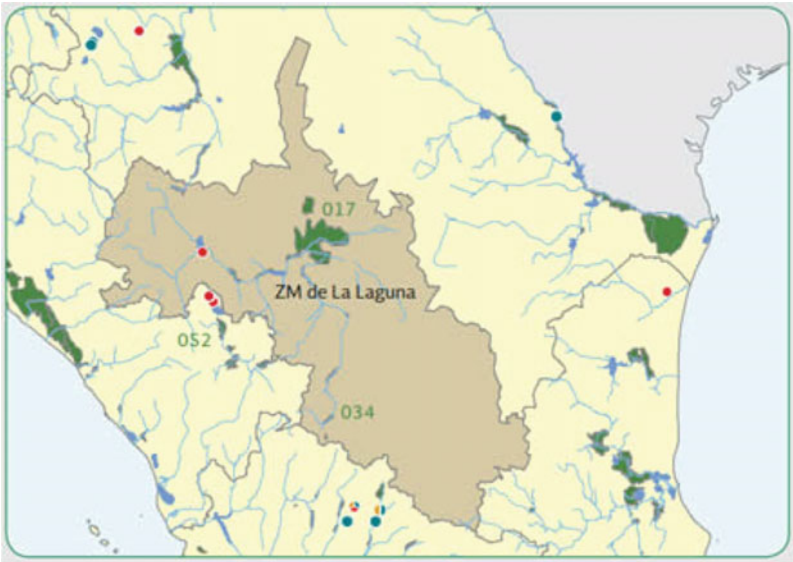
Regarding other factors such as pollution and wastewater discharge, Fig. 4.11 establishes an overview regarding the generation and management of wastewater, be it water collected in sewage, wastewater or treated; it is evident that the volumes measured in Thousands of hm^3/year of wastewater tend to decrease, increasing the sewage collection and treatment linearly, as evidenced by the trend line in the graph. These elements were analyzed in a period between 2004 and 2016. Moreover, they are representative of all RHA in the country as well as the variables of water quality.

Although the water quality is satisfactory at the national level, this is entirely different for the region of the Valley of Mexico, where the indicators do not show the same behavior as the national average, since in this region, the conditions oscillate between heavily contaminated and acceptable except for the SST indicator where it reaches excellence in some specific periods.

For its part, the importance of water treatment and water quality is a fundamental element in the current situation of Covid-19 disease. The current need to give full control and monitoring of water treatment is vital in the presence and evolution of the SARS-CoV-2 virus in water, soils and other environmental compartments (Núñez-Delgado 2020). The etiologic agent of the current COVID-19 pandemic is accompanied by the elimination of the virus in the sediments. Therefore, the adequate quantification of SARS-CoV-2 in waters should allow monitoring the prevalence of infections in the population through wastewater-based epidemiology (Ahmed et al. 2020).

Table 4.9 Characteristics of RHA VII, own elaboration based on SINA records and (Naturales 2018) page 229 RHA and federal entities

RHA- VII Northern Central Basins



Analysis topics	Measurements obtained from the analysis of the variables
Aquifers	*Availability (hm^3) = **438.10,** *Precipitation per year (mm) = **444.36,** *Deficit (hm^3) = **848.95,** * Medium recharge (hm^3) = **2,346.86,** *Extraction (hm^3) = **2,722.94,** *Area (km^2) = **182,991.26,** *Total of aquifers =**65,** * Overexploited =23**,** * With marine intrusion =**0,** *Salinization =1**8**
Renewable waters	Total renewable water (hm^3/year) = **7,920.57**, renewable water per capita (m^3/population/year) = **1,696.27**, Total surface average natural wring (hm^3/year) = **5,573.93**, Renewable water per capita at 2030 (hm^3/year) **= 1,545.7**
Demographic characteristics	*Population = **4,340,249.07,** *Continental surface (km^2) = **194,024.29,** * Population density (population/km^2) = **2922.31**

(continued)

Table 4.9 (continued)

Risk factors. Farming	*Harvested area (ha) = **314,174.31,** *Total irrigated area (ha) = **340,034.94,** * Number of users = **31,229.36,** *Production (thousands of tons) = **9,404.070,** *Performance (ton ha) = **29.95**
Precipitation	*Precipitation per year (mm) = **444.36**, *Average Precipitation mm = **37.03**
Dams	*Capacity NAMO (hm^3) = **3,369.27**, *Volume storage (hm^3) = **2,495.93**, *Number of dams = **7**
Rivers and Basins	*Volume of natural annual wring (hm3) = **5,091.592,** *Volume of extraction (hm3) = **1,120.10,** *Average annual availability (hm3) = **4,032.05,** *Area (km2) = **217,300.10**

Furthermore, wastewater management is an increasing issue in Mexico, as well as the importance of strict treatment in critical places such as hospitals, as they are essential sources of contaminants resulting from diagnostic, laboratory and research activities, as well as excretion. of medications by patients (Wang et al. 2020).

4.4.5 The Impacts of Drought and its Effects Related to Available Water Resources

The database obtained from the Mexico open data platform, which corresponds to the disaster records issued by CENAPRED between the years 2000–2015, was analyzed based on three aspects: drought and two complementary to it, extreme temperatures and forest fires. The amount of recorded data contained provided enough information to create a perspective regarding the details of the variables selected for the analysis. However, during some periods, the data series did not contain all the corresponding records. However, the statistical measurements of the variables turned out to be the best way to reach an understanding of these conditions since, due to a large number of elements, descriptive analysis of them was impractical.

The data concentrated in Tables 4.16 and 4.17 contain the characteristics of extreme temperatures and drought as a whole due to the affinity between them, and Table 4.17 only reports the conditions related to forest fires.

Table 4.10 Characteristics of RHA VIII, own elaboration based on SINA records and (Naturales 2018) page 229 RHA and federal entities

RHA- VIII Lerma Santiago Pacific

Analysis topics	Measurements obtained from the analysis of the variables
Aquifers	*Availability (hm^3) = **735.86,** *Precipitation per year (mm) = **803.34,** *Deficit (hm^3) = **1,803.81,** * Medium recharge (hm^3) = **8,910.21**, *Extraction (hm^3) = **8,189.16,** *Area (km^2) = **188,905.98,** *Total of aquifers =**63.55,** * Overexploited =**15.36,** * With marine intrusion =**4,** *Salinization =**8**
Renewable waters	Total renewable water (hm^3/year) = **35,041.24**, renewable water per capita (m^3/population/year) = **1,423.61**, Total surface average natural wring (hm^3/year) = **26,130.93**, Renewable water per capita at 2030 (hm^3/year) **= 1,265.14**
Demographic characteristics	*Population = **22,572,794.47,** *Continental surface (km^2) = **191,712.71,** * Population density (population/km^2) = **116.80**
Risk factors. Farming	*Harvested area (ha) = **851,014.241,** *Total irrigated area (ha) = **57 544.90,** * Number of users = **33,425.57,** *Production (thousands of tons) = **20,199.32,** *Performance (ton ha) = **23.74**
Precipitation	*Precipitation per year (mm) = **803.34**, *Average Precipitation mm = **66.95**
Dams	*Capacity NAMO (hm^3) = **16,247.07**, *Volume storage (hm^3) = **13,126.80**, *Number of dams = **51**
Rivers and Basins	*Volume of natural annual wring (hm3) = **17,928.72,** *Volume of extraction (hm3) = **20 035.41,** *Average annual availability (hm3) = **26,652.38,** *Area (km2) = **103,295.46**

Table 4.11 Characteristics of RHA IX, own elaboration based on SINA records and (Naturales, 2018) page 229 RHA and federal entities

RHA- IX North Gulf

Analysis topics	Measurements obtained from the analysis of the variables
Aquifers	*Availability (hm^3) = **713.55,** *Precipitation per year mm) = **910.76,** *Deficit (hm^3) = **196.05,** * Medium recharge (hm^3) = **2,913.57**, *Extraction (hm^3) = **1,054.37,** *Area (km^2) = **137,144.86,** *Total of aquifers =**65,** * Overexploited =**17,** * With marine intrusion =**6,** *Salinization =**0**
Renewable waters	Total renewable water (hm^3/year) = **27,045.75**, renewable water per capita (m^3/population/year) = **4,932.85**, Total surface average natural wring (hm^3/year) = **24,132.36**, Renewable water per capita at 2030 (hm^3/year) **= 4,535.86**
Demographic characteristics	*Population = **5,132,624.20,** *Continental surface (km^2) = **127,107.71,** * Population density (population/km^2) = **40.22**
Risk factors. Farming	*Harvested area (ha) = **348,463.82,** *Total irrigated area (ha) = **319,037.65,** * Number of users = **88,493.57,** *Production (thousands of tons) = **8,279.16,** *Performance (ton ha) = **25.51**
Precipitation	*Precipitation per year (mm) = **910.76**, *Average Precipitation mm = **75.90**
Dams	*Capacity NAMO (hm^3) = **6,773.60**, *Volume storage (hm^3) = **5,249.53**, *Number of dams = **12.13**
Rivers and Basins	*Volume of natural annual wring (hm3) = **21,013.08,** *Volume of extraction (hm3) = **7,069.87,** *Average annual availability (hm3) = **54,674.48,** *Area (km2) = **109,531.25**

Table 4.12 Characteristics of RHA X, own elaboration based on SINA records and (Naturales, 2018) page 229 RHA and states

RHA- X Central Gulf

Analysis topics	Measurements obtained from the analysis of the variables
Aquifers	*Availability (hm^3) = **1,244.94,** *Precipitation per year (mm) = **1,792.44,** *Deficit (hm^3) = **12.07,** * Medium recharge (hm^3) = **4,379.50**, *Extraction (hm^3) = **827.22,** *Area (km^2) = **102,705.22,** *Total of aquifers =**65,** * Overexploited =**18,** * With marine intrusion =**7,** *Salinization =**0**
Renewable waters	Total renewable water (hm^3/year) = **94,035.85**, renewable water per capita (m^3/population/year) = **8,530.95**, Total surface average natural wring (hm^3/year) = **89,656.36**, Renewable water per capita at 2030 (hm^3/year) **= 8,101.57**
Demographic characteristics	*Population = **10,145,231.93,** *Continental surface (km^2) = **103,398.00,** * Population density (population/km^2) = **97.72**
Risk factors. Farming	*Harvested area (ha) = **94,280.18,** *Total irrigated area (ha) = **31,001.41,** * Number of users = **7,097.93,** *Production (thousands of tons) = **3,891.28,** *Performance (ton ha) = **41.15**
Precipitation	*Precipitation per year (mm) = **1,792.44**, *Average Precipitation mm = **149.37**

(continued)

Table 4.12 (continued)

Dams	*Capacity NAMO (hm³) = **10,993.53**, *Volume storage (hm³) = **8,356.73**, *Number of dams = **9**
Rivers and Basins	*Volume of natural annual wring (hm3) = **79,633.08,** *Volume of extraction (hm3) = **29,937.34,** *Average annual availability (hm3) = **210,551.86,** *Area (km2) = **103,428.14**

4.5 Conclusions

The importance of analyzing the variables that define the conditions of the water resources in Mexico and the affectations of the drought has as a goal the conformation of new knowledge related to the same. It facilitates the configuration of a strategic environment for the development of actions that counteract its effects, no doubt knowing in detail the resources and the state of their projected conditions would be of great help to understand further the operation of the drought and its danger among the most unsafe environments in Mexico, as an example, the social and agricultural. The variables analyzed, plus the need to produce an extensive collection of data about the 13 RHA analyzed, have to do with the behaviors and patterns detected from their evaluation.

To better illustrate this point, we can refer to the behavior of water availability in the southeastern areas of the country and specifically in the Peninsula of Yucatan and the Southern Border, places with the highest rainfall rate per year and with a considerable proportion of aquifers, and rivers (bodies of water) nationwide. Currently, the Peninsula of Yucatan does not have a dam infrastructure. Most of these water infrastructure resources are located in hydrological regions in the north of the country, where crop irrigation seems to be less intensive. However, with better results than in the south, On the other hand, the number of agricultural users is less in the southeast regions, increasing considerably in the North-Central Mexico where the agricultural dependence on dams is much higher, on the other hand, the availability of water in most dams is close to of its specified capacity.

In the case of water quality, its level is maintained in optimal conditions in most of the national territory, the recovered waters, and the treatment of residuals present an upward trend as means to increase the availability of water for various uses through these processes.

Water resources are under high pressure, mainly due to factors such as population growth, social and economic development that generates higher demands, especially for industrial use and services (Cisneros et al. 2010) on the availability of vital liquid. In this way, this scarcity can collapse and render the governments operations and their useless infrastructure (Esparza 2014), limiting the country's economic development and its correct management, which would directly affect local and regional growth.

Table 4.13 Characteristics of RHA XI, own elaboration based on SINA records and (Naturales, 2018) page 229 RHA and federal entities

RHA- XI Southern Border	
	
Analysis topics	**Measurements obtained from the analysis of the variables**
Aquifers	*Availability (hm³) = **10,601.99,** *Precipitation per year (mm) = **1,980.19,** *Deficit (hm³) = **4.89,** * Medium recharge (hm³) = **20, 731.43**, *Extraction (hm³) = **543.01,** *Area (km²) = **99,525.92,** *Total of aquifers =**66,** * Overexploited =**20,** * With marine intrusion =**9,** *Salinization =**0**
Renewable waters	Total renewable water (hm³/year) = **157,095.45**, renewable water per capita (m³/population/year) = **20,252.63**, Total surface average natural wring (hm³/year) = **136,364.29**, Renewable water per capita at 2030 (hm³/year) **= 17,762.71**
Demographic characteristics	*Population = **7,151,683.60,** *Continental surface (km²) = **100,009.86,** * Population density (population/km²) = **71.02**
Risk factors. Farming	*Harvested area (ha) = **36,826.818,** *Total irrigated area (ha) = **26,408.63,** * Number of users = **6,244.43,** *Production (thousands of tons) = **1,519.95,** *Performance (ton ha) = **41.46**

(continued)

Table 4.13 (continued)

Precipitation	*Precipitation per year (mm) = **1,980.19**, *Average Precipitation mm = **165.02**
Dams	*Capacity NAMO (hm³) = **28,084.67**, *Volume storage (hm³) = **26,434.93**, *Number of dams = **5**
Rivers and Basins	*Volume of natural annual wring (hm3) = **885.79,** *Volume of extraction (hm3) = **2,273.92,** *Average annual availability (hm3) = **32.65,** *Area (km2) = **14,435.69**

Today more than ever, there is an evident need to improve the understanding of the economic, political, and social aspects of drought through more consistent methodologies that can reflect significant changes in the degree of vulnerability and its associated costs (National Water Commission 2018).

Given this panorama, the development of tools that can add value to the existing information on drought and adapt it to specific decision-making contexts becomes propitious (Towler and Lazrus 2016). Moreover, if the problem is analyzed from a risk perspective, it is possible to identify the factors that generate it to avoid it or decrease the impact's magnitude. That is why it is essential to identify the actions before, during, and after the phenomenon, since this helps to recognize and reduce the essential vulnerability factors (Barojas-Payán et al. 2019; Magaña-Rueda et al. 2018).

Finally, it should be noted that water uses are concentrated in the most vulnerable sectors, in the specific case of public and agricultural use, where almost 80% of the water extracted from any source is almost always used, followed by 15% of public use. Finally, demographic conditions had a significant impact on both availability and distribution per capita per inhabitant. To illustrate this particular case, we could consider that the current water situation in the Mexico Valley has the most dangerous conditions regarding distribution and availability. Similarly, salinization and marine intrusion phenomena affect basins near the sea and with deficient levels of water availability in any of its forms of extraction, except the Peninsula of Yucatan where there is availability. However, intrusion conditions exist in marine aquifers.

In summary, this research considers the identification of this type of pattern.

It is a vital result to assess the effects of drought in Mexico and, more particularly, in any of its 13 RHAs. They were disaggregated into basins and sub-basins. It facilitates the development of strategies to mitigate the effects of the drought phenomenon.

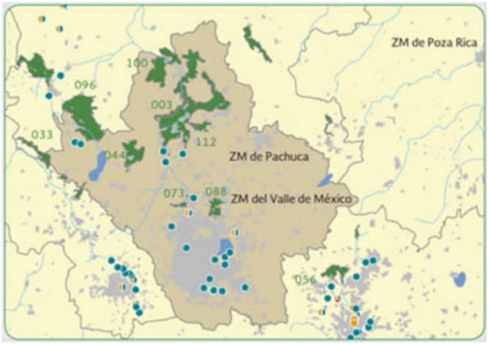
Table 4.14 Characteristics of RHA XII, own elaboration based on SINA records and (Naturales, 2018) page 229 RHA and federal entities

RHA- XII Peninsula of Yucatán

Analysis topics	Measurements obtained from the analysis of the variables
Aquifers	*Availability (hm^3) = **4,550.26,** *Precipitation per year (mm) = **1,220.42,** *Deficit (hm^3) = **0,** * Medium recharge (hm^3) = **25,316.00**, *Extraction (hm^3) = **1,343.50,** *Area (km^2) = **139,605.38,** *Total of aquifers =**67,** * Overexploited =**21,** * With marine intrusion =**10,** *Salinization =**1**
Renewable waters	Total renewable water (hm^3/year) = **29,641.33**, renewable water per capita (m^3/population/year) = **6,383.26**, Total surface average natural wring (hm^3/year) = **4,325.64**, Renewable water per capita at 2030 (hm^3/year) **= 5,080.29**
Demographic characteristics	*Population = **4 249 370.27,** *Continental surface (km^2) = **138,978.14,** * Population density (population/km^2) = **30.25**
Risk factors. Farming	*Harvested area (ha) = **59,999.99,** *Total irrigated area (ha) = **12,205.66,** * Number of users = **4,643.79,** *Production (thousands of tons) = **1,110.47,** *Performance (ton ha) = **18.50**
Precipitation	*Precipitation per year (mm) = **1,220.42**, *Average Precipitation mm = **101.70**
Dams	* It does not contain data in this regard.
Rivers and Basins	*Volume of natural annual wring (hm3) = **3,041.29,** *Volume of extraction (hm3) = **15.16,** *Average annual availability (hm3) = **5,466.06,** *Area (km2) = **48,859.85**

Table 4.15 Characteristics of RHA XIII, own elaboration based on SINA records and (Naturales, 2018) page 229 RHA and federal entities

RHA- XIII Waters of the Valley of Mexico



Analysis topics	Measurements obtained from the analysis of the variables
Aquifers	*Availability (hm^3) = **314.98,** *Precipitation per year (mm) = **630.53,** *Deficit (hm^3) = **800.45,** * Medium recharge (hm^3) = **2,235.14**, *Extraction (hm^3) = **1,955.61,** *Area (km^2) = **16,222.92,** *Total of aquifers =**15,** * Overexploited =**4,** * With marine intrusion =**0,** *Salinization =**0**
Renewable waters	Total renewable water (hm^3/year) = **3,431.19**, renewable water per capita (m^3/population/year) = **142.37**, Total surface average natural wring (hm^3/year) = **1,196.00**, Renewable water per capita at 2030 (hm^3/year) **= 135.07**
Demographic characteristics	*Population = **22,261,507.60,** *Continental surface (km^2) = **17,461.43,** * Population density (population/km^2) = **1,269.71**
Risk factors. Farming	*Harvested area (ha) = **82,020.85,** *Total irrigated area (ha) = **90,198.22,** * Number of users = **64,890.86,** *Production (thousands of tons) = **2,697.17,** *Performance (ton ha) = **32.99**
Precipitation	*Precipitation per year (mm) = **630.53**, *Average Precipitation mm = **52.54**
Dams	*Capacity NAMO (hm^3) = **543.27**, *Volume storage (hm^3) = **464.40**, *Number of dams = **10.67**
Rivers and Basins	*Volume of natural annual wring (hm3) = **885.79,** *Volume of extraction (hm3) = **2,526.58,** *Average annual availability (hm3) = **32.65,** *Area (km2) = **16,039.65**

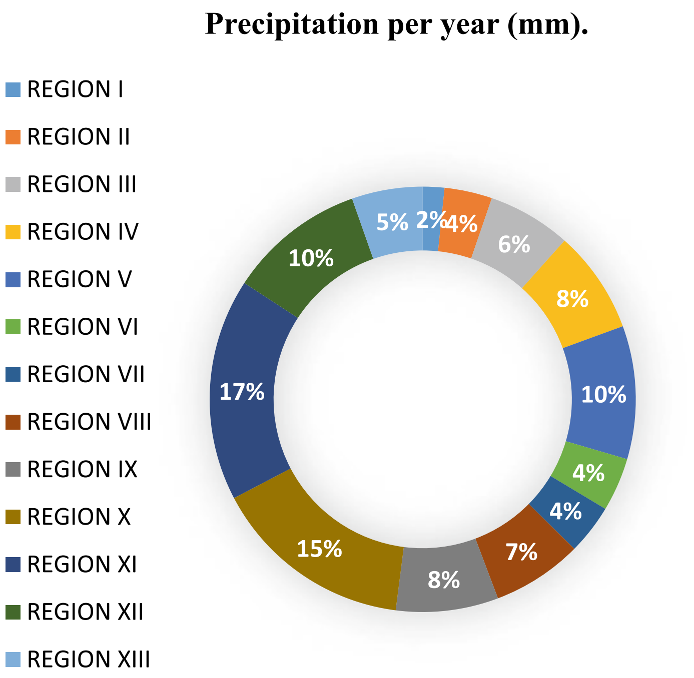


Fig. 4.4 Average precipitation in Mexico (2004–2018) percentage distribution by hydrological region

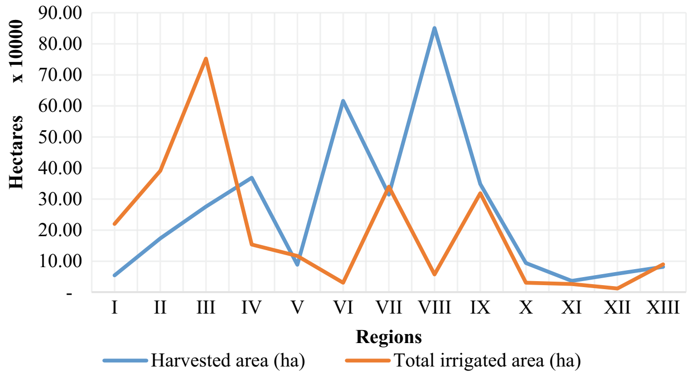


Fig. 4.5 Comparison between harvested and irrigated areas

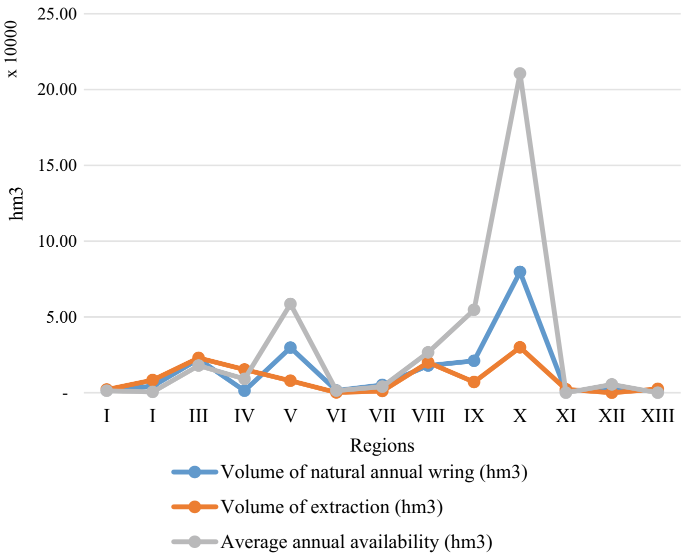
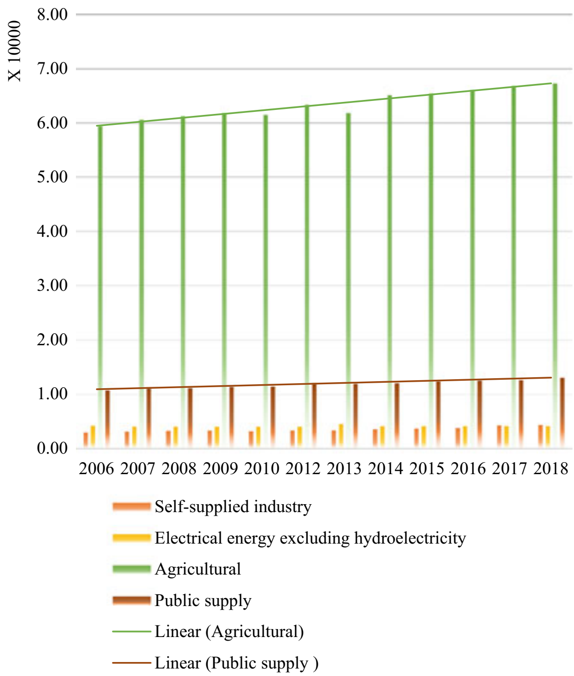


Fig. 4.6 Comparison between extraction volumes, availability, and wring for the rivers and basins of the RHA

Fig. 4.7 Graph of the behavior of water consumption by sector and the trend in extraction volumes



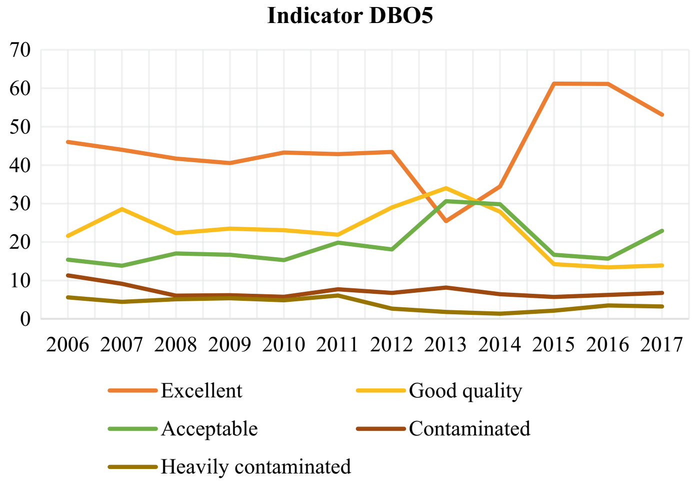


Fig. 4.8 Graph of the behavior of the indicator DB05 in the country's water

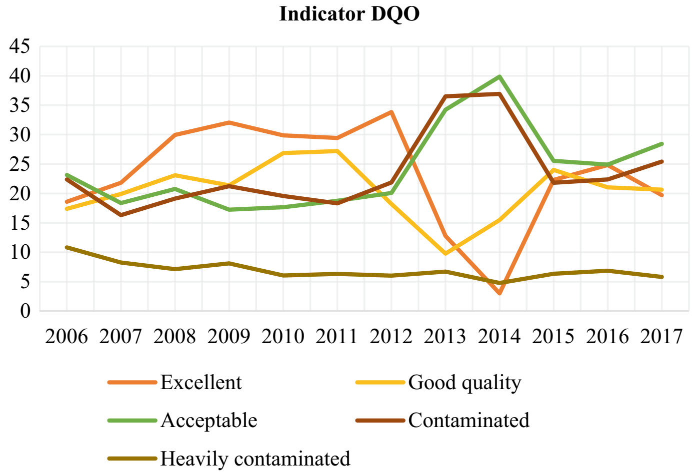


Fig. 4.9 Graph of the behavior of the COD indicator in the country's water

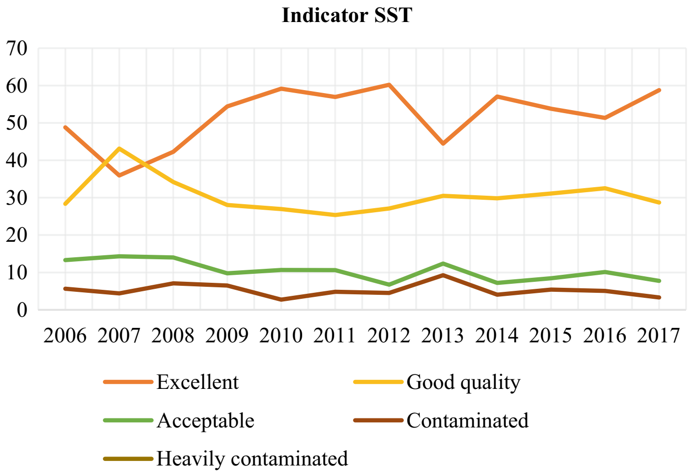


Fig. 4.10 Graph of the behavior of the SST indicator in the country's water

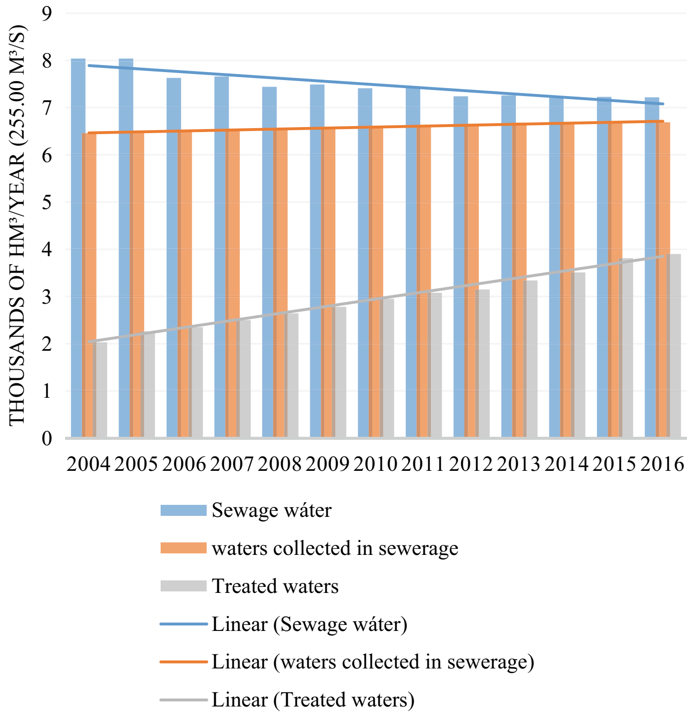


Fig. 4.11 Conditions that impact wastewater discharge

Table 4.16 Average of the variables analyzed for droughts and extreme temperatures

Analysis variable	Average
Duration (months)	5
Affected population	4599
Damaged growing area/grassland (h)	18,721
Total, damages (Millions of pesos)	105
Number of affected municipalities	12

Table 4.17 Average of the variables analyzed for forest fires

Analysis variable	Average
Duration (months)	8
Damaged growing area/grassland (h)	6844
Total, damages (Millions of pesos)	9
Number of affected municipalities	8

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Chapter 5
A Proposal to the Reduction of Carbon Dioxide Emission in Inventory Replenishment: Mitigating the Climate Change

Irma-Delia Rojas-Cuevas, Santiago-Omar Caballero-Morales, Diana Sánchez-Partida, and José-Luis Martínez-Flores

Abstract The climate changes resulting from contaminant emission can be classified as a human-made disaster of type slow-onset. The purpose of this paper is to propose a methodology to mitigate the human-made disaster in the most critical contaminant, Carbon Dioxide (CO_2) emissions. The CO_2 comes from different sources; one of them is vehicles. Vehicles contributed in 2004 with almost 25% of the CO_2 emission. This study proposes a methodology based on a new model to consider the CO_2 emission in calculating economic lot quantity under the continuous revision model (Q, R). In addition, this paper proposes a methodology with a new integrated model to tax the CO_2 emission in inventory planning and proposes the Three-Dimensional Bin Packing Problem. The new model is an extended Q.R. model that uses the metric of CO_2 emission. In the same way, the proposed methodology consists of: first, calculate the shortest path; second calculate the economic lot quantity under the continuous revision model without CO_2, with lowest CO_2, and with maximum CO_2 to obtain a comparative using the new model; and finally obtain the loading in the vehicle improving the space utilization of the bins using fewer vehicles to obtain less CO_2 emission. The new model for taxing CO_2 emission and the proposal of loading must obtain results that permit to decide the best size of economic lot quantity under the continuous revision model. The analysis presented allows choosing the best strategy to stock the inventory under the continuous revision model with CO_2 emission and obtain the best utilization of vehicles to decrease the number of vehicles needed and reduce carbon dioxide emissions to disaster risk reduction in environmental changes.

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Keywords CO_2 emissions · A methodology to obtain less CO_2 emission · Inventory replenishment · Continuous revision · Three-dimensional bin packing problem

5.1 Introduction

According to Van Wassenhove (2006), for humanitarians, logistics refers to the processes and mechanisms involved in mobilizing individuals, resources, expertise, and experience to assist disaster victims. On the other hand, a disaster is a disruption that affects a system threateningly, and it can be natural or human-made. The types of these disasters can be sudden-onset or slow-onset. In disaster management, there are four phases. The phase of mitigation where can be taken actions to lessen the impact. The preparation phase finds to train people to know what to do in case of disaster. Third, the phase of response enables people to act in a disaster. Fourth, the phase of rehabilitation is the phase where the infrastructure is rehabilitated.

The consequences of CO_2 emission can be classified as a human-made disaster of type slow-onset. Therefore, the proposal works in the phase of mitigation in disaster management. The main idea is to reduce the CO_2 emissions in the Supply Management to mitigate the human-made disaster.

According to Pachauri et al. (2014), the emission of CO_2 is one of the most important contributors to climate change, and with this, the increase of risk in people health by exacerbating health problems, extinction of species, the risk in food production among others. For this reason, although Supply Chain considers Distribution Logistics (DL) that performs an efficient distribution and movement of goods, to obtain order processing, warehousing, and transportation, it is necessary also considers the environmental impact.

In this context, order processing and warehousing are focused on inventory management, while transportation involves other task-route planning. Both are involved in CO_2 emissions. The CO_2 emissions are currently a concern because of climate change, and it has been considered in the Supply Chain to obtain models that allow a decrease of these emissions. Zhang et al. (2012) mentioned that Green Logistics (G.L.) had been developed to find global environment maintenance and sustainable development. Logistics processes of materials, waste management, packaging, and transport are considered environmental damage according to McKinnon et al. (2010), Rodrigue et al. (2008).

Kakouei et al. (2012) mentioned that vehicles have an active link to the emission of air pollutants such as CO_2, CO, $NO_{x,}$ and SO_2. For example, the CO_2 emissions from on-road vehicles in Europe contribute 20% to Europe and 10% globally. At the same time, McKinnon et al. (2010) mentioned that in the United Kingdom, commercial vehicles contribute 22% of CO_2 emissions. For this reason, it is crucial to reduce the CO_2 emission, improving transportation planning as is mentioned in Caballero Morales and Martínez-Flores (2017) and inventory replenishment.

Furthermore, proper inventory management usually leads to an increase in transportation pollutants. Companies have a high inventory turnover because it involves a high transportation rate for inventory replenishment, according to Carvalho and Cruz-Machado (2012). Therefore, it is necessary to focus not only on the lower inventory but also on the decrease of pollutants.

The relationship between inventory replenishment and transportation in the context of CO_2 emission needs to be explored to quantitatively assess their economic impact on the Supply Chain (S.C.). Thus, in this work, an integrated model to analyze the economic effect of CO_2 emissions on inventory planning is presented. In this context, the contributions of the present work are the following:

- Integration of the CO_2 emission cost within the Reorder Quantities (Q.R.) inventory replenishment model. The QR model considers a normally distributed demand with significant variability (i.e., the standard deviation of demand/average demand >0.20).
- The CO_2 emission metric is considered customarily distributed based on statistical data.

  Three-dimensional Bin Packing Problem (3D-BPP) is presented to replenish the inventory according to the Q.R. model with CO_2 emission.
- An assessment of uncertain demand for the increase of CO_2 emission and ordering cost is also presented.

The outcomes of this research can be used to explore the assessment of pollution in the economic aspects of S.C.

This work is organized as follows. In Sect. 5.2, a literature review establishes the background necessary for the research. Then, in Sect. 5.3, the Q.R. extended model is presented. In Sect. 5.4 of this study, the assessment is presented to show how the proposed model works. Finally, in Sect. 5.5, the conclusions and future research are presented.

5.2 Literature Review

There are different contaminants in the environment, the most critical being N_2O, CH_4, CO_2, but according to OECD/IEA (2018), CO_2 contributes to 90% of the pollution, and 33% of these emissions come from fuel combustion. Friedlingstein et al. (2010) mentioned that the emission of CO_2 is the main contributor from men to climate change. In the vehicles, 99% of the fuel is transformed into CO_2, according to U.S. Environmental Protection Agency—Office of Transportation and Air Quality (2014).

According to Bigazzi and Bertini (2009), to reduce the CO_2 emission from vehicles, it is necessary to take into account the distance that vehicles travel, steep highway roughness, the characteristics of the vehicles, the driver behavior, the weather, the traffic, average speed models, modal models. In this work, randomly selected routes are considered with the steep highway.

The CO_2 factor has also been considered for inventory replenishment and transportation. In Hovelaque and Bironneau (2015), an EOQ that considers a "carbon tax" for CO_2 emission on holding and ordering cost is presented. While in Li et al. (2017), the EOQ model was adapted to minimize the CO_2 costs in a two-echelon S.C. (retailer and manufacturer). Another work was presented by Wahab et al. (2011), where an EOQ model considering CO_2 emission depending on the distance traveled between vendor and buyer, vehicle type, vehicle age, average speed, and the vehicle weight. It led to the proposal of an integrated fixed-variable cost for the adapted EOQ model.

As presented, the CO_2 emissions are of great importance for the health of the people, and there is research focused on decreasing the CO_2 emissions and developing models to calculate the taxes that the companies will pay for this type of emissions. In addition to this, it is vital to verify that the items can be loaded in the vehicles when there are different package volumes, and to solve this problem, the Three-Dimensional Bin Packing Problem (3D-BPP) is used.

The 3D-BPP is a strongly NP-hard problem. It consists of packing three-dimensional rectangular items without overlapping in the minimum number of bins.

Researchers like Hifi et al. (2010) propose exact algorithms to obtain optimal solutions to solve 3D-BPP. However, also, there are proposals to solve this problem with heuristics algorithms, as Tabu Search used by Lodi et al. (2002), extreme point proposed by Crainic et al. (2008). Gonçalves and Resende (2013) obtain good results using metaheuristics like genetic algorithms. In this work, the proposal of beds beginning on the left-bottom corner and moving on the *y*-*x* axes filling the bed and moving on the *z*-axis to fill the next bed until all the boxes are loaded or until no more space can be used is presented.

5.3 Methods

The methods presented in this section will be used in the methodology. The first method presented is the Carbon Dioxide Emission formula in Caballero Morales and Martínez-Flores (2017) to calculate CO_2 emissions. The second method presented is the extended Q.R. model, where the Carbon Dioxide Emission formula is adapted to the Q.R. model. Finally, the third method presented is the Three-Dimensional Bin Packing Problem; this method is explained in its raw form, and the new proposal is explained.

5.3.1 Carbon Dioxide Emission Formula

The metric of CO_2 emission is based on the work of (Caballero Morales and Martínez-Flores 2017). The metric to use in this work is based on the kgCO_2/km emission factor. The emission metric is presented as follows:

$$E_{CO_2} = X \pm z \cdot S \tag{5.1}$$

$$E_{CO_2} = 183.89 + random(-2.326,\ 2.326) \cdot (51.82) \tag{5.2}$$

According to Caballero Morales and Martínez-Flores (2017), the constant X (183.89) is the average of gCO_2/km generated by the most common on-road vehicles, and the constant S (51.82) is the standard deviation. Therefore, the value of the variable z is 2.326 to model the general practical uncertainty of the emission dynamically.

The distance metric is based on the Earth's spherical model to obtain distances between two geographical locations, as shown in Eq. (5.3). Where the distance between points i and j is denoted by d_{ij}, while r (6374 km) is the radius of the spherical Earth and θ_i and θ_j are the latitudes while φ_i-φ_j are the longitudes of the respective points.

$$d_{ij} = r \cdot Arccos\left[\cos\theta_i \cos\theta_j \cos\left(\varphi_i - \varphi_j\right) + \sin\theta_i \sin\theta_j\right] \tag{5.3}$$

Multiplying (5.2) and (5.3), a customarily distributed emission factor per kilometer is obtained. In this work, this emission factor will include an emission tax (t_{CO2}) to estimate a standard emission cost per gCO_2/km between location k and location l.

$$CE_{kl} = E_{CO2} \cdot d_{kl} \cdot t_{CO2} \cdot C_0 \tag{5.4}$$

The emission factor per kilometer will be used to obtain and minimize the emission of CO_2 to replenishment under uncertain demand.

5.3.2 Extended QR Model

The QR model uses a lot size Q and the reorder level R with a non-deterministic demand, and both are decision variables, and the inventory cycle time is not constant. Q is placed when the inventory level falls below the reorder point R, as mentioned in Hariga (2009).

According to Gel and Keskinocak (2013), C_0 is the setup cost per order while C_h is the holding cost per unit. C is the purchase cost per unit, and p is the stock-out cost per unit. D is the annual demand, and d is the mean daily, weekly, or monthly

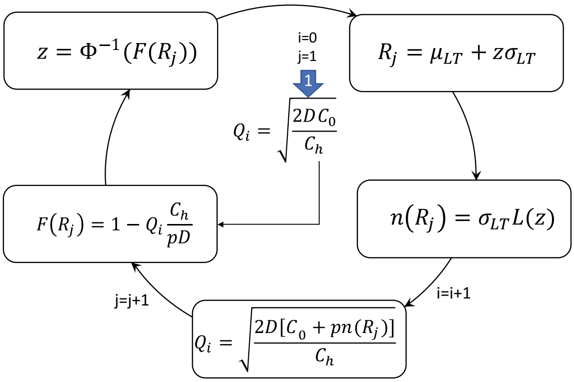

Fig. 5.1 Estimation process for the Q.R. model

demand. *L.T.* is the lead time, μ_{LT} and σ_{LT} are the mean and standard deviation of the demand during the lead time. *L(z)* is the standard loss function, and *n(R)* is the expected shortage per cycle. The formula to calculate the values of Q and R is shown in Fig. 5.1.

Where $(i = 0, 1, \ldots, n - 1)$, $(j = 1, 2, \ldots, n)$, and n is the number of iterations needed to obtain the convergence of R.

In this work, the standard Q.R. model is extended as is shown in Fig. 5.2, where N is the number of locations that the vehicle will travel from the supplier to the retailer and CE_{kl} is the additional CO_2 ordering cost associated with the transportation. The

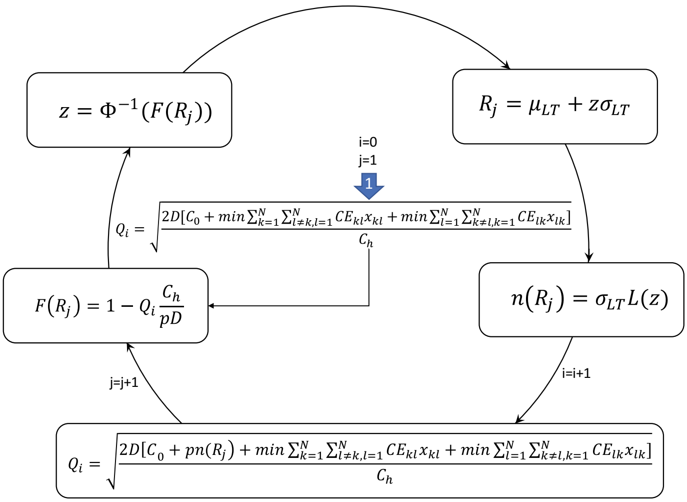

Fig. 5.2 Estimation process for the extended QR model

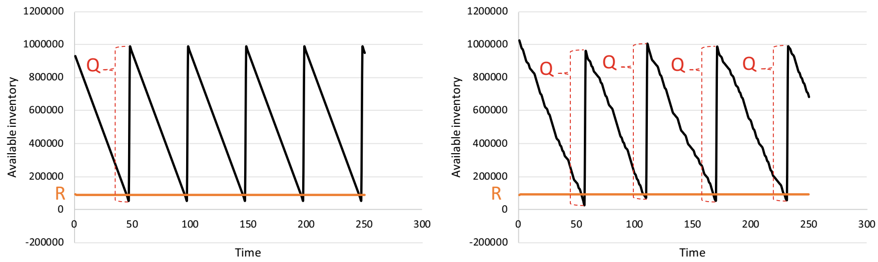

Fig. 5.3 Inventory replenishment patterns under the EOQ and Q.R. strategies

binary variable x_{kl} is equal to 1 if there is an optimal path between the location *i* and *j*, 0 otherwise.

Figure 5.3 illustrates the inventory replenishment patterns under the EOQ and Q.R. strategies with constant and uncertain demand. In the Q.R. results, the weekly demand variability was considered in the range ($\mu \pm 2\sigma$) with a lead time of four weeks. As presented, the EOQ has not varied while the Q.R. has uncertain demand leads to varying inventory cycle times.

5.3.3 Three-Dimensional Bin Packing Problem (3D-BPP)

The 3D-BPP consists of loading a set of three-dimensional items without overlapping in the minimum number of bins. For the solution to this problem, it is assumed that the items cannot be rotated.

The proposal uses the principles of extreme point to place the items. The extreme point is used when an item *k* with sizes w_k, d_k, and h_k is loaded with its left-back-down corner in position (x_k, y_k, z_k). Thus, it generates three new potential points to load new items. The new extreme points in axis x is ($x_k + w_k$, y_k, z_k), in axis *y* is (x_k, $y_k + d_k$, z_k), in axis *z* is (x_k, y_k, $z_k + h_k$). The concept of Extreme points is illustrated in Fig. 5.4.

The algorithm of extreme points consists in:

1. If the container is empty the first item is placed in position (0, 0, 0), obtaining three new potential position for next items, on x-axis (w_k, 0, 0), on y-axis (0, d_k, 0), on z-axis (0, 0, h_k).
2. Then, the item is placed in (x_k, y_k, z_k), and new extreme points are obtained.

    a. In x-axis ($x_k + w_k$, y_k, z_k)
    b. In y-axis (x_k, $y_k + d_k$, z_k)
    c. In z-axis (x_k, y_k, $z_k + h_k$)

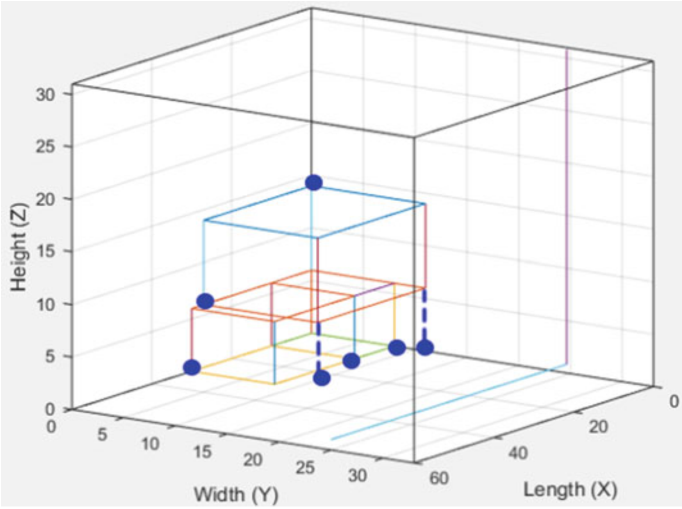

Fig. 5.4 Extreme points

The concept of extreme points is used to obtain the following points to load the next items. Thus, the vehicle loading considers first the *y*-axis, after the *x*-axis, and finally, the *z*-axis permits a load of all the items in one bed (level) before advancing in the *z*-axis. With this load method, the items are tested to be placed in one level before advancing in the *z*-axis to the next level.

The loading proposal is shown in Fig. 5.5. It consists of sorting the boxes in decreasing order of height; the next step is to group the boxes to fill the vehicle's width after the first box is loaded in (0, 0, 0), and the subsequent potential coordinates to place the following boxes are calculated. The next step consists of a loop that continues until all the boxes are placed, or the loop is finished when the variable ok is false.

Ordinarily, the boxes are placed first, considering the *z*-axis. However, few researchers considered the first place the boxes in *x*-*y* or *y*-*x* axes; these researchers are Lacomme et al. (2013); in their paper, they consider four steps. First, they place the items in *x*-*y* axes; after they pull the boxes to the extreme of the container, finally they order the items and place them considering the height of the previously placed boxes. The difference with the proposal is that one algorithm solves all the proposal problems, and always the value of *z* is equal to zero, adapted to the maximum value of height in the coordinates, and the support is considered.

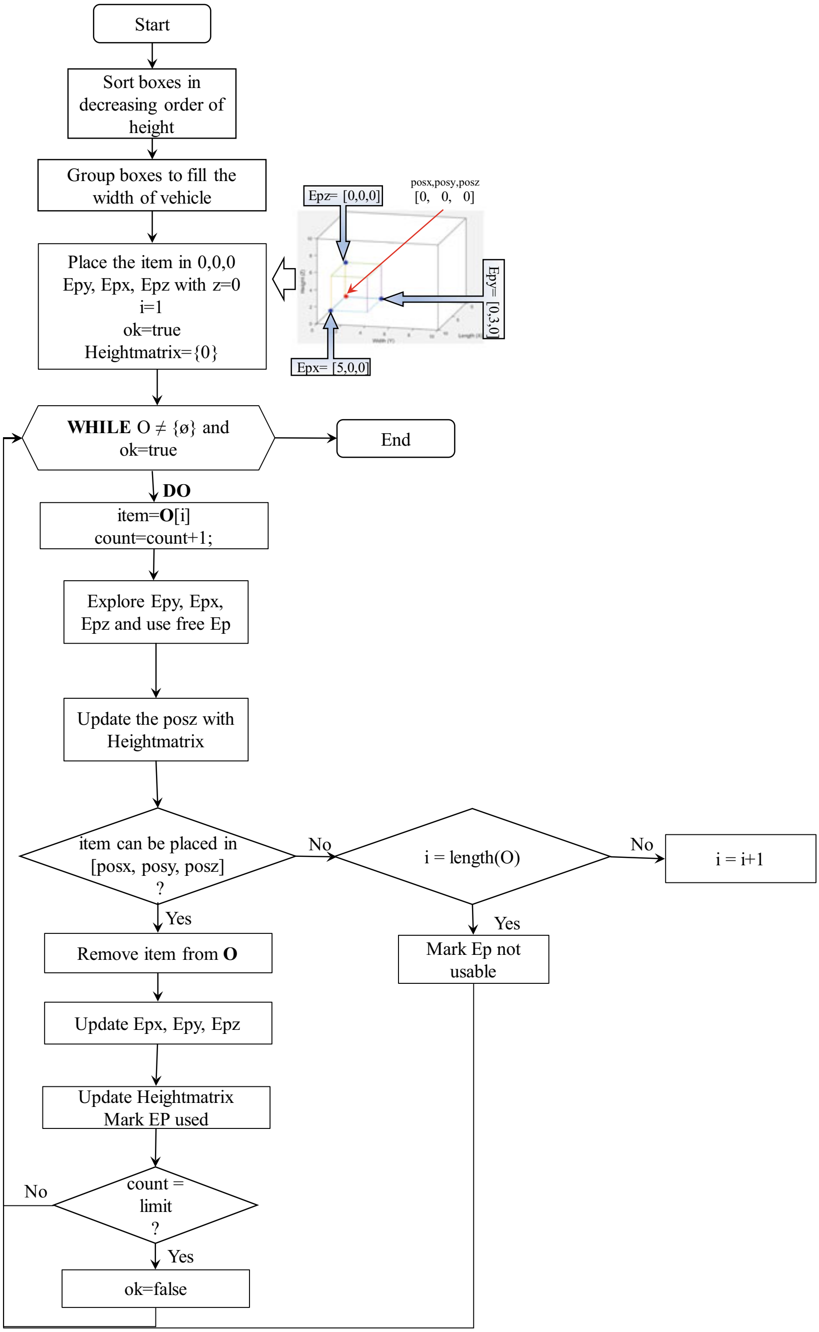

Fig. 5.5 Loading proposal

5.4 Assessment

For the assessment, an instance from the TSPLIB95 adapted to geographical coordinates in work Caballero-Morales et al. (2018) is used. For this work, random slopes were considered in the distances between nodes. Instead of using the TSP algorithm, the Floyd–Warshall algorithm calculates the shortest path between one supplier and one customer. The assessment is solved using MATLAB software.

Two scenarios were considered for the assessment of the Q.R. model:

- Minimum CO_2 emission cost (min CO_2): The Floyd–Warshall algorithm is used with the values of $t_{CO2} = 0.00001$, $C_0 = 0.0187$ per gCO_2/km.
- Maximum CO_2 emission cost (max CO_2): The Floyd–Warshall algorithm is used with the values of $t_{CO2} = 0.00001$, $C_0 = 0.1867$ per gCO_2/km.

For the Q.R. model, the following data from a case study was considered:

LT = 1 month; Planning horizon = 48 months; Total demand = 1,544,771 units; p = 2.5143; unit cost C = 3; the holding cost per unit C_h = 10% of unit cost; order cost C_0 = 1867.3; average monthly demand (μ) = 32,183 units; monthly standard deviation (σ) = 11,236 units. The variable monthly demand was considered within the following ranges: $\mu \pm \sigma$, $\mu \pm 2\sigma$, and $\mu \pm 3\sigma$.

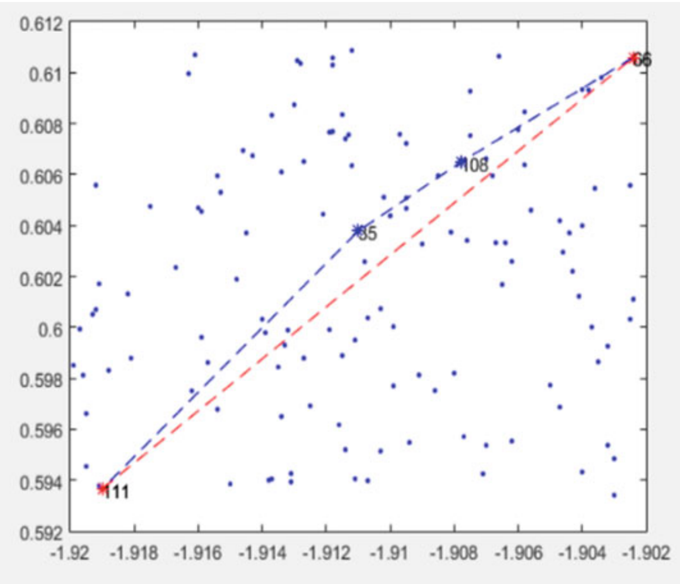

Fig. 5.6 Floyd–Warshall shortest path var CO_2

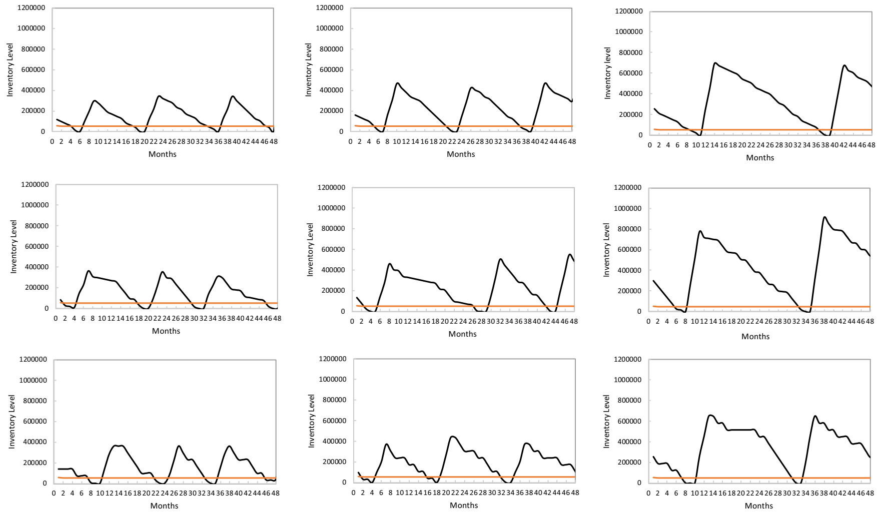

Fig. 5.7 Q.R. inventory replenishment pattern without CO_2, with minimum and maximum CO_2 transportation cost

Figure 5.6 presents the routes obtained with the Floyd–Warshall algorithm using the adapted instance ch130.tsp. Where the supplier is node 66, and the customer is node 111. The route is 66-108-35-111-66 because of the slopes considered. The cost from 66 to 111 was 158.844, while the cost from 111 to 66 was 138.7200. Thus, the total cost was 297.564.

Figure 5.7 presents the inventory replenishment without CO_2 (in the left column) and with minimum CO_2 (in the middle column) and maximum CO_2 (in the right column) transportation cost, considering variable monthly demands in the ranges: $\mu \pm \sigma$ (in the first row), $\mu \pm 2\sigma$ (in the second row), and $\mu \pm 3\sigma$ (in the third row).

Without considering CO_2	Considering min CO_2	Considering max CO_2
Q = 142,492; R = 57,915;	Q = 184,803; R = 56,786;	Q = 396,866; R = 53,209;

As presented in Fig. 5.5, the CO_2 transportation cost affects the reorder point R decreasing it by 2% for min CO_2 and by 8% for max CO_2 emission (57,915 →56,786 →53,209) it also affects Q increasing it by 29.7% for min CO_2 and 178.5% for max CO_2 (142,492 →184,803 →396,866). Regarding the variability of the monthly demand, the number of orders increases throughout the planning horizon of 48 months.

On the other hand, it is essential to consider the vehicle load for the items with the minimum and the maximum CO_2 to obtain the vehicle's best utilization. This assessment's load was based on Gendreau et al. (2006), where the vehicle's loading

Table 5.1 Quantity of boxes to satisfy the demand of the customer with min CO_2 emission

Box capacity	l	w	h	Box quantity	Total capacity
54500	32	6	15	3	163 500
4200	22	11	11	1	4 200
2800	20	13	8	3	8 400
2300	32	8	8	2	4 600
2100	15	14	7	2	4 200
Total					184 900

Table 5.2 Quantity of boxes to satisfy the demand of the customer with max CO_2 emission

Box capacity	l	w	h	Box quantity	Total capacity
54500	32	6	15	7	381 500
2100	15	14	7	4	8 400
1800	13	6	16	4	7 200
Total					397 100

space is defined as W = 25, H = 30, L = 60. Also, the sizes of the boxes were taken from his work. For the customer, the requested items were generated in different sized boxes to obtain the total of 166,604 items in the boxes for min CO_2 and 307,099 for max CO_2, for this, six different sizes were considered, as is shown in Tables 5.1 and 5.2, where the number of boxes for the different capacities were randomly generated between zero and seven.

The boxes' capacity is 184,900, enough to transport the 184 803 items for the min CO_2. The boxes generated are loaded in the vehicle, and the loading distribution is shown in Fig. 5.8.

The boxes' capacity is 397,100, which is enough to transport the 396,866 items for the max CO_2. The boxes generated are loaded in the vehicle, and the loading distribution is shown in Fig. 5.9.

5.5 Conclusions and Future Work

Global warming is increasingly a concern in the countries, which will significantly impact ecologically friendly companies. One of the gases which are produced and impact the atmosphere is CO_2; it is one of the essential factors in climate change, increasing the risk for people's health, extinction of species, and the risk in food production; for this reason, it was considered in the present work.

In this paper, an integrated methodology to analyze the effect of CO_2 emissions on inventory planning was presented. The analysis presented allows choosing the

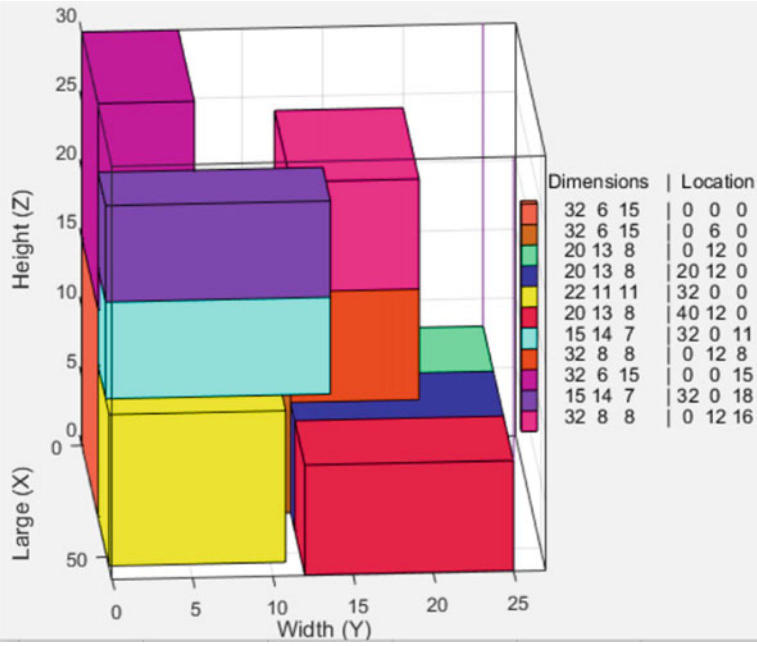

Fig. 5.8 Loading of the boxes in the vehicle for min CO_2 emission

best strategy to stock the inventory under the continuous revision model with CO_2 emission.

In the extended Q.R. model, the CO_2 emission costs in transportation were added to the order cost. Therefore, the total order costs are presented in Fig. 5.8, where there is a significant variation in Q although the low tax imposed on CO_2 emissions and the short distance traveled to satisfy the customer. Considering that if the distance is increased, the cost for CO_2 emission will proportionally increase, it is necessary to obtain proper planning in the route determination to supplying the customers.

Without $CO_{2,}$ the Order Quantity (Q) is 142,492, with the lowest $CO_{2,}$ the Order Quantity is 184,803, and with maximum $CO_{2,}$ the Order Quantity is 396,866. These results show that when the CO_2 increases, the order quantity increase, it is better to have less travel to provide the customers when the CO_2 increases.

On the other hand, it is essential to consider the loading of goods to distribute to know the number of vehicles or tours previously to satisfy customers' demand and obtain the best utilization of the vehicle. The vehicle loading considers first the y-axis, after the *x*-axis, and finally, the *z*-axis permits to load all the items in the vehicles. With this load method, all the items are tested to be placed in one level before advancing in the *z*-axis to the next level.

This kind of research can benefit public policies regarding the establishment of environmental taxes for contaminants emissions.

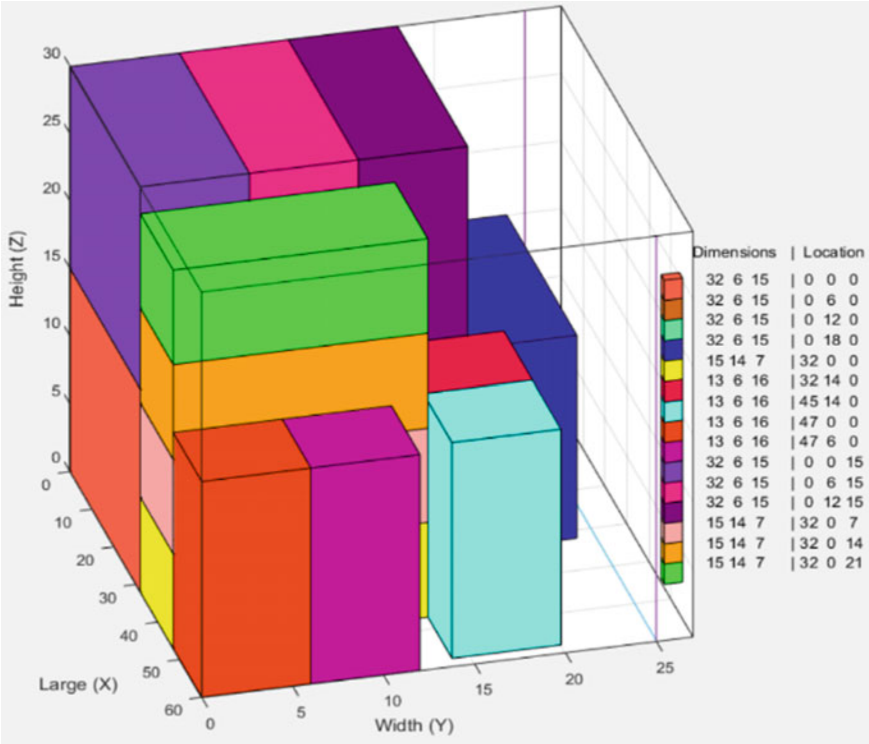

Fig. 5.9 Loading of the boxes in the vehicle for max CO_2 emission

As future work, another probability distribution can be considered to model the uncertain demand and work with 3L CVRP instances in this context.

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Chapter 6
Theoretical Approaches to Risk Reduction in Urban Form

Marisol Ugalde Monzalvo and Claudia Yazmin Ortega-Montoya

Abstract Human beings are dependent on the environment and space. Although this space provides resources, energy, and usability, it also holds a certain risk potential. Risk is understood to be a fundamental aspect of space and dependent on natural and human factors. The investigation of geographic risk explains dangers expressed as a product of the probability, frequency, and amplitude of occurrence of the risk, which can be calculated theoretically for any city in the world. Risk assessment associated with space is used to evaluate disease outbreaks and financial risks, spatially evaluate problems involving environmental risks, spatially predict high-risk contamination, or determine the geographic distribution of perceived risks. The study contributes by identifying the literature on urban form and its relationship with risk reduction. Using different approaches to urban form, the study aims to obtain a reference of the spectrum of risks encountered by cities. Each approach presents multiple risk factors because individuals, communities, and policies interact with spaces in a complex, synergistic, and uncertain manner.

Keywords Risk reduction · Vulnerability · Resilience · Urban form

6.1 Introduction

Human beings are dependent on their environment and space. Although this space is able to provide resources, energy, and usability, it holds a certain risk potential. Conversely, the risk is understood to be a fundamental aspect of space and dependent on natural and human factors. Spatial analysis and risk are two topics that, when taken together, cover important strategic content.

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The convergence between a hazard and a potentially affected system can lead to risk scenarios. Notably, disasters occur when people and assets are exposed to hazards they cannot cope with (UN-Habitat & Disaster Risk Management, Sustainability and Urban Resilience 2020). The characteristics of the hazard (an extreme natural or human disruptive event) and the system that exhibits a certain degree of vulnerability and exposure configure the probability of loss in a specific time and location. Therefore, scholars understand disasters as unsolved problems of development (Lavell 2005).

The evaluation and comparison of this risk with other risks as well as with the usefulness of space, which is fundamentally subject to social factors (how people perceive and evaluate them), depend on culture, and change all the time, along with access to economic and social resources, all of which is unevenly distributed in society, manifests as unequal risk distribution (Haltermann 2011).

Risk assessment associated with space and prospective space–time analysis is used for monitoring several factors, such as disease outbreaks, because it enables the detection of active, emerging clusters and the relative risk for sites affected by epidemics (Kulldorff 2001). Moreover, it identifies financial risks in an insurance context, which renders explicit the influence of regions where policies are underwritten on risks undertaken by companies and the notion of spatial risk measure (Koch 2019). It provides support for policymakers in spatial evaluation problems involving the environmental risks of a spatial nature. Examples include risks that lead to spatial impacts, spatial vulnerabilities, and spatial risk-mitigation alternatives with developments in multicriteria spatial analysis (Ferretti and Montibeller 2019). Furthermore, spatial risk assessment predicts high-risk contamination from Escherichia coli in household drinking water (Khan and Bakar 2020). In terms of geographic distribution, it can be used to determine the perceived risks of meteorological events and trends and the alignment of subjective perceptions with exposure to actual weather risks (Allan et al. 2020). Lastly, it can provide insights into the subjective perception of risk during urban cycling (von Stülpnagel and Krukar 2018).

Typically, the most vulnerable people are the ones that experience the most significant loss in terms of goods and services when a hazard materializes during a disruptive event. Disasters exhibit human, social, and institutional vulnerabilities and reveal development issues (e.g., poverty, inequality, social exclusion, or income distribution). At the same time, social and institutional capacities to respond to such events determine the outcomes of such circumstances: an emergency when a situation can be managed by local authorities or a disaster when the required response exceeds national capacities and necessitates international aid.

The spatial connotations of the concept of sustainability refer to the structural causes, modalities, and impacts of the possible internalization of environmental valuations and values in a system (i.e., the ecological space) that is assumed closed (Paulsen 2005).

6.2 Risk and Resilience

Sustainability strategies related to Sustainable Development Goals, especially Goal 11 (Making cities and human settlements inclusive, safe, resilient, and sustainable) can reduce vulnerability. In this manner, urban resilience is increased by establishing appropriate measures to promote equity in social and economic development, planning strategies, and strengthening institutional capacities to identify, prevent, and monitor hazards and promote attention to and recovery from disruptive events.

Spatial analysis can play a significant role in enabling dynamic and timely decision-making and understanding of the phases of disaster relief, that is, preparation and prevention, immediate response, and reconstruction (Chiappetta Jabbour et al. 2019). The interlinkages between risks, urban planning and priorities, and the perceptions and decisions of individuals can contribute to humanitarian logistics and supply chain management. Therefore, this study aims to analyze spatial risk by investigating urban form.

Inhabited spaces display qualities that make them vulnerable to certain types of risks and more or less suitable to obtain adequate responses for long-, medium-, or short-term situations. Despite its significant impacts on the growth and evolution of cities, research remains limited on the influence of urban form on resilience by increasing the cities' abilities to plan for, absorb, recover from, and adapt to adverse events (Sharifi 2019). Urban land planning shapes urban form and could be considered an effective approach for risk mitigation and adaptation. However, little knowledge exists on which aspects of urban form can reduce risks, what type of risks exist, and their relationship and trade-offs with humanitarian logistics.

Social sustainability is the ability of a social system to indefinitely maintain an adequate level of social wellbeing (Comstock 2020). Even without a universal consensus (Vallance et al. 2011; Woodcraft 2012), this concept is related to attributes connected to physical and perceived wellbeing in a community. According to Barrado-Timon (2020), the first group of attributes includes equity, social justice, fairness in resource distribution, health, education, and housing conditions. The second is related to perceived wellbeing given social capital, involvement, community participation and stability, pride and sense of place, interactions within the community and social networks, interconnectedness, diversity, experience, and collective identity.

Scholars define human vulnerability as the characteristics of a population group that influences their capacity to perceive, cope with, resist (Wisner 2006), and recover from the impact of a hazard that can be modified by programs, plans, and projects to address urban social problems. The first group of attributes, which are related to equity in a community, accompanies the physical vulnerabilities of society. The vulnerability has two sides: an external side composed of risks, shocks, and stress to which an individual or household is subjected, and an internal side defenseless or lacks the means to cope without damaging loss (Chambers 1989).

Evaluating urban risk is complex and multi-scaled because a combination of multiple variables influences it. Sources of risk can be environmental, socioeconomic, physical, and political and are often regarded as external influences on cities and inhabitants (Chambers 1989). They may also be internal, such as land-use change, which holds the potential for negative, unintended consequences (Füssel 2007).

In this context, territorial organization, appropriation, and occupation of land in urban areas notably occur in accordance with differential access to the land market, which, in turn, constitutes a sign of social segregation (Herzer Hilda and Gurevich 1996). Disruptive events are linked to social vulnerability when poverty exposes segregated groups to dangers, whereas disruptive events accentuate social vulnerability due to the loss of property and housing. In addition, poverty and the lack of economic resources influence the capacity of such groups to recover from the disruptive event and to return to the base stage before its occurrence.

The second group of social sustainability attributes can contribute to addressing a cohesive society that can participate and build a resilient community. Considering how disasters reverberate in a marginalized society (i.e., women, children, older adults, people with disabilities, and excluded groups; UN-Habitat 2007), resilience capacity requires building an adaptable social infrastructure. In this manner, meaningful participation and the achievement of equity can be ensured in the face of socioeconomic change and disturbance. Furthermore, meaningful participation by stakeholders in planning and policy decisions can be observed (Ahern 2011). Moreover, the soft attributes of social wellbeing are important in terms of education and hazard perception given the intentional hazard exposition of vulnerable populations that pursue economic benefits in oil spills and theft of hydrocarbon pipelines.

The study conducts an analysis of the literature on humanitarian logistics and supply chain management. The results point to the following classification of types of disaster: (a) man-made with slow onset, (b) man-made with sudden onset, (c) natural with slow onset, and (d) natural with sudden onset. Furthermore, the phases of disaster relief are (a) preparation and prevention, (b) immediate response, and (c) reconstructing (Chiappetta Jabbour et al. 2019).

Spatial information enables a holistic view of urban planning, design, and numerous individual decisions that shape how cities organize and arrange space according to various spatial–social logics and cultures (Boeing 2021).

Evaluating urban risk is complex and multi-scaled because it is dependent on multiple variables. Sources of risk can be environmental, socioeconomic, physical, and political, which are frequently regarded as external influences on cities and inhabitants (Chambers 1989). Moreover, they may be internal, such as land-use change, which holds the potential for negative, unintended consequences (Füssel 2007).

Risk can be presented as a function of two variables (Maskrey 1989):

$$\text{Risk} = \text{Hazard} \times \text{Vulnerability}$$

Economic risk assessment defines risk as follows (Blong 1994):

$$\text{Risk} = \text{Hazard} \times \text{Vulnerability} \times \text{Value}$$

Hazard, as a natural or anthropogenic phenomenon, is an extrinsic factor of the risk equation and is capable of causing damage to a vulnerable system within a particular time and space. Hazards are classified as man-made or natural (origin) and sudden or slow onset (development) (Chiappetta Jabbour et al. 2019).

Social vulnerability is a factor that prevents the community from coping with threats and inhibits recovery to its initial state once it occurs. In this manner, programs, plans, and projects to address urban social problems can modify human vulnerability.

The term vulnerability refers to two aspects (Chambers 1989) as follows:

- an external side of risks, shocks, and stress to which an individual or household is subject (physical vulnerability).
- an internal side that is defenseless or lacks the means to cope without incurring loss (social or human vulnerability).

Cardona (1996) refers to vulnerability as a deficit in development and a negative environmental account that requires efforts toward direct preventive management from the perspective of planning to reduce or avoid social, economic, and environmental consequences.

Disruptive events become associated with social vulnerability when poverty exposes segregated groups to dangers and disruptive events accentuate social vulnerability due to the loss of property and housing. Poverty and the lack of economic resources also influence the capacity of such groups to recover and return to the base stage before the occurrence of the disrupted event. Spatial information enables the identification of the urban determinants of hazard, as shown in Table 6.1.

Previous studies employed the indicators of: human and social vulnerability assessment to analyze environmental justice, such as the sensitivity of the population (Hassani et al. 2020), population density (Török et al. 2020), gender, age, disability, literacy (Tahmid et al. 2020), socioeconomic status (Chakraborty et al. 2020), social fragmentation, dependency structure (Khazai et al. 2013), coping capacities (Ardalan et al. 2019; Rajeev et al. 2019), residential life and health, urban economy and wealth, urban resource availability, and urban ecosystem diversity (Ye et al. 2021).

6.3 Urban Form and Planning

The term *urban form* is used to describe a city's physical and non-physical aspects/characteristics, such as size, shape, and configuration of an urban area or its parts. It pertains to how a city is understood, structured, or analyzed according to scale. Its characteristics range from, at a very localized scale, features, such as building materials, facades, and fenestration, to a broader scale, housing type, street type, and spatial arrangement or layout (Živković 2020).

Urban form is defined as the spatial structure of a city that organizes, orders and accumulates resources, matter, energy, and information in a timely manner. It is the result of human self-organization processes that follow diverse logic. This structure is described qualitatively, quantitatively, or spatially in different scales, and in many

Table 6.1 Types of hazard and spatially related influential factors

Hazard	Spatial influential factors	Source
Flood	Elevation, slope, flow accumulation, land use, soil types, and distance from the river, distance from the channel, curve number, precipitation, geology, soil drainage, and retarding basin	Hossain and Meng (2020)
		Darabi et al. (2021)
		Lee et al. (2018b)
		Darabi et al. (2021)
		Rahmati et al. (2020)
Land side	Standardized height, slope, terrain surface, slope aspect, distance to fault, distance to streams, distance to roads, precipitation, land use, geology, slope angle, slope roughness, peak ground acceleration (PGA), distance to the epicenter, normalized difference vegetation index (NDVI), land use and land cover, mean annual precipitation, soil drainage, soil depth, terrain curvature, and topographic relief	Lee et al. (2018a)
		Mokhtari et al. (2020)
		Mahalingam and Kim (2021)
		Lee et al. (2020)
		Wang et al. (2020)
Volcanic	Pyroclastic flows	Alberico and Petrosino (2015)
Seismic	Stratification degree and typological alteration degree	D'Amico and Morganti (2019)
Coastal	Wave exposure, wind exposure, surge potential, relief, geomorphology, habitats, and rates of changes in sea level	Ballesteros and Esteves (2021)
Chemical	Industries' location, type and storage volume, pipelines, and meteorological conditions	Pontiggia et al. (2010)
		Sebos et al. (2010)
		Tahmid et al. (2020)
		Ortega Montoya et al. (2014)
Climate change	Urban scale microclimate, climate-vulnerable fields and system, environmental radiation, and urban heat islands	Ye et al. (2021)
		Huang et al. (2021)
		Zhu et al. (2021)
Hazmat collision risk	Street-level road network with road lengths and travel times, impact radius by hazmat type, estimated miles or kilometers for vehicles carrying hazmat, truck accident (collision/crash) rates by road type, probability of release given a truck accident (collision/crash), and truck speeding by road type	Ak et al. (2020)

(continued)

Table 6.1 (continued)

Hazard	Spatial influential factors	Source
Health risk	Concentration at $PM_{2.5}$, concentration and composition of PAHs, source apportionment, potentially toxic concentration, hotspots of diseases, proximity to industries, water availability, proximity to open canals and streams, water storage at the dwelling, vegetated/non-vegetated surfaces, vehicular and train emissions, proximity to cemeteries, dumps, and open landfills, proximity to dumps and landfills, source of water used for human consumption, and percentage of households without a sewer connection	Adimalla et al. (2020)
		Ishtiaq et al. (2021)
		Dzul-Manzanilla et al. (2021)
		Morandeira et al. (2019)

instances through isolated one-dimensional measurements. However, this visualization limits the understanding of the complexity of urban form and reduces the possibilities of integrating strategies to solve diverse problems. The combination of factors in constructing urban form indicators may indicate the development of strategies to achieve co-benefits, albeit with different goals. According to UN-Habitat, one-third of the world's population inhabits one of approximately 2,000 metropolitan areas. At the same time, 60% of the world's urban population are concentrated in metropolises with more than 300,000 inhabitants. UN-Habitat (2020) estimates that the majority of the world's population will become urban by 2035. This insight places cities as the main scenario of challenges and opportunities related to sustainability.

Simultaneously, the pace of growth in cities, especially in developing countries, is notable mainly in peri-urban areas due to socio-economical dynamics, where migration and haphazard patterns of urbanization play a significant role (Simon 2008). Problems related to the rapid and unplanned urbanization of cities increase the probability of new settlements to be exposed to environmental hazards due to the lack of development planning.

In this context, urban initiatives toward sustainable development can contribute to modifying variables related to risk scenarios. According to the UN, a sustainable city can retain the supply of natural resources and simultaneously achieve economic, physical, and social progress and remain safe against environmental risks, undermining any achievement in development (Hassan and Lee 2015).

Cities are the world's platform for production, innovation, and trade, which generate substantial economic values that may transform the productive potential of residents into wellbeing. Economic growth may be beneficial to the society's resilience if it remains inclusive and configured as a tool that provides financial support for safe city initiatives to strengthen risk management and land-use regulation. Economic development and its association with physical wellbeing generate the material basis for social development. Economic growth generates new formal employment and ensures social benefits, such as access to housing and medical services. Thus, the ability of cities to absorb new inhabitants is related to their ability to provide education and training and maintain production capacities to sustain economic growth.

Economic growth should be planned to avoid exposing the urban population to anthropogenic risks or the results of poorly managed development. This scenario erodes ecosystem services and increases the population's vulnerability due to exposure to risks resulting from poorly executed urban settlements.

In addition, economic growth can foster institutional coping capacities in pre-emergency monitoring and hazard control as well as in land-use planning and emergency response capabilities. For example, smart cities use data collected through sensors to automate a range of services that improve performance and reduce costs and harmful environmental impacts (Ullah et al. 2021).

At the same time, environmental sustainability principles related to the conservation and protection of ecosystem services in urban scenarios should guide economic development. To address societal risk challenges, nature-based solutions should encompass diverse ecosystem-based approaches, such as (1) ecosystem-based disaster risk reduction, sustainable management, conservation, and restoration and (2) well-managed ecosystems as natural infrastructure, reduction of physical exposure to hazards, and increased socioeconomic resilience of people and communities (Partnership for Environment and Disaster Risk Reduction [PEDRR] 2021). Nature can also be an inspiration for diversity when applied to urban biophysical systems with low-impact development practices, such as permeable pavement and bioswales and the management of urban tree canopies to intercept rainfall (Ahern 2011).

Ecosystem conservation and natural resource management are key elements for the sustainability of economic processes and the material wellbeing of society. In the same manner, environmental education, life cycle analysis, and circular economy can be key elements for the transformation of current patterns of consumption into more sustainable ones. Therefore, a shift in cultural paradigm is required to evolve from the actual compulsion to acquire and consume physical capital to non-material forms of self-fulfillment and social relationships as personal and social capital (Rees 2003).

Song et al. (2017) describe the evolution of urban morphology and spatial analysis methods over time. These concepts can be traced back to Aristotle's density and division of labor. Specifically, density leads to a method for understanding and measuring towns and villages. Another important concept is rent theory, which is based on a single-core city dependent on economy and employment. However, in terms of multi-core cities, an urban agglomeration, and megalopolis, density becomes an inadequate measure for understanding cities and their details and complexity. A series of spatial analysis indexes, such as compactness, diversity, and permeability, including density, are integrated to measure the urban system jointly.

The most consolidated approaches to the study of urban morphology are those of the Anglo-Saxon countries since the 1960s. Notable approaches were proposed by the Urban Morphology Group, which urban geographer M.R.G. Conzen founded. In Germany, approaches continue a long-term tradition of morphogenetic studies. The visions of G. Cullen or K. Lynch in the United States are also considered. In southern Europe, lines of analysis of urban fabrics are developed, derived from Italian schools, such as the morphotypological studies of S. Muratori and his followers G. Caniggia and G. Cataldi, or architects and historians, such as L. Quaroni and A. Rossi. French and Spanish schools feature P. Panerai/D. Mangin and M. Solá-Morales, respectively.

Modern urban morphology, by investigating urban spatial structures' formation and change processes, combines urban infrastructure, road systems, public facilities, residential areas, urban functions, and social relationships related to the urban construction environment. It focuses on developing economic, cultural, and technological issues as an inheritance bestowed by urban form to the urban development, reconstruction, planning, and organization of the future. This concept is increasingly similar to that of sustainable development (Song et al. 2017).

The majority of research on the urban form has been constrained by disciplinary boundaries, with few attempts to undertake a multidisciplinary review. These perspectives can be classified into five categories: (a) landscape for ecology oriented toward environmental protection, (b) economic structure for economic efficiency, (c) transportation planning oriented toward accessibility, (d) community design oriented toward urban social welfare, and (e) urban design oriented to esthetics and walkability (Clifton et al. 2008).

From these various approaches for analysis and study, urban form has been described and evaluated as functional (with clear zoning and rationalized locations of the four collective functions), efficient (capable of responding to the needs of institutions, companies and inhabitants with minimum resources), sustainable (balanced in terms of economic, social, and environmental aspects), complex (composed of connected, interdependent, diverse, and adaptive elements), suitable (changing through planned interventions), vulnerable (with more or less capacities diminished), readable (understandable) and resilient (ability to overcome adverse situations and repair and respond to all types of obstacles). Based on these descriptions, the current study proposes an assessment of the shape of risky cities. Figure 6.1 presents the relationship among these concepts.

Tables 6.2a and 6.2b present a review of the 36 indicators of urban form and its related concepts, methods, and studies. Blue boxes represent the origins of these indicators, whereas yellow boxes indicate their areas of application. The main references for urban form are transportation, economics, sociology, urban planning, security, and geography of perception and spatial information (geometric and geographic information systems).

Mapping potentially exposed urban areas using the spatial influential factors in Table 6.1 facilitated the preparation stage of humanitarian supply chains related to assessing the vulnerability of key infrastructure. In addition, this analysis enabled the study to assess potentially safe locations for logistic bases, supply distribution centers, and fuel distribution points, which are considered crucial assessing risk reduction.

The indicators that configure urban form, as described in Tables 6.2a and 6.2b, are related to the spatial factors of humanitarian supply chains and the configuration

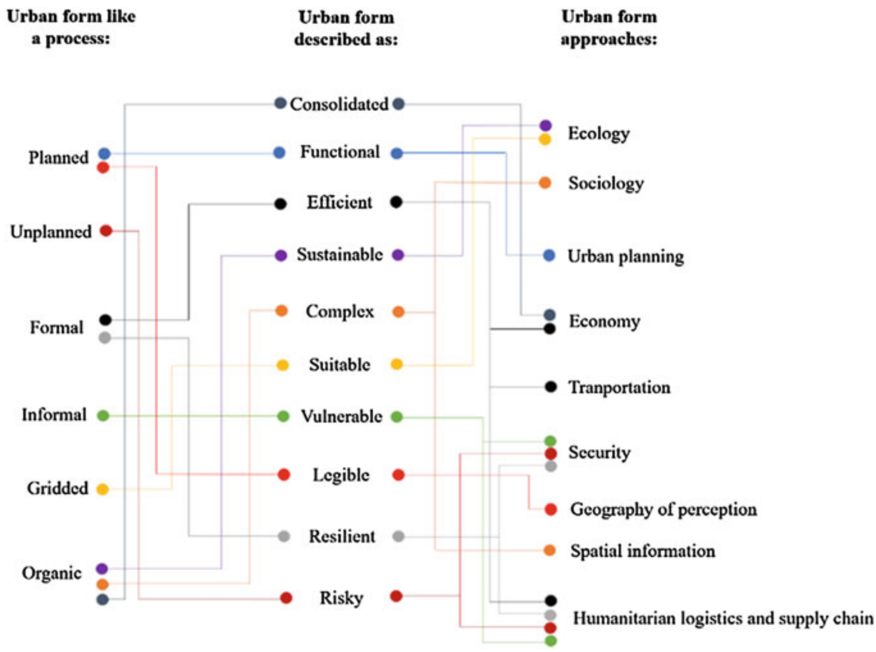

Fig. 6.1 Process, descriptions, and approaches of urban form

of urban risk scenarios. Table 6.3 describes the relationship between urban form risk and humanitarian supply chains.

6.4 Urban Renovation for Risk Reduction

The material and energy resources used and introduced into the constructed or built environment have a useful life similar to other products. Reuse, renovation, rehabilitation, and recycling are concepts of sustainable, ecological, or environmental aspects applied to various products for responsible consumption. The following text defines each term.

- Reduce: Refraining from the unnecessary consumption of matter or energy
- Reuse: Extending the useful life of products
- Recycle: Using the materials of a utilized product to create new ones or reincorporating them into the life cycle.

Renovation, revitalization, rehabilitation, reintegration, remodeling, recovery, and restoration are concepts related to the reuse and recycling of built systems. This notion is that the energy or material investment in all products is considered to adapt to the

Table 6.2a Description of indicators of urban form

	Indicators of urban form	Definitions	Methods and related studies	a) Transportation	b) Economy	c) Sociology	d) urban planning	e) Security (public health)	f) Geography of perception	g) Spatial Information	h) Ecology
1	Accesibility	A measure of the effort (or ease) of overcoming spatial separation.	1. Gravity model 2. Floating catchment area (FCA) method								
2	Spatial adjacency	Neighboring relations in space	1. Voronoi diagrams 2. Euclidean-distance nearest-object Voronoi diagrams 3. Spatial neighboring relations (contagion, aggregation, edge density, and probability of adjacency indices)								
3	Agglomeratio n economies	Spatial clustering allows for a variety of external benefts such as labor pooling, sharing of suppliers, and specialization									
4	Building typology	The expansion of an area will become the focus for the construction of public facilities that will create regional imbalances and disparities that lead to inequality.	1. Williamson's Index approached method to quantify the building imbalance 2. Klassen's tipology 3. Shift-share analysis 4. location coefficient								
5	Centrality	The degree to wich observations of a given urban land use area locater close to the center of a urban area, is a measure best suited to mononuclear urban areas.(Galster et al., 2006).	1. Polycentricity 2. Centrality index 3. Space syntax techniques								
6	Continuity	Continuity is the degree to which developable land has been built upon at urban densities in an unbroken fashion and it may occur at any level of density. The density dimension does not tell us anything about how residential uses are distributed (Galster et al., 2006)	1. A one-half-mile-square grid is considered developed if it contains 10 or more housing units or 50 or more employees. The proportion of all such grids in the UA that are so developed is a mea- sure of continuity								
7	Concentration	Concentration is the degree to which development is located disproportionately in relatively few square miles of the total UA rather than spread evenly throughout (Galster et al., 2006).	1. Very high density grids (with respect to housing units or employees) as a percentage of all grids with developable land. 2. The coefficient of variation (standard deviation divided by the mean) of the density of housing units or employees among the grids. 3. Delta index. This is analogous to the dissimilarity index and can be interpreted as the share of land use i (e.g., housing units) that would need to shift areal units of scale m to achieve a uniform distribution across the UA								
8	Compactness	Urban physical compactness expresses the proximity of the components that make up the city, urban uses and functions in a limited space.Urban functional compactness is usually measured directly based on the degree of land use mixing or indirectly based on economic indicators. (Lan et al., 2021)	1. Gibbs Compactness (Gibbs, 1961) 2. Cole Compactness (Cole, 1964) 3. Richardson Compactness (Richardson, 1973) 4. Compactness index of Bertaud and Malpezzi (1999) 5. Compactness Index (Thinh et al., 2002)								
9	Connectivity	Street connectivity is defined as the measure of direct and alternative routes available from one point within a street network to another (Gul et al., 2020).	1. Number of intersections per unit area 2. T- and 4-way intersections as a percentage 3. Average block area or median block area 4. The count of entrance and exit links street network 5. Centerline in GIS and Space Syntax (Axial maps/lines) 6. Space Syntax method								
10	Clustering	The degree to which high-desnsity subareas are clustered or randomly distributed.									
11	Density	Density is the average number of residential units per square mile of developable land, it is usually expressed simply, as the ratio of the total population of a metropolitan area to its total land area (Galster et al., 2006)	1. Total number of housing units (or employees) in a UA/area of a UA.								
12	Distances pertinent to travel by vehicles	Travel distances for mode types	1)simulation-base 2)data-driven methods								
13	Employment density around railway stations.	Number of jobs accessible via the railway services	1) Graphical comparisons and the metropolitan structure 2) Statistical regression modelling								
14	Entropy	Is a measure of the quality of heat energy in relation to temperature, and a characterization of irreversibility (Fistola, 2010). In a city, entropy categorize an area in terms of the concentration and / or dispersion patterns of the elements that characterize it, with the idea that the greater the disorder of said elements, the greater the urban entropy.	1. Entropy maximizing method 2. Fractacl geometry 3. Shannon's index entropy 4. Shape index								
15	Journey Equity	Disparity in distance/time traveled by income profile	Transit circuity of a journey: ratio between the network distance traveled and the Euclidean distance between the origin and destination of the journey.								
16	Floor area ratio	Total floor area of a building divided by the plot size	1. Locally Weighted Regression (LWR) 2) Ordinary least squares (OLS)								
17	Fractal dimension	Urban patterns and processes are analysed using fractal geometry	1)Logistic function 2) Generalized Boltzmann's funtion								
18	Inner-city connectedness	Distance to inner city									
19	Intersection density	Number of intersections (junctions at which three or more road segments intersect) per square kilometer at a local scale	1) configurational analysis; 2)perceptive analysis 3) tissue analysis								

system to extend its useful life or meet new needs, which reduces risks and enhances the process. In the case of cities, renovation is based on the following contexts:

1. The possibility of improving the system's characteristics using the same resources: a city can be transformed into efficient, sustainable, and complex. The study proposes an assessment of the shape of risky cities to improve less risky cities.

Table 6.2b Description of indicators of urban form

Indicators of urban form	Definitions	Methods and related studies	a) Transportation	b) Economy	c) Sociology	d) urban planning	e) Security (public health)	f) Geography of perception	g) Spatial Information	h) Ecology
20 Land use	Land use is the human use of terrestrial space for economic, residential, recreational, conservation, and government purposes. The concept of land use is closely linked to the development of the human community and their patterns have shaped the local and global environment (Camara et al., 2019).	1. Digital land use data 2. Land use changes in the process of urbanization 3. Land use mixture 4. Spatial functions 5. Fitness		yellow		dark, yellow				yellow
21 Legibility	Urban legibility is the ease with which people understand the layout of a place (Lynch, 1997).	1. Urban legibility elements 2. Legibility and aesthetics in urban design 3. Big data in urban morphology 4. Space syntax			yellow	yellow	yellow	dark, yellow		
22 Man-made infrastructure and major traffic arteries,	Major vehicular travel routes that connect between cities within a metropolitan area	1. Hierarchy of roads	dark, yellow							
23 Mixed uses	Mixed uses means the degree to which two different land uses com- monly exist within the same small area (Galster et al., 2006).									
24 Monocentric theory of urban form	Explains that cities are shaped by urban rent gradients that peak in the city center and fall exponentially to the urban edge, where urban rents equal agricultural rents. (Clifton et al., 2008).			dark, yellow		yellow		yellow		
25 Urban growth	Urban growth has a double meaning; on one hand, it signifies the constant rise of urban population (urbanization) and, on the other hand, the expansion of urban lifestyle and infrastructure within the settlement system (Peponi & Morgado, 2020).	1. Spatial patterns of urban growth 2. Morphologic change of urban pattern 3. Urban growth patterns 4. Smart growth		yellow		dark, yellow				yellow
26 Network measures:	Ratio of intersections to cul-de-sacs, the percent of road networks that are gridded or the ratio of linear distance-to-network distance.	Indicators that describes the geometric structure of the street network	yellow	yellow		yellow			dark	
27 Permeability	Permeability refers to the ease that a person has to move through an environment, the ease with which a person traverses an area through some mode of transport. (Zúñiga et al., 2017).	1. Pedestrian flows circulation 2. Degree of urban permeability 3. Permeability and connectivity of urban neighbourhoods	yellow		yellow			dark, yellow		
28 Proximity	Proximity is the degree to which different land uses are close to each other, is the dimension that establishes the typical distance between different uses (Galster et al., 2006)					dark, yellow				
29 Spatial intensity	The relationship between the occupied lots with construction within a block and the total of lots included in it (Clifton et al., 2008).	1. Urban Intensity Index 2. Occupation metric measures 3. Sustainable intensification	yellow			dark, yellow	yellow			
30 Segregation	The combination of social and geographic disparities for different sectors of the population that are manifested in unequal housing, infrastructure, services, environmental conditions, and risks (Nel·lo & Gomà, 2018)	1. Vulnerability 2. Gentrification 3. Spatial equity			dark, yellow	yellow				
31 Sprawl and conurbation	Integration of urban spaces to form a single system, that comes form geographic proximity as essential factor for both internal and international integration of neighborhood cities or towns and also countries (Carneiro et al., 2021).	1. Urban extent 2. Remote sensign datsets 3. Mapping intra-urban structures 4. Land surface temperature	yellow			yellow		yellow		dark, yellow
32 TAZ-gravity model of security, of risk.	Estimate the flow of goods or persons between two zones based on two factors: distance and attractiveness.	Multiple gravity model forms exist, the choice of model depends on the purpose for its use, as well as the data available for model fitting.	dark, yellow							
33 Transportation Analysis Zones	Special area for tabulating traffic-related data.	1)Hierarchical groups of mutually exclusive subsets 2)Hierarchical heuristic procedure 3)Cluster techniques on census data within GIS	dark, yellow							
34 Urban fabric	Physical urban environment and to its psychological, socio-cultural, ecological, managerial and economic structures.	1. morphometric indicators (density measures, floor Space, ground Space, open Space and building height. 2. Fractals. 3. Cartographic generalization research. 4. Space syntax research							dark, yellow	
35 Urban structure	Analyses the spatial distribution of resources, elements and socioeconomic activities.	1)single-center and multi-center distribution 2) concentration and diffusion				dark, yellow			dark, yellow	
36 Walkability	Walkability is a set of capacities of any given neighbourhood that is embodied in urban morphologies in three main ways: the densities of buildings and people; the mix of different functions and the access networks we use to navigate between them (Dovey & Pafka, 2020).	1. Measures of density, mix and access 2. Assemblage studies 3. Urban vitality	yellow			dark, yellow				

2. Less risky cities are livable cities when their existing urban heritage is preserved, regenerating and improving equipment through the optimal use of natural, human, and productive resources of each territory (Geng et al. 2019).
3. Renovation is a process that helps prevent the deconfiguration of the territory and assigns a rational use to the land resource that it occupies with more urban settlements, which were previously agrarian systems and natural resources of the productive and livelihood system. Each square meter of soil subtracted from support systems (agriculture) should be provided with the highest added value and contain the maximum information incorporated in terms of uses, functions, technology, or security. This process ensures the optimization of land use if the built infrastructure is taken advantage of.

Table 6.3 Usage of urban form categories in risk and humanitarian supply chain scenarios

Category of urban form indicators	Use	
	Risk scenarios	Humanitarian supply chains
Transport	Collision risk	Time/cost efficiency in supply chain logistic
Economy	Depopulation, market collapse, and property abandonment	Location of food and supplies
Sociology	Resilience as a social capital	Available local capacity and resources
Urban planning	Segregation: concentration of hazards and urban settlements	Location of critical infrastructure
Security (public health)	Epidemic outbreak	Supply chain (vaccination)
Geography of perception	Risk perception	Social and cultural customs
Spatial Information	Network resilience	Supply distribution
Ecology	Ecosystem risk reduction strategies	Identification of destruction of food stocks

Urban renovation refers to the renovation of the building, equipment, and infrastructures of the city, which is necessary to prevent its aging or adapt to new uses and activities. Urban renovation can be used on other types of urban processes, such as rehabilitation and redevelopment:

- Redevelopment: the demolition, rearrangement, and reconstruction of an area;
- Reintegration: parts of the urban fabric that are disconnected from the rest of the city (i.e., marginal areas or areas with irregular growth);
- Urban remodeling: improvement of buildings, squares, gardens, and streets in general, by changing their physical appearance to enhance urban image; and
- Regularization: properties located in sectors that require improvement, and introduction works of public services.

The first urban renewal operations occurred in the early industrial cities of the 19th century, and rehabilitation works were applied in many middle western cities. The sanitation of working-class neighborhoods, in which the demolition of walls plays a decisive role in medieval cities, the opening of communication axes, and the construction of extensions that permeate complex medieval plots (Guerrero 2012).

In developed countries, urban regeneration policies are popular to address problems related to urban development without regard for environmental conditions or the deterioration of the quality of life in cities. Operations related to urban renewal are mainly aimed at rehabilitating neighborhoods, investing in private and public capital, and land revaluation. In this regard, urban renewal becomes a part of development.

The evolution of urban renewal can be identified in five phases, namely, a reconstruction based on master plans in the 1950s, growth, and revitalization of suburbs and peripheral regions in the 1960s, on-site renovation and neighborhood schemes in the 1970s, redevelopment schemes of the 1980s, and the management of policies and integrative treatments of the 1990s. Along this timeline, leadership was transformed from the local to the national level, whereas policies have become more comprehensive (Roberts 2016).

Large-scale interventions necessarily imply the involvement of the public administration. Therefore, maintaining a home in good condition is only profitable if the rest of the buildings maintain a satisfactory level of maintenance. Incremental urban intervention is a strategy for renewal in steps based on the following reasons: (a) limited availability of financial resources, (b) limited time to conduct in-depth analysis, (c) unpredictable situations, (d) lack of control of the behavior of variables, (e) models that do not imply complex transformations of the current productive industry (uses common materials in the construction process), (f) changing resources or risk conditions, and (g) changing objectives. Interventions are applicable on different scales, such as individual housing, small or large groups of houses, small communities, residential settlements, districts, or complete cities.

An advantage of incremental renewal is that it is a response based on the possibilities of each situation; that is, prior to its implementation, other possibilities can be explored to obtain the best form of intervention. The analysis and review of cities through subsystems determine the convenience of conducting general analyses and presenting particular proposals. The implantation process of new urbanized spaces is necessarily slow to fit and interrelate the various components that compose cities and increase their complexity. In parts of cities or urban centers that were built slowly and without interruption and major disturbances, consolidating and renovating their supporting structures increases the diversity of its components. Consequently, organized information increases, providing stability and opportunities in contrast to an excessive increase of new structures that led to a sustained waste of land, energy, and time and increased resource consumption. As such, mature systems tend to preserve numerous testimonies from the past in the same place. Therefore, that incremental design increases the organization of the city system.

The difference between *renewal* and *sustainable renewal* is that renewal is characterized by the addition of material or energy information to a built system to preserve or recover the services provided by the environment to its inhabitants. In other words, only a *maintenance* investment is made. Alternatively, sustainable renewal aims to increase the ability of the environment to reduce the energy consumption of its inhabitants in the long term.

Another concept is sustainable renovation, which adds information to the system to improve it and maintain it. In this manner, rebuilt cities, rehabilitated buildings, and revitalized neighborhoods could ensure the sustainability of this renovation. Toward this end, support should be provided through technical solutions considering social trends, integration into existing policies, effects on the environment, and economic development.

For McHarg (1998), the concept of a “good city” coincides with Henderson’s description in his book entitled *The Fitness of the Environment*. The author affirms that a suitable environment can be defined as one in which the greatest consumer needs are satisfied by the same environment, which indicates that the body is burdened with less adaptive work.

Based on this analogy, the concept of aptitude is considered and from which the study concludes the following:

1. Fitness is a measure of the ability of a system to meet the needs of its population;
2. Fitness is dependent on the characteristics of the environment and needs of the inhabitants;
3. If these characteristics or needs change, then the suitability of the environment accordingly changes, which may increase if its features are improved or decrease if the demands increase;
4. Economy is defined as "resources that are scarce and needs that are unlimited." Therefore, the study affirms that, given the current trends in growth, the aptitude of a built system cannot increase indefinitely. In other words, development has its limitations;
5. On the contrary, the inability of the system to meet the needs of inhabitants can grow indefinitely if the favorable characteristics of the system increase the demands, that is, the ineptitude of the system can tend to infinity;
6. If no renewal of the system occurs, then the condition of ineptitude will grow; and
7. Each system has a fitness range with upper and lower limits that tend to infinity.

Renewal is adding materials or energy capital to a system to maintain its operation. In terms of renovation for risk reduction, the capital (material or energy) added should improve the aptitude or capacity of the system (environment) to meet the needs of its inhabitants and render the system more efficient.

The final concept, that is, the fitness of a system, should then be equal to its initial fitness less the degraded energy and material plus the added material and energy through renewal. If the investment for renovation is less than the final aptitude of the system, then such a renovation can be considered sustainable.

Therefore, the sustainability renewal of urban areas can play a substantial role in improving the resilience of cities. Such renewal can be oriented toward reducing physical vulnerabilities, such as the addition of new construction codes after an earthquake. In addition, it can be oriented to adjust the indicators of urban form sustainability to improve social cohesion, perceived factors of wellbeing related to social resilience, and low levels of social vulnerabilities. Considering that risk configuration evolves in space and time, urban renewal can include new land-use segregation initiatives to protect urban settlements.

6.5 Conclusions and Future Research

1. This study focuses on the relationship between urban form and risks. Thus, the themes refer to balancing systems that were previously created and promote their transformation using the concept of the *intentional control* of urban variables related to the aspects of security. This process is accompanied by actions outside the system, which are referred to as *urban risk reduction.*

2. Although the urban system satisfies basic needs (i.e., protection of the environment), the qualities necessary to solve this need differ for each city. Thus, the study infers to buildings and cities according to the different levels of security.
3. The definition of the current situation, objectives, strategies, and monitoring require measurement tools that should be integrated into the different existing social, environmental, economic, and political aspects. These tools are referred to as indices and indicators of urban risk.
4. The system of urban risk indicators, such as the spatial components of hazards, urban density, number of homes per hectare, compactness, diversity of land use, percentage of basic services, percentage of rented dwellings, economic accessibility of dwellings, useful square meters per inhabitant, foliar mass per inhabitants, transport and accessibility, management waste, social cohesion, and economic development is related to the different environmental, social, economic, and political aspects and are useful for describing relationships, monitoring progress, and establishing lines of action.
5. The challenge to urban risk reduction is that scenarios may change quickly, whereas others, such as specific building conditions, may progressively change. Notably, natural conditions remain the same. To redesign cities, social, economic, and environmental objectives should be considered as well as structure-specific characteristics to identify achievable objectives.
6. The neighborhood should be taken as the unit of analysis, given that it shares the physical, social, and urban form used for the construction of a natural air conditioning model. An advantage of the neighborhood-scale analysis is that it enables the generalization of situations and establishes lines of action that can lead to a generalization or a regulation of conditions.
7. A city can be conceived as a material for rehabilitation and recovery and is occupied with the process of entropic degradation of matter and energy, such that emphasis should be placed on construction energy instead of maintenance energy. A city's objectives should include the rehabilitation of built and degraded structures, recovery of urban spaces, such as material structures, and recycling or reuse of abandoned spaces to recover their informative content.
8. Renovation, revitalization, rehabilitation, reintegration, remodeling, recovery, and restoration are concepts related to the reuse and recycling of built systems. These concepts consider energy or material investments to extend the useful life of structures or adapt them to meet new needs. Orienting interest to the interior of cities indicates movement from the logic of urbanization to a centripetal centrifuge. Moreover, it highlights urban renewal as part of urban development. Thus, renovation initiatives can be oriented to reduce physical and social vulnerability, promote urban resilience, and reduce risks and land-use segregation programs.

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Chapter 7
Allocation Model Applied to Preventive Evacuation for Volcanic Risk in Localities Near the Popocatepetl Volcano in Puebla, Mexico

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Abstract The management of volcanic crises is one of the biggest problems that volcanology currently faces. In natural phenomena such as earthquakes the reaction occurs after the impact, while in hurricanes or floods, the reaction occurs during the impact or a few hours in advance. In the case of volcanic crises, the pre-alert phase can last for a long time, and the total evacuation of the population is the only response to this type of event. In general terms, volcanic hazards can lead to the destruction of the infrastructures that are in their path, and it is necessary to proceed to the preventive evacuation of the population from the probably affected areas to save lives. Furthermore, observable activities usually precede volcanic eruptions, the most obvious being increased seismicity, gas emissions, rising magma, or changes in the conditions of the magmatic chambers. Therefore, it can be stated that volcanology is a natural phenomenon that can be predicted, which allows the design of prevention and mitigation plans. This project presents an allocation model whose objective is to transfer evacuees from the different localities of the State of Puebla near the Popocatepetl volcano to established temporary shelters to give the solution to setbacks typical of an evacuation considering the geographical location.

Keywords Volcanic crises · Preventive evacuation · Prediction · Volcanic risk

7.1 Introduction

Volcanic crisis management began in the early eighties, a period in which new tools were improved and developed to facilitate this work. Many of the problems that occur during a volcanic crisis are well identified, especially those that refer to the role played by scientists, authorities, and the media (Tomblin 1982). The guidelines and strategies

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adopted by any population to reduce and mitigate their exposure and vulnerability to a natural phenomenon must be considered to manage natural phenomena. In this sense, the International Decade for Natural Disaster Mitigation (UNPLDGDR 2016) promotes understanding how a natural phenomenon turns into a disaster.

The crisis phase starts when the volcanic system shows a high probability of an eruption occurring. Thus, it is necessary to give an efficient response that considerably reduces the final impact of this natural phenomenon.

It should be borne in mind that current knowledge of the forecast of eruptions forces us to consider a high probability when we reach values between 1 and 10% (Woo 2008). Suppose the hazard or probability of occurrence is expressed as fractions between 0 and 1. In that case, the risk can be quantified as a quantity between 0 and 100%. It represents the proportion or probability of loss or damage of life, property, or productivity in a volcanic area due to the effect of an eruptive manifestation. Considering the volcanic risk as to the probability of loss due to the possible occurrence of an eruption, the problem of risk reduction or mitigation arises. Although the danger is a characteristic of the phenomenon that cannot be modified, vulnerability can be considerably reduced through preparedness, which consists of an organized response by society aimed at carrying out a series of coordinated and precise measures that reduce the exposure and fragility of the assets threatened by these manifestations.

The classification of natural disasters is used as an action carried out solely and exclusively by nature, where the population receives a strong impact from a natural phenomenon that has exceeded a scale of intensity. The analysis of the latest volcanic crises has shown that there is not a direct relationship between the disaster and the magnitude of the phenomenon (De la Cruz-Reyna and Tilling 2008).

The biggest disasters have occurred with eruptions of moderate or small magnitude with a Volcanic Explosivity Index (Newhall and Self 1982) between 2 and 3, confirming that, regardless of the intensity of the natural phenomenon, it is crisis management that will lead to reduce this impact or cause a catastrophe. Table 7.1 shows the different volcanic explosiveness indices that may occur, as well as their particularities. It is fundamental and crucial for managing natural phenomena that can cause severe damage to exposed populations. However, for it to be implemented, the population and the authorities must be aware of the dangers derived from the natural environment in which they live, especially if the return periods are long enough to erase from the collective memory the events that occurred in the past (Coburn et al. 1991).

Like any natural phenomenon under study, surveillance must always be done from a multidisciplinary perspective, adapted to the knowledge we have of the volcano. Unfortunately, at present, the alert references based on seismic activity are the most advanced; the other surveillance techniques are still in development or depend on the volcano is in a very advanced state of activity (Scarpa and Tilling 1996; Spark 2003).

The design of Emergency Plans must be based on knowledge of the volcanic system and, above all, on the damage that it can cause to the population (UNDRO and UNESCO 1985).

Table 7.1 Volcanic explosivity index (VEI)

VEI	0	1	2	3	4	5	6	7	8
Description	Not explosive	Lower	Moderate	Moderate/large	High	Outsize	–	–	–
Volume issued (Km^3)	<10,000	10,000–1,000,000	1 a 10 Millions	10–100 Millions	100–1,000 Millions	1–10 (Km^3)	10–100 (Km^3)	100–1000 (Km^3)	+de 1000 (Km^3)
Column height (Km)	0.1	0.1–1	1–5	3–15	10–25	+25	–	–	–
Duration (h)	<1	<1	1–6	1–6	1–12	6–12	+12	–	–
Troposphere injection	Minimum	Lower	Moderate	Substantial	High	–	–	–	–
Injection into the stratosphere	Null	Null	Null	Possible	Defined	Significant	High	–	–

A crisis phase is understood to be one in which the management of the volcanic phenomenon is addressed immediately, given the possibility of an eruption occurring in a short period, updating all the previously designed mechanisms. Therefore, when the surveillance network detects any variation in the data it usually receives, the first thing to do is check if there are any defects in the instruments. Once satisfied that the works instrumental correctly is passed to a new situation where it is speculated a possible change in the volcanic system, in most cases, indicating the start of a crisis phase, though not necessarily mean an eruption immediate (Ortiz 1996).

Once the Danger Scenarios have been obtained and from the update of the socio-economic databases and the cartography of the affected area, the Risk Scenarios, fundamental for the Civil Protection Emergency Plans, can be carried out (Bonifaz et al. 1995; Lirer and Vitelli 1998; Felpeto et al. 2007). These scenarios can approximate the number of people affected, damaged infrastructure, among others, and, therefore, of the necessary means that would have to be mobilized when activating the Emergency Plan.

The overall objective of this project is to define, identify, and plan the distribution of people who will be moved from nearby localities to the volcano to the various temporary shelters. This by interacting within an allocation model connecting origins and destinations using routes, whose trajectory will be carried out at a minimum cost, in this case, time. This quantitative technique allows the generation of optimal solutions to contribute to the anticipation of volcanic risk that endangers the general population, such as part of the mitigation and preparation stages of humanitarian logistics.

7.2 Literature Review

Tools are currently being developed to help manage an emergency, especially for fires, hurricanes, and floods, applicable at very detailed scales, a fire in a building, or a small town (Fahy 1994; Malone et al. 2001). For example, evacuation simulators are a helpful tool to calculate, among other aspects, the necessary times, and the most suitable routes to carry out the evacuation. However, like the rest of the simulators, they should be considered aid and not the problem's solution (Liu and Tuttle 2008).

Activation of the Emergency Plan is a fundamental decision because when the actions affect many people, the complexity of management and decision-making must be done with low probability values (Woo 2008) increases. Moreover, it is at this time when the education and information of the population acquire particular importance.

On the other hand, there is talk of preventive evacuation because it is still difficult to establish a clear forecast for the time of the eruption. Even with all the indicators showing a high probability of eruption, there have already been numerous cases in which the process stops and remains stable for years (SMEC International Pty Ltd. 1999). Therefore, it is always advisable to carry out an evacuation despite everything, even if the eruption does not ultimately occur. For this reason, it is classified as preventive (Barberi et al. 1984).

Keeping the population evacuated is difficult, especially when the prognosis fails or is prolonged over time. There are a loss of credibility of scientists, politicization, and spending increases notably. Despite everything, it is the only viable option today if lives are to be saved (Cardona 1997).

Current scientific knowledge does not allow to guarantee the success of the forecast, with the anticipation required to carry out the evacuation that allows saving all the inhabitants, so the decision to evacuate is made when the probability of an eruption of only 10% is estimated (Marzocchi and Woo 2007; Woo 2008). Preventive evacuations are carried out within a time window mainly given by the time necessary for Civil Protection to evacuate the area.

The behavior of the population in emergencies depends on many factors, and panic is the most prominent. The population's experience of the phenomenon presents positive aspects, but, in many cases, it can become counterproductive when the phenomenon has a recurrent nature with a medium intensity level since they do not conceive events of greater magnitude. Therefore, specific education about the phenomenon and its consequences must make up for the lack of experience in some cases or correct the routine in others (Llinares et al. 2004).

Carrying out exercises and drills is the only possibility it must evaluate the qualities of an Emergency Plan for a phenomenon with very high return periods; otherwise, there is no opportunity to test it and correct errors before its application in an actual situation. To this must be added that the human environment and the available means change continuously, implying having to readjust and modify the Emergency Plan constantly. In the case of volcanic risk, this situation is even more pronounced due to the need to coordinate a broad multidisciplinary team in which the participation of the group of experts that make up the Scientific Advisory Committee is essential. As an example of an exercise of this type, we can take the MESIMEX, carried out around the Vesuvius volcano to evaluate the Emergency Plan (DPC 1995), Naples (Italy), in October 2006 (Marzocchi et al. 2008) and the one carried out in 2009 in the Chichón volcano, Mexico with the same goal.

Until now, there are computer applications for the modeling of eruptions that include very elementary models. These applications are implemented at the moment for a quick definition of the impact of a possible eruption (Felpeto 2002, 2007), up to very elaborate models that require supercomputers and that they are applied to the study of the physics of the eruptive phenomenon (Ongaro et al. 2008; Macedonio et al. 2008). Currently, they are working on programs that establish forecasts (Tárraga 2007) and integration of susceptibility and event tree with the monitoring system (Marzocchi et al. 2008).

Although it is a subject that has been studied since 1970, it is from the 90s when an increase in the development of evacuation models is observed, mainly the reduction of computer costs and the increase in calculation capacity, which allows the elaboration of more complex models. The number of specific models for hurricanes stands out (Mei 2002), the production that has been increasing after the Katrina disaster and recently, for evacuating limited spaces due to terrorist attacks (Kwan and Lee 2005).

Another consideration of the evacuation model is that many of them specialize in treating specific aspects of the evacuation process, such as managing crossings, optimizing the transport network, among others (Cova and Johnson 2003). Likewise, we do not consider the models that require supercomputers since, with difficulty, they can be used in a situation of a volcanic crisis unless the volcano is close to a highly developed area to have direct access to these means.

In hurricanes, evacuations occur a maximum of 24 h before arrival and tend to be less organized; people use their means of transportation to carry it out the final decision to evacuate is not always followed by everyone (Barrett et al. 2000). On the other hand, in the case of volcanoes, evacuations are planned, when possible, well in advance, among other things, because it is not always easy to determine the exact moment in which the eruption will occur, and a comprehensive security window must be left (Woo 2008). In addition, evacuations are usually directed and organized, mainly because the affected population often does not perceive the danger and/or lacks the resources to evacuate independently.

Both phenomena, hurricanes, and volcanic eruptions, damage the transport network. Therefore, it is essential to carry out evacuations before impact (Barrett et al. 2000). The only difference is that hurricanes tend to affect a larger area, while the central impact zone of volcanoes, except in the case of significant eruptions, is more delimited. Nevertheless, this aspect is not usually treated in hurricane models, focusing more on managing intersections and adding lanes to the possibility that some transport routes remain out of service. In general, they assume that evacuation takes place before impact and not while it occurs.

For the development of many evacuation models due to hurricanes, or other natural or anthropic phenomena, data from surveys are used, especially those related to the behavior of evacuees. These data, in combination, are used to calculate approximately the reaction times and preparation gave the alert, the possibility that decides to stay or not, and the destinations. In general, they help determine the behavior of evacuees and, therefore, the decisions made during the evacuation process (Post 1999; Mei 2002).

Also, Sime (1999) stresses the importance of content and how alert messages are transmitted, and how they can condition people's reactions when making decisions. This same author distinguishes between three types of models representing the relationship between how the alert is given and the response of the social group to which it is addressed: in the first, psychological aspects of social issues prevail when it comes to an understanding the alert and executing a response; in the second is the external physical agents, the threats, which condition the alerts and responses, and finally, the third is a mixture of the previous two.

In Frieser (2004), a study of mass evacuations is done by flooding in the Netherlands, introducing distribution functions for study behavior of the population, from the time when a flood forecasting is obtained. He also considers the opportunity to evacuate based on the cost-benefit of the operation.

The time that passes from the time the evacuation order or recommendation is officially given until the evacuee sets off is known as mobilization time. One of the main differences between evacuations carried out for hurricanes in the area south of the United States and carried out in volcanic zone is that hurricanes in that area, self-evacuations occur, while for volcanoes they are usually directed evacuations where the population is placed in the hands of the authorities (Valdés-González et al. 2001).

It should be noted that, as a consequence of the management problems revealed by Hurricane Katrina in the southern United States, this self-evacuation model is currently being reviewed (Margulis 2006). In this sense, an evacuation with a very just-in-time forecast will likely require external assistance in transportation to ensure its effectiveness and avoid blocking the communication routes (Margulis 2006).

This aspect refers to the time required to completely evacuate a particular area, counting from the moment the evacuation order is given. Most evacuation models calculate this value (Mei 2002).

The models based on the demand for trips number of trips generated in space and time have incorporated possible destinations from the safe area. For example, many models have been carried out for hurricanes in the southern part of the United States and can even consider the capacity of hotels or motels located near freeways. Furthermore, with the incorporation of the data obtained in surveys carried out from the 80s, it has been possible to evaluate factors related to the behavior and decision-making of the affected people, key aspects to determine the number of trips that can be generated (Mei 2002). This aspect refers to the time required to completely evacuate a particular area, counting from the moment the evacuation order is given. Most evacuation models calculate this value (Mei 2002).

A volcanic crisis is that the pre-eruptive period can last several days, even years, as happened in the Rabaul eruption in Papua New Guinea (Aysan and Davis 1993). If the eruption occurs, there is a possibility that the area will be destroyed, with which the possibilities of return are very complicated, for many years. It is also likely that homes can be used for short periods, but not for long periods, as is the case with temporary shelters (Baxter et al. 2008).

Another issue that seems to be decisive in self-evaluation processes is the driver's behavior concerning route choice. Generally, drivers routinely go to the exact location, but they do not always use the same route, instead choosing secondary roads depending on traffic conditions (Barrett et al. 2000). It should be noted that, in many models, only the main communication routes are used, an aspect that significantly simplifies the calculation algorithm to simulate the traffic flow.

Many of the models developed to try to recreate traffic conditions as faithfully as possible, especially those that work on large scales with great detail, highlighting the management of intersections or junctions as one of the main elements (Cova and Johnson 2003). Understanding and modeling the traffic flow in these hot spots is vital to be able to establish adequate time calculations for an evacuation, regardless of whether they are controlled and directed or not.

As indicated, volcanic activity, unlike other natural phenomena of great intensity, has a previous phase that can last for tens of years before erupting, although the final phase of acceleration of activity before impact can be reduced to less than 48 h (Ortiz et al. 2003).

The disaster that occurred due to the Nevado del Ruiz eruption, Colombia, 1985 (Voight 1990) revealed the disconnect between the warnings issued by Civil Protection and how the population interpreted this information. For six months before, the volcano had been subjected to intense surveillance and study by the National Institute of Geology and Mining of Colombia (INGEOMINAS), supported by international experts, and hazard maps had been drawn up. On the day of the eruption, two warnings were issued (at 4:00 p.m. and 7:00 p.m.), with enough notice so that the population of Armero could evacuate the town, which was destroyed at 11:00 p.m., causing the death of more than 20,000 people. As a result of this event, the United Nations declared the International Decade for the Mitigation of Natural Disasters, 1990–2000 (resolution 44–236, 1989), whose objective was to study the mechanism by which a natural phenomenon becomes a disaster, changing the mentality with which crises caused by natural phenomena are analyzed and managed. This change is especially relevant for volcanic risk, one of its most studied aspects being the behavior of the population and the perception of risk; however, in many countries with active volcanic zones, this analysis has not yet been carried out.

The results of the work of Barberi et al. (2008), Gaillard (2008), Paton et al. (2008), and Perry and Lindell (2007), all of which refer to areas of recent volcanic activity, reflect that a significant part of the population is aware of the danger to which they are exposed. However, the measures it takes to protect itself and mitigate risk are not directly related to the degree of sustainability, regardless of the training campaigns that have been carried out. Furthermore, the factors that explain this behavior vary significantly from one community to another, depending on their socio-economic, historical, educational, and political characteristics, making a model that has been developed for one specific area challenging to apply to another. On the other hand, there is usually little contact between the exposed communities and the agencies responsible for monitoring and preparing Emergency Plans (Berrocal 2008), resulting in a lack of interest and distrust in others, ultimately reducing the population's preparedness.

A method is used based on considering a series of concentric rings to the volcano to assess the volcano's impact on the population. This method allows to quickly know the level of threat to which it is subjected without requiring a profound knowledge of the volcano, and, therefore, it is widely used. In our case, it has been applied to three volcanoes, the Teide, the Chichón, and the Popocatepetl, to maintain a comparative framework between them. Although the dynamics and eruptive history of each volcano is different, the three of them have high dangerousness values, as it is evident in the different published works (Macías et al. 1995, 2005; De la Cruz-Reyna et al. 2001, 2009; Martí et al. 2008a, b, c; Martí and Geyer 2008) and in the USGS file (Ewert et al. 2005) that has been used.

For the application of this method, the Popocatepetl volcano has been chosen, following the procedure described in Vidal et al. (1995), which establishes a radius of 80 km and, using a Geographic Information System, crosses with the populations existing at the time to determine the number of people expected. Subsequently, Delgado et al. (2008), comment on the distribution of the population based on a series of concentric rings whose distances to the emission centre4 are 10, 20, 30, 40, 80, and 100 km, rings that we have crossed with the population centers using the same technique as in Vidal et al. (1995).

7.3 Problem Description

With an elevation of 5,419.43 m above sea level, the Popocatepetl volcano is the third highest in Mexico. It is a stratovolcano of composition andesitic-dacitic located in the central part of the Volcanic Belt Transmexicano with coordinates 19°01′23″ N and 98°37′22″ W. It has a crater with elliptic geometry dimensions of 800 × 600 m and 307 m depth (only 90 m depth relative to the Northeast border, the lower altitude) (CENAPRED 2019). It constitutes the southern end of the Sierra Nevada, bordering to the North with the volcanic complex Iztaccihuatl through the Step of Cortez (3,685 m above sea level), with a gap in this sector 1,734 m. On its slopes, East and Southeast, surrounded by the valleys of Puebla and Atlixco, presents a more significant elevation, with a relative height of 3,300–3,800 m and an average slope of 34°. To the West and Southwest, the slopes of Popocatepetl rest on a terrain of more intricate relief, with a morphology of mounds (hummocks) product of the giant landslides (avalanches) of the volcano (Siebe et al. 1995).

Eighteen municipalities have territory on the slopes of the volcano and the surrounding plains, all of them vulnerable, to a greater or lesser degree, to the different dangers that emanate from the current and possible future activity of the volcano. Several of these municipalities have towns and communities located within 15 km of the crater of the Popocatepetl volcano: to the northeast, Santiago Xalizintla and San Nicolás de Los Ranchos; to the Southeast, San Pedro Benito Juárez and Guadalupe Huxocoapan.

The information used for the Popocatepetl volcano, Mexico, comes from sources such as INEGI (National Institute of Statistics and Geography), Government of Mexico, CENAPRED (National Center for Disaster Prevention, SEDESOL (Secretary of Social Development). The layers corresponding to the assessment routes of the Popocatépetl Volcano Emergency Plan were provided by CENAPRED, and the maps showing the information related to its use can be downloaded from the website of this same institution.

For the characterization of the environment of the Popocatépetl volcano at present, the II Population and Housing Count 2010 carried out by the INEGI was used. For the statistical data, phases, and characterization, the Report of the Actions of the Operational Plan of the Popocatépetl volcano of the year 2019 carried out by Civil Protection has been used. Considering that the proposed work area for the Popocatépetl volcano is relatively small and that only the communication routes indicated as evacuation routes are used, the assembly of the data has not presented any problems.

Due to the activity of the Popocatépetl Volcano, three dangerous areas are considered, starting as the central axis of the volcano crater: within a radius of 15 km "high-risk zone." It comprises 16 municipalities in Puebla, 6 in Morelos, and 8 in the

Table 7.2 List of Towns of the State of Puebla in High-Risk Area

Location	Municipalities	Population
San Andrés Calpan	Calpan	7161
San Lucas Atzala	Calpan	2483
San Mateo Ozolco	Calpan	2713
San Nicolás de los Ranchos	San Nicolás de los Ranchos	5685
Santiago Xalitzintla	San Nicolás de los Ranchos	2196
San Pedro Yancuitlalpan	San Nicolás de los Ranchos	2694
Total		22,932

state of Mexico. Within a radius of 30–60 km "medium risk zone." It comprises 22 municipalities in Puebla, 9 Morelos, 6 in the State of Mexico, and 18 in Tlaxcala. In a radius greater than 60–90 km "low-risk zone." It includes the rest of the populations near the volcano in the States mentioned.

Considering evacuate in case of a volcano eruption, 30 municipalities in the high-risk zone and 56 in the medium risk, calculating that the population is exposed is 3,562,596 people; of which 685,776 are located in the high-risk zone. Therefore, as shown in Table 7.2, the study was carried out to evacuate the localities near the volcano as quickly as possible.

In Fig. 7.1, it is possible to see the six Localities in a high-risk zone due to the proximity to the Popocatepetl volcano, described in Table 7.2

Fig. 7.1 Towns with the highest volcanic risk in the State of Puebla

7.3.1 Methodology

Operations Research is a method of problem-solving through which mathematical models can be worked to elaborate analyses and, in this way, make decisions that give solutions to various approaches presented. Several solution techniques have been implemented to address allocation in different areas of knowledge by different authors.

Linear Programming corresponds to an algorithm through which real situations are re-emerged. It is intended to identify and solve difficulties to increase productivity concerning resources, thus increasing profits. The primary goal of Linear Programming is to optimize functions on several variables with constraints, optimizing an objective function. This technique allows integrating decision variables with the constraints present in the research objective, either searching for maximization or minimization of desired situations.

The objective function is directly related to the general objective of the research; by having different questions that we want to answer through modeling, this function seeks to satisfy the fundamental question in search of the optimal solution for the solution of the problem. We have a relationship between the decision variables and the objective function. These variables can be controllable according to the problem being modeled to take various possible values of which it is desired to know their optimal value.

The restrictions refer to the limitations presented in the values that the decision variables can take. In the development of the model, the researcher must consider different limitations to optimize the research problem.

An observing of any industry can conclude that any activity is present the transport of goods or products from the production sites called origins to consumption centers called destinations: so, carrying out this activity in an optimal way, that is, at the lowest possible cost, will represent economic and competitive advantages. Moreover, the transport of goods or products is immersed in the current trend of globalization.

Historically the allocation problem was solved using the same techniques used for the transport model. However, it is tedious to do it this way due to its particular characteristics.

Assignment problems appear in various contexts, where it is required to assign indivisible objects or people to specific tasks optimally. It is necessary to have information to build any model, such as the unit costs of transport from each origin to each destination and each center's supply and demand. We use the term supply as the number of goods or products available at each source from the production center, and the term demand is associated with the number of goods or products that each destination requires. With the previous information, it is evident that the decision variables are the number of products that sent from an origin to destination j, which we denote by X_{ij} and unit costs for transporting a product from the ith origin to the jth destination are denoted as C_{ij}. Thus, the objective function associated with the transportation problem represents the total cost of the same, minimizing the total cost

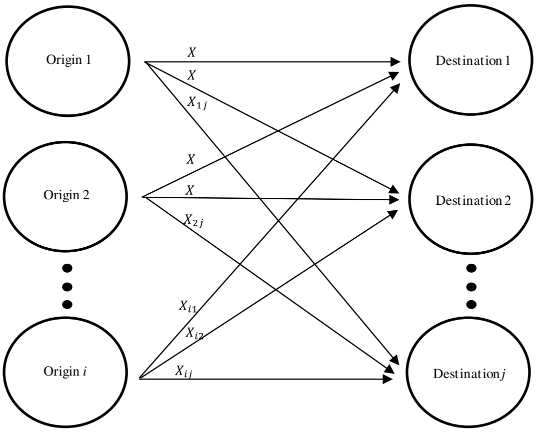

Fig. 7.2 Schematic representation of the Transportation Problem (Taha, 1998)

of transporting the products from each origin to each destination, always satisfying the demand. Schematically, the transport problem can be represented as in Fig. 7.2.

7.3.1.1 Application of the Allocation Model

To solve the issues raised in this project, integer linear programming was implemented to solve limited resources to optimize its use, i.e., an allocation problem, which arises when the level of certain activities that compete for scarce resources must be designated. To do so, we use the Google Maps tool to obtain the necessary information, which was entered in the commercial software LINGO. The localities' data, i.e., their demands, temporary shelters, and capacities, were also gathered and presented in Table 7.3. As a result, it was possible to obtain the optimal results of the older people over 65 years of age and those with some disability with the different temporary shelters predisposed to decide the best disposition of the evacuees.

Table 7.3 The capacity of temporary shelters in the Localities of Cholula

	Capacity
Centro Escolar Lic. Miguel Alemán	1000
CETIS 67	720
Sec. Fed. Porfirio Moisés Sáenz	720
Esc. Prim. Emperador Cuauhtémoc	450
Esc. Prim. Paz Montaño	300
Centro Escolar Dr. Alfredo Toxqui de Lara	800
Auditorio Municipal	600
Total	4590

Table 7.4 Distribution of vulnerable people to evacuate from Localities to Temporary Shelters

	Population 65 and+	Population Disability	Total Evacuate	Percentage 65 and+	Percentage Disability
San Andrés Calpan	816	317	1133	72	28
San Lucas Atzala	458	83	541	85	15
San Mateo Ozolco	463	38	501	92	8
San Nicolás de los Ranchos	701	344	1045	67	33
Santiago Xalitzintla	384	134	518	74	26
San Pedro Yancuitlalpan	342	96	438	78	22
Total	3164	1012	4176		

The quality of the possible scenarios for the evacuation model does not depend solely on the detail of the cartographic data or databases but also on the proposed departure places for the evacuation proposed, which are considered the localities' center.

Multiple possible scenarios can be obtained depending on the initial configuration; however, directed evacuation without panic will be considered for the proposed case. The scenario works for small areas in which meeting points are introduced to which it is possible to reach by foot. From that point, the inhabitants are transported in vehicles provided by those responsible for the evacuation.

Zoning is used to direct evacuation to appropriate assembly points. In this case, the center of each locality is used as the only point of departure.

There are scenarios in which the total population is considered; however, an important part to consider is the most vulnerable inhabitants, among those with some disability and older people or over who has priority to be evacuated to the different temporary shelters in the Localities of Cholula, Puebla. This population can be seen in Table 7.4.

To evaluate the solutions, we consider the travel time, which is defined as the time from the point of departure to the point of arrival with free routes. The travel times shown in Table 7.5 are conditioned by the kilometers to be traveled, which can be seen in Table 7.6.

This procedure allows to quickly adapt the structure of the data tables and software applications. Each line of the data table contains, among other numerical attributes, the primary public source of cartographic data in Mexico is INEGI (National Institute of Statistics and Geography).

7.3.1.2 Mathematical Assignment Model

The algorithm uses the search method known as branching and bounding to find the assignment of temporary shelters to minimize the cost of evacuating people. The solution considers the following assumptions:

Table 7.5 Times of Transfers from the Towns to the Temporary Shelters of the Localities of Cholula

		Localities					
		San Andrés	San Lucas	San Mateo	San Nicolás de	Santiago	San Pedro
		Calpan	Atzala	Ozolco	los Ranchos	Xalitzintla	Yancuitlalpan
Shelters Municipality of Cholula	Centro Escolar Lic. Miguel Alemán				36		34
	CETIS 67	23	31				
	Sec. Fed. Porfirio Moisés Sáenz	23			35		
	Esc. Prim. Emperador Cuauhtémoc	23				38	
	Esc. Prim. Paz Montaño					41	
	Centro Escolar Dr. Alfredo Toxqui de Lara			43		43	
	Auditorio Municipal	25					
		Transfer time					

1. The localities are the only places of origin for vehicles involved in the evacuation.
2. The number of vehicles available are determined by the availability of the resource, responsibility of the Ministry of Infrastructure, Mobility, and Transportation of the State of Puebla, based on the Popocatépetl Plan (2020) of the State Coordination of Civil Protection. The model to optimize the trips for evacuation can be formulated as shown in Eq. (7.1)

Objective function:

$$\text{Min}Z = \sum_{i=1}^{m} \sum_{j=1}^{n} C_{ij} X_{ij} \tag{7.1}$$

Table 7.6 Kilometers to travel from the Towns to the Temporary Shelters of the Localities of Cholula

		Localities					
		San Andrés	San Lucas	San Mateo	San Nicolás de	Santiago	San Pedro
		Calpan	Atzala	Ozolco	los Ranchos	Xalitzintla	Yancuitlalpan
Shelters Municipality of Cholula	Centro Escolar Lic. Miguel Alemán				20.9		20.7
	CETIS 67	16.1	18.7				
	Sec. Fed. Porfirio Moisés Sáenz	16.3			20.4		
	Esc. Prim. Emperador Cuauhtémoc	16				26.9	
	Esc. Prim. Paz Montaño					25.1	
	Centro Escolar Dr. Alfredo Toxqui de Lara			30.4		26	
	Auditorio Municipal	17.9					
		Kilometers traveled					

Subject to:

$$\sum_{i=1}^{m} X_{ij} \geq b_j \ \forall j \in J \tag{7.2}$$

$$\sum_{j=1}^{n} X_{ij} \leq a_i \ \forall i \in I \tag{7.3}$$

$$X_{ij} \geq 0 \ \forall i \in I, \ j \in J \tag{7.4}$$

Sets:

i identifier of the localities participating in the evacuation.
j identifier of temporary shelters available for evacuation.

Parameters:

C_{ij} associated times to transport people from the *i*-th location to the *j*-th temporary shelter.

m number of temporary shelters participating in the evacuation. Each temporary shelter has a different capacity.

n localities that are participating in the evacuation.

a_i capacity of the *i*-th temporary shelter.

b_j number of people to evacuate in the *j*-th localities.

Decision variables:

X_{ij} number of people to evacuate from the *i*-th location to the *j*-th temporary shelter.

In Eq. (7.1), the objective is defined considering a cost minimization function. This function is subject to a series of restrictions, where Eq. (7.2) restricts the model to the combination of the different resources to ensure the total evacuation of the localities. Furthermore, Eq. (7.3) ensures that the model does not allocate a more significant number of available temporary shelters. Finally, Eq. (7.4) forces the model to make all the variables involved positive and integer.

7.3.2 Allocation Model Solution

The resolution of the linear programming model consists of finding out the number of people 65 and over or with a disability to evacuate from each locality to the defined temporary shelters, optimizing the cost, travel time, and mileage traveled.

The problem is based on solving a classic linear programming problem where an objective function to optimize (transport time weighted by the number of transported people) and the appropriate constraints (capacities of temporary shelters and demands of the localities) is proposed.

Once the LINGO tool was run with the Assignment Model, the software presented an optimal solution that can be seen in Table 7.7. The letters M represent the Localities and A the temporary shelters, as people to be transferred from each locality to each temporary shelter located in the Localities of Cholula, Puebla. Furthermore, it considers the minimum times and distances in road kilometers, also considering the capacities of each of the seven temporary shelters. Finally, it seeks to evacuate the total older people and people with disabilities as shown in Fig. 7.3.

7.4 Discussion for the Allocation Model

When applying the optimization allocation model, we can observe that not all the people in the same localities are directed to a single temporary shelter to avoid the saturation of the Cholula sites. This latter avoids that people have to look for a place

Table 7.7 Values obtained from the LINGO optimal solution

Variable	Value
CANTIDAD (A1, M4)	562
CANTIDAD (A1, M4)	438
CANTIDAD (A2, M4)	179
CANTIDAD (A2, M4)	541
CANTIDAD (A3, M4)	237
CANTIDAD (A3, M4)	483
CANTIDAD (A4, M4)	417
CANTIDAD (A4, M4)	33
CANTIDAD (A5, M4)	300
CANTIDAD (A6, M4)	501
CANTIDAD (A6, M4)	185
CANTIDAD (A7, M4)	300
Total	4176

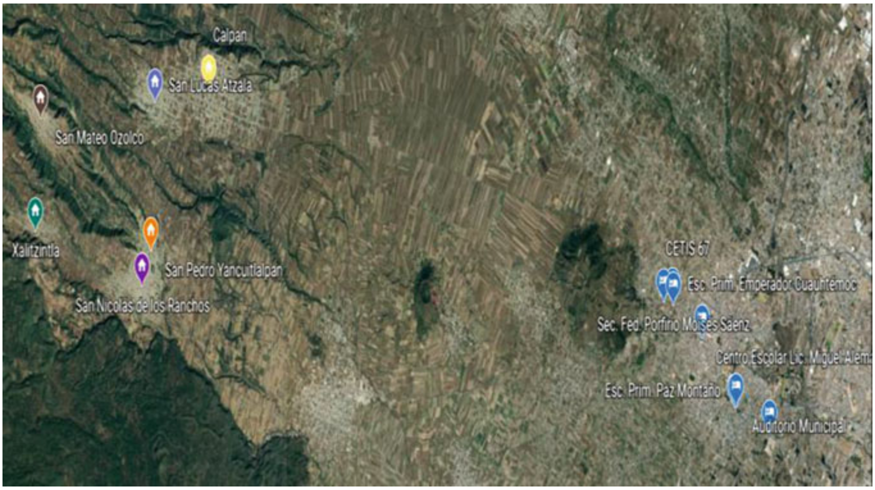

Fig. 7.3 Location of localities at high risk and Temporary Shelters in the Localities of Cholula, Puebla

in the shelters. With this, it is possible to evacuate all the people of the target from all the towns near the volcano and be able to direct them to the pre-established temporary shelters, generating a distribution like the one shown in Table 7.8.

It is also observed in Table 7.8. that while the demand and the capacity are respected, the evacuation of the entire target population fulfills the objective function set out in the problem analyzed, even when capacity was available in two temporary shelters. It can be understood that even though all these shelters were required, these

Table 7.8 Assignment of people aged 65 and over and with some type of disability from localities to temporary shelters

		Municipalities								
		San Andrés Calpan	San Lucas Atzala	San Mateo Ozolco	San Nicolás de los Ranchos	Santiago Xalitzintla	San Pedro Yancuitlalpan	Total Evacuate	Capacity Total Hostel	Difference
Shelters Municipality of Cholula	Centro Escolar Lic. Miguel Alemán				562		438	1000	1000	0
	CETIS 67	179	541					720	720	0
	Sec. Fed. Porfirio Moisés Sáenz	237			483			720	720	0
	Esc. Prim. Emperador Cuauhtémoc	417				33		450	450	0
	Esc. Prim. Paz Montaño					300		300	300	0
	Centro Escolar Dr. Alfredo Toxqui de Lara			501		185		686	800	114
	Auditorio Municipal	300						300	600	300
	Total	1133	541	501	1045	518	438	4176	4590	414

two proposed ones were the furthest from the localities that need to be evacuated; thus, the allocation was lower.

Response time is essential due to the nature of the risk involved in a volcanic eruption, hence the importance of carrying out an evacuation in the shortest possible time, complying with premises such as the demand of each of the municipalities was completely satisfied by the different shelters. The level of use of each of the shelters was less than or equal to their capacity. Due to the amount of data inherent to the model, it is necessary to systematize it, to have more agile and reliable handling, avoiding making mistakes, which is feasible with a computer tool that reduces execution times. The use of a computational system is so important when deciding and optimizing a system. The commercial LINGO software facilitates the generation and structure of the data, allowing to generate results efficiently using variables from the allocation model.

Government entities must resort to this type of technology that allows them to obtain optimal solutions schemes that they can apply in risk situations and transfer the experience to other entities and localities to use them as a basis for the implementation of their risk models evacuation.

For designing an allocation model that contributes to the evacuation of people, it is necessary to have full knowledge of the environment of the localities, population characteristics, routes, times of transfers, kilometers to go, shelters' capacity, among others.

Also suggested is to monitor the state of roads and communication routes to be used by people wanting to perform evacuation to reduce both risks and transfer times.

It is also advisable to update the values of the variables that make up the model to generate as much precision as possible.

It is important to note that the recommendations that are developed emphasize the need for a joint effort of society to promote the learning of all participants. In this sense, public and private investments are recommended to conserve and modernize the necessary infrastructure required for a successful evacuation.

7.5 Final Remarks

Nature is complex, but it is possible to describe its behavior using an exact language like mathematics. From this, it is possible to develop models that allow us to give exact solutions. Without a doubt, this is one of the most significant challenges that modern society demands to mitigate the impact of volcanic eruptions.

The preparation and mitigation stages are part of a process and not isolated activities. The stakeholders in this process must be part of a broad and representative sector with national and local coordination, which allows early detection of the volcanic risk.

The prediction and monitoring of volcanic hazards require accessible infrastructure and resources, especially for vulnerable localities. The government must issue timely alerts when it has been scientifically determined that the population is in danger.

Pre-disaster planning can be effective if vulnerable populations can incorporate such planning into the routine process of daily life. Local communities should be familiar with the hazards to which they are exposed and help to expand local capacity to interpret early warnings and take appropriate action to increase the safety of people.

There should be training programs at all levels (localities, government, and the private sector) covering topics such as:

- Preparation and mitigation programs considering risks derived from volcanic disasters as a measure to reduce their impact.
- Information management. The media should be aware of their influence and prevent disasters by providing information about the population's actions, using messages understandable to the majority of the population.
- Coordination between all levels involved.
- Promote better community organization as a basis for improved response at the local level.
- Help local organizations improve their capacity by conducting a pre-disaster needs assessment and identifying risks and vulnerabilities.
- Assist local authorities in developing their contingency plans for volcanic disasters, including drills.
- Generate a multisectoral and inter-institutional focus on disaster preparedness, mitigation, and prevention, emphasizing the education and health sectors.
- The health sector must strengthen the development, dissemination, and implementation of contingency plans that define the participation of each of the actors, linking primary health care with emergency hospital care.
- Technical manuals should be made available for consultation, updating, and improvement.
- Strengthen capacity for food supply through training in humanitarian logistics, development of distribution and transport networks, both locally and regionally.

In this document, the Assignment Model was applied in the presence of a natural disaster due to volcanic risk to the six localities closest to the high-risk area in the State of Puebla; the results show that feasible solutions can be obtained applying methods optimization. It is important to note that it was enough for the demand for the proposed temporary shelters' capacity; however, it could hardly be covered with the current capacity.

This type of model can be applied to other localities in danger zones to evaluate their evacuation. In this way, older adults and people with disabilities may be evacuated using a shorter (i.e., less travel time) route to the temporary shelters indicated by Civil Protection. Even if these routes were connected, the model would consider and give results close to reality.

Future research will compare the presented method and simulation, propose large-scale instances, and use metaheuristic procedures such as genetic algorithms.

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Chapter 8
Identification of Homogeneous Hydrological Administrative Regions in Mexico Using Analysis of Variance

Hugo Romero-Montoya, Diana Sánchez-Partida, José-Luis Martínez-Flores, and Patricia Cano-Olivos

Abstract This chapter examines and identifies the homogeneity between the Administrative Hydrological Regions (RHAs) of Mexico using analysis of variance. The analysis was carried out through the ANOVA and Kruskal-Wallis tests, both, applied between the 13 RHAs, concerning 26 variables in common extracted from the records of the National Water Information System (SINA) platform. The methodology is based on a quantitative approach with explanatory scope, focused primarily on the statistical treatment of the observations inherent in each selected variable. The design is non-experimental, transectional since it is based on a single period between the years 2004–2018. The results confirm the generation of homogeneous groups by the type of variable analyzed, achieving a maximum of 4 regions per group and four groups per variable. These mimes were organized before analyzing similarities under the proximity approach between the means of the regions. The practical implications are beneficial to understand and improve the development of strategies for access, distribution, and water management and a better understanding of related variables between regions.

Keywords Administrative hydrological regions (RHAs) · National water information system (SINA) · Homogeneity · Basin · ANOVA test · Kruskal-Wallis test

8.1 Introduction

Climate change has intensified the frequency and intensity of extreme weather events. As a result, the seasons have become less predictable and the rains more variable, which has resulted in off-season events that favor the degradation and scarcity of natural resources (Lupián and Campos 2015).

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Due to these physical and biological systems changes, there are also significant effects on the availability and quality of resources such as water and soil on all continents and in most oceans (Diéguez et al. 2014).

Given these changes, it is convenient to remember that water is a limited and non-renewable resource on our planet. Its availability is calculated between 9,000 and 14,000 km^3, of which only 4,200 km^3 are viable for use by society (Cantú-Martínez 2017), making it a transcendental subject in every possible way. Due to this, it is essential to emphasize that there is no human activity with which water has no relation. Therefore, the problems around it are as diverse as its actors (CEMDA 2006).

At present, studies related to water resources have increased due to the significance of this issue in the world. The latter is derived from: the unequal distribution of water on the planet, the disparity in power relations, social and environmental challenges (i.e., accelerated urbanization, climate change, increasing pollution, and the waste of water resources due to demographic expansion), and the Industry and agricultural overexploitation (Ferrer and Torrero 2015).

For its part, Mexico is considered a country with low water availability, unlike other countries in America such as Canada and Brazil, which are among those with the most incredible abundance of vital liquid (CEMDA 2006).

The average natural availability of water in the country is considered relatively low, establishing a heterogeneous distribution in the national territory, with greater availability in the South-Southeast and in less quantity in the Central-North region of the country. It is worth mentioning that the Central-North region is characterized by the highest rate of urbanization and economic growth and a high concentration of the population, and significant restrictions on water availability. In summary, renewable water is concentrated in the southern region, while in the central and northern regions, it is relatively scarce, resulting in an unequal distribution of the vital resource (Cantú-Martínez 2017; CEMDA 2006; Denzin and Taboada 2017; National Water Commission 2018; Nacional and Agua 2017; Perevochtchikova and Arellano-Monterrosas 2008).

Still, if compared with the rest of the world, the national renewable supply places Mexico among the countries with medium-high supply due to its absolute values (25th place) and in per capita terms with a medium-low availability (94th place) (Denzin and Taboada 2017).Thus, it is possible to establish a national perspective where 12 million people do not have access to drinking water; 102 of the 653 aquifers in the national territory present overexploitation, and 80% are contaminated by discharges of water pollutants. Moreover, 46% of the water is lost due to failure in the supply (Denzin and Taboada 2017).

These facts make us think more carefully about the role of hydrological resources management and its orientation towards systemic thinking to develop a comprehensive approach to water, which should be oriented towards using resources and taking them into account. Moreover, it counts other factors that affect the processes, environmental, social, legal, among others (Velasco and Montesillo-cedillo 2007).

8.2 Literature Review

8.2.1 Water Management in Mexico

The correct management of water has objectives that mainly focus on resolving conflicts based on minimum temporary availability and scarcity. Therefore, water management is a process for resolving real and potential conflicts. The implications impact as little as possible, and an adequate balance is achieved between all the parts that intervene in the hydrological cycle (Velasco 2018).

For its part, the integral management of water resources in Mexico is in charge of the National Water Commission, which has carried out an unprecedented task to create a participatory water management system in basins that currently cover the entire national territory. (CONAGUA nd; Dourojeanni et al. 2002). Similarly, in its article 9, section XXVI, the National Water Law indicates that Conagua will promote the efficient use of water and its conservation in all phases of the hydrological cycle. All this, to promote the development of a culture that considers water a vital resource, scarce and of high economic, social, and environmental value, constitutes a national priority (Arreguín-Cortés et al. 2016).

However, regarding the management of the hydrological cycle, "the National Water Law, reformed in 2004, considers the hydrographic basin as the basic unit for water management" (Perevochtchikova and Arellano-Monterrosas 2008).

Watersheds are the basic unit in the delimitation of territorial spaces useful for sustainable management. In addition, they have local implications among natural resources and regional development projection (Barrientos 2006).

Still, there is a growing concern for the environmental quality of the basins. Although it is evident the role that the territorial units of intervention have developed for the policies of the Ibero-American countries (Braz et al. 2020; Ferrer and Torrero 2015), it is a conern also present in Mexico, which, since 2006 has made substantial efforts to update and unify the delimitation by hydrographic basins (Perevochtchikova and Arellano-Monterrosas 2008).

Consequently, water represents a fundamental element for elaborating management and conservation plans since it is a critical environmental and social good for the basin, considered a structure of strategic territorial ordering (Braz et al. 2020).

Nevertheless, generating a water management program based on the way the basin works is not easy since the political and administrative divisions of the regions do not correspond to the area that the basin occupies. It generates an incompatibility among some basin councils with insufficient mechanisms for the management of aquifers (Barrientos 2006; Cantú-Martínez 2017; Denzin and Taboada 2017; Dourojeanni et al. 2002). The hydrographic basin was not a correct criterion to establish national development priorities since some regions behind economic, social, and infrastructure terms could not be located within this concept. They lacked the necessary characteristics to assign the character of a region-plan (Barrientos 2006). Thus, basins as a unit facilitate sustainable management but complicate political-administrative and strategic management (CEMDA 2006).

"It should be noted that the management of water use systems are continuously evolving and the direct and active participation of the users themselves is conferring characteristics of social good to them" (Velasco and Montesillo-cedillo 2007). Furthermore, it has allowed a period of experimentation in which old practices still coexist and are mixed with new ones, giving rise to a generation of watershed management programs developed with a new approach and a new strategy (FAO 2007).

Nevertheless, it is difficult to ignore the great challenge faced by the joint management of basins from the improvement and use of natural resources and the needs and aspirations among local societies (FAO 2007; Velasco and Montesillo-cedillo 2007). It is necessary to understand the hydrographic basins as fundamental systemic units to propose measures and actions of environmental planning and integrated management that seek to order and standardize the use of the land and the preservation of the water, to minimize the effects caused by the socioeconomic activities carried out within them (Braz et al. 2020).

8.2.2 The Role of RHAs in Watershed Management

For planning, institutional organization, and social participation purposes, watersheds are constituted by complete hydrological systems identified as administrative hydrological systems (CEMDA 2006). In Mexico, the National Water Commission (Conagua) exercises its attributions from 13 basin organizations, whose limits of competence are based on the RHAs. They are made up of basin groups, considered basic units for managing water resources. These regions tend to be based on municipal demarcations to facilitate the integration of socioeconomic information (National Water Commission 2018; National and Water 2017).

Although, according to the legal framework, these RHAs are not dependent on the Conagua, their management, and the activities associated with the council are financed by said body, so their complicated structure overlaps the state political division as at the three levels of government. Furthermore, it explains that different environmental conditions are linked to this structure and different social and cultural environments (Romero Navarrete and Olvera Molina 2019).

Figure 8.1 represents the division of the 13 RHAs proposed at the national level according to Conagua, which becomes the fundamental structure for monitoring and following the issues related to each of the RHAs above, which in turn make up the national territory.

The study of the differences between the RHAs brings new research that can improve the situations in different areas based on recognizing the various characteristics associated with each region. These characteristics are specialized human resources to understand the phenomena and the necessary inter-institutional and intergovernmental coordination mechanisms to understand the complex needs in each of them (Arreguín-Cortés et al. 2016).

Fig. 8.1 Mexico and its administrative hydrological regions according to CONAGUA (National Water Commission 2018)

This study examines the similarities between the various RHAs that impact Mexico's water resources management framework. It intends to group them according to the intrinsic relationships between variables concerning homogeneous regions, to improve the strategic understanding of water availability and the management of the country's water resources and, therefore, the regions.

For this, data and records were extracted from the national water information system (SINA) between the years 2004–2018 as a starting point for analyzing the sample universe of the variables that make up the monitoring and performance of the management among the 13 RHAs in Mexico. Subsequently, statistical strategies were applied for data treatment, identifying the most significant similarities between the RHAs.

The document is organized as follows. The first section represents an approach to current water conditions and their management in Mexico. The second part contains the details describing the methods and materials used to compare the RHAs, followed by their discussion results. Finally, the conclusions corresponding to the findings evidenced by applying the aforementioned statistical techniques in the data extracted from the SINA platform are presented.

8.3 Discussion and Findings

The methodology applied in this study is based on a quantitative approach. Its scope is explanatory because it seeks to clarify the homogeneity between the RHAs through a set of variables collected and related to each other through statistical methods. The design is of the non-experimental transectional type since it assumes using a

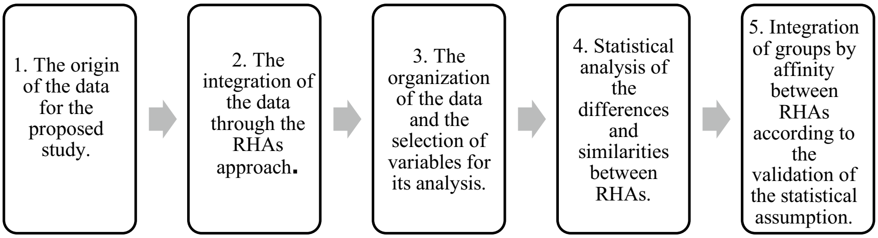

Fig. 8.2 Proposed methodology to evaluate the similarities statistically between the RHAs, based on the variables selected for analysis

set of variables during a specified period between the years 2004–2018. The use of hypotheses formulated to establish a difference or similarity between the established groups, attributed to causality, stands out (Hernández Sampieri et al., 2010; Sampieri and Lucio 2014; Sampieri Hernández et al. 2003).

Among the primary resources used are the data provided by the reports and records of the SINA platform and the statistical software used to treat the observations obtained.

Figure 8.2 represents the sequence of steps developed to carry out the homogeneity study among the 13 RHAs.

8.3.1 The Origin of the Data for the Proposed Study

In order to be able to identify the similarities and differences between the RHAs, it was necessary to obtain a set of data from reports and records related to the management of water resources in Mexico. In general, federal and national agencies' information on natural and biological resources is mainly provided (Wilhite et al. 2014). For this particular study, we use the platform of the National Information System on quantity, quality, use, and conservation of Water (SINA), in charge of the National Water Commission. Following the provisions of the National Water Law, the SINA is the source of consultation and responsible for the function, integration, and processing of data related to the management of water resources between the different RHAs of the country (National System of Water Information (SINA)|National Water Commission|Government|gob.mx, na).

8.3.2 The Integration of Data Through the RHAs' Approach

Before integrating the data for its analysis, we considered the critical role of the basin and its conception as a central unit for the management of water resources (Barrientos 2006; Braz et al. 2020; CEMDA 2006; Dourojeanni et al. 2002; Ferrer and Torrero 2015; Perevochtchikova and Arellano-Monterrosas 2008; Navarrete and Molina 2019). The biophysical, socioeconomic, and political-administrative systems are integrated from this unit, relating to each other to form a unique natural system, which is included in the current perspective of regional water resources management (Barrientos 2006).

This conceptualization about the factors that make up the basin helped to understand better the data extracted from the SINA platform. In addition, the concept reinforces the idea of a fundamental basic unit of measurement integrated jointly with others to become a more extensive region (RHAs).

The hydrological cycle resource management is an essential part of the SINA, since it incorporates the basins into complete hydrological systems. These are known as administrative hydrological systems or RHAs (CEMDA 2006). Said regionalization for the administrative management is markedly topographic and distinguished through the names of rivers and mountains, which are figurative elements of them (Navarrete and Molina 2019).

The records of the SINA platform are organized based on this regional perspective, which considers the particularities of the geographical distribution of water at the national level (Denzin and Taboada 2017). Therefore, the RHAs were considered the fundamental unit of contrast to establish similarities and differences between the country's different regions.

8.3.3 The Organization of the Data and the Selection of Variables for Its Analysis

After carefully analyzing and detailing the reports and records grouped into categories by the SINA (i.e., based on elements such as Aquifers, Renewable Waters, Demographic Characteristics, Irrigation Factors, Dams and Rivers-Basins), a total of 26 variables were delimited and contained in Table 8.1. This table contextualizes the variables, their categorization, and description.

It should be noted that the variables were selected through a compilation process that integrated all the variables available by category in the SINA platform. The objective of being able to characterize the variables of the 13 hydrological regions in a much broader and homogeneous manner was to develop a comprehensive and detailed analysis of them. However, due to the lack of statistical consistency among some observations, variables such as: overexploited aquifers, aquifers with marine intrusion, aquifers with salinization and water use by sector, which is integrated from the following subsectors such as: self-sufficient industry, electric energy, agriculture and public supply, were discarded from the analysis.

On the other hand, the unspecific nature of some records, as well as the generality of some observations, made the categorization of the variables mentioned above incompatible. For this reason, they were not compared using the statistical tests used in the subsequent steps. Likewise, the duration of the single analysis period for the

Table 8.1 Categorization, classification, and definition of the 26 variables extracted from the SINA platform

Category	Variable	Description
Aquifers	Availability (hm^3)	The total volume of surface and underground renewable water that occurs naturally in a region
	Weighted drought index	Average calculation stipulated from the conditions referred to by the records of the national drought monitor
	Precipitation per year (sum mm)	Precipitation is any product of the condensation of atmospheric water vapor-deposited on the Earth's surface
	Deficit (hm^3)	The water deficit is, in short, the lack of water, so the concept is closely related to drought or scarcity
	Average Recharge, Total Aquifers (hm^3)	Average Aquifer Recharge is the average annual volume of water that enters an aquifer
	Total of aquifers	Total number of underground structures that house water
	Total renewable (hm^3/year)	Renewable water is called the maximum amount of water that is feasible to exploit annually in a country without altering the ecosystem, and that is renewed through the rain
	Per capita renewable water (m^3/Hab/year)	The per capita renewable water of a country results from dividing its renewable resources by the number of inhabitants
	Upper average natural runoff total (hm^3/year)	It is the average annual volume of surface water that is captured by the hydrological basin itself
Renewable	Water average renewable water (hm^3/year)	Renewable water is called the maximum amount of water that can explode annually in a country without altering the ecosystem and renewed through the rain
	Renewable water per capita 2030 (m^3/Inhabitant/year)	Renewable water at the maximum amount of water that is feasible to exploit per inhabitant is projected to 2030

(continued)

Table 8.1 (continued)

Category	Variable	Description
Demographic characteristics	Population (Habs.)	Set of inhabitants of the country
	Continental surface (km^2)	The continental surface refers to the part of the national territory articulated with the American Continent and the insular one, to the surface of the country's islands
	Population density (Hab/km^2)	The population density is equivalent to the number of inhabitants divided by the area where they live
Irrigation factors	Harvested area (ha)	It is the area from which agricultural production was obtained
	Irrigated area (ha)	Area of all the plots that, during the census year, have been effectively irrigated at least once
	Number of users	The number of agricultural users per region
	Production (thousands of tons)	It is the result of the practice of agriculture
	Yield (ton/ha)	It is the ratio of the total production of a particular crop harvested per hectare of land used
Dams	Capacity in NAMO (hm^3)	Maximum Ordinary Water Level, the maximum level with which the dam can be operated to satisfy the demands, it can be drinking water, power generation, and/or irrigation
	Volume stored (hm^3)	It is the amount of water stored by dams
	Number of dams	The number of dams currently existing
Rivers and basins	Natural runoff volume (hm^3)	The average annual volume of surface water is captured by the natural drainage network of the hydrological basin itself
	Extraction volume (hm^3)	Amount of water extracted

(continued)

Table 8.1 (continued)

Category	Variable	Description
	The average annual availability of rivers and basins (hm^3)	The average annual volume of water s that, when positive, can be extracted from an aquifer for various uses, in addition to the extraction already under concession and the compromised natural discharge, without putting into it, threatens the balance of ecosystems
	Area (km^2)	Territorial delimitation of the regions expressed in km^2

observations that make up the variables was specified for a period between the years (2004–2018).

Consequently, once the analysis variables were defined, their observations were analyzed in the same way. These, were ordered according to the RHAs, simplifying the comparative statistical analysis that would later be carried out.

8.3.4 Statistical Analysis of the Differences and Similarities Between RHAs

In order to establish the similarities or differences between the 13 RHAs from the 26 variables used, it was necessary to carry out a set of tabulations with the observations of each variable to carry out the treatment and statistical analysis of the data through the MINITAB and STATA software.

Due to the different nature of the variables at the regional level, significant variations in the magnitude of the observations were identified from one region to another. Its impact on each variable's statistical conditions compared by region makes it difficult to use a single approach or data treatment strategy. The analysis of the regions was carried out from statistical methods based on different tests but that focus on the same result.

The data treatment strategies to carry out the comparison of the regions were the parametric test of variance (ANOVA) and the non-parametric Kruskal-Wallis test.

ANOVA is one of the most widely used tests to compare groups or treatments with each other (Cardoso et al. 2008). The simplest way is the so-called one-way or one-way ANOVA (Dagnino 2014). The focus of this method is to separate the total variation into parts that each source of variation contributes to the experiment. In this analysis between the RHAs, the variability due to the RHAs' treatments and error was separated. When the first predominated over the second, it was possible to conclude that the treatments had more effect or that the RHAs' means were different.

When the treatments did not dominate or contributed the same or less than the error, the means were considered similar (Humberto Gutiérrez Pulido 2008).

Regarding the Kruskal-Wallis test, which is the non-parametric equivalent of ANOVA (Guillen et al. 2012; Harris et al. 2008; Hecke 2012; Hopkins et al. 2018; Kitchen 2009; Nahm 2016; Rana et al. 2016), was used for the same purpose as its counterpart, to analyze the observations of the variables and establish similarities. It should be emphasized that this test has the 95% statistical power of a one-way ANOVA (Guillen et al. 2012).

Under this approach, parametric and non-parametric tests are presented as broad classifications of statistical tests. Their application and development depended mainly on the nature of the data treated (Rana et al. 2016). Both approaches obtain a greater scope in the comparisons made for each variable concerning the 13 regions.

It should be noted that the application of non-parametric tests in the development of the study was derived from the fact of having identified transgressions in the parametric ANOVA test. Therefore, the assumptions to obtain the statistical validity of ANOVA are related to the normality of the data, the independence of the observations from each other, and the differences between the variances for the groups (Pinel and Márquez 2017). Such assumptions were also evaluated in the test residuals and the groups suggested by the post hoc tests.

8.3.5 Integration of Groups by the Affinity Between RHAs According to the Validation of the Statistical Assumptions

The conformation of related groups was carried out and confirmed by statistical treatments applied among all the integrated groups. It is important to emphasize that it was necessary to use a statistical significance or a p-value of 5% to confirm the groups' confirmation according to their similarities (Harris et al. 2008). In other words, this was the border value used for the a priori rejection probability in the ANOVA, Kruskal-Wallis, Anderson Darling, Levene, Bartlett, and Shapiro Wilk tests. The tests were developed based on the conditions of equality of means, normality of variables, equality of variances, and normality of residuals (Pinel and Márquez 2017). These parameters helped confirm the results of the tests of similarity of means between the regions. The key arguments were considered to integrate or not a group of corresponding regions following some specific variable, such as water availability.

8.3.6 *Obtained Results*

A simultaneous initial test was carried out from the extracted data per the 13 RHAs. According to each of the 26 variables, this first simultaneous comparison was carried out using the ANOVA test.

The results showed differences between at least one pair of means of the 13 RHAs. Although this effect was kept for each of the 26 variables, no group of variables could be configured when the test was performed. Corresponding regions in this first step, mainly due to the excellent dispersion existing between the measurements of the observations by region according to the variable analyzed.

8.3.6.1 The Dispersion Between the Data of Each Region by Variable Analyzed

The differences identified between each of the compared regions are expected, given the irrefutable fact of the great climatic diversity in Mexico. This condition causes the dispersion patterns between the groups formed by the tests suggested post hoc tests once the ANOVA test was performed for the equality of means jointly between all the regions and for each of the variables analyzed.

This natural dispersion inherent to the country's conditions affected the first results obtained from the ANOVA test. They were considered insufficient for the formation of related groups between regions due to the significant dispersion evidenced at the time of carrying out a simultaneous comparison among all regions. This was equivalent to trying to find homogeneity in the country's territorial and climatic variability (Humberto Gutiérrez Pulido 2008; María José Rubio Hurtado 2012).

Due to this, the groups made up of the Fisher and Tukey multiple range tests were also discarded since there was not enough statistical evidence to establish homogeneity between the regions that their similarities from them had grouped.

Once it was verified that the simultaneous analysis of the 13 RHAs and the use of the post hoc tests of multiple ranges provided by it did not determine similar adequate groups per variable between the regions, a new group formation strategy was chosen for its analysis and subsequent validation. It was based on generating small analysis groups due to regions were grouped following the closeness between the average values of their observations for each variable analyzed. This proximity procedure between the averages calculated for each of the 13 RHAs is exemplified in Fig. 8.3, where they explicitly detailed the Availability variable interactions (hm^3).

In a summarized way, Fig. 8.3 explains how, according to the colors of each box, the closeness of the estimated average by region was considered, said proximity generated the groupings that would later be evaluated through the ANOVA and Kruskal-Wallis tests. The evaluation mechanism was repeated in each of the 26 selected variables, which helped to identify similar groups between the regions until the similarities were exhausted, making up the most influential groups per variable.

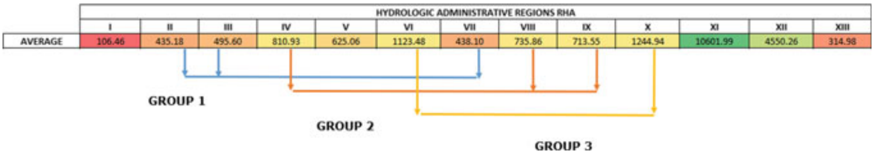

Fig. 8.3 Comparison between RHAs used to generate groups according to the magnitudes of the mean, exemplified for the specific case of the variable availability (hm^3)

The formation of groups according to the procedure described in the previous paragraph increased the homogeneity of the compared regions, resulting in greater precision in applying the statistical methods provided. It also influenced the number of groups formed between regions by each variable analyzed.

Table 8.2 summarizes the information of those variables where it was possible to form groups with similar characteristics between the regions. This table specifies the means of the regions and the confidence intervals for the set of observations that make up the stipulated group. In addition, since statistical estimates were used for contrast, the data corresponding to the confidence intervals are appended to demonstrate the differences and ranges of the means in each specified group (Pinel and Márquez 2017).

The results of the tests demonstrated their statistical significance. These tests were carried out from the p-values of each evaluated assumption. Table 8.3 shows the results of the tests for normality by variable and the hypotheses tested for the residuals of ANOVA in the specific case of the variable population (inhabitants). The last column is reserved for the Kruskal-Wallis test, which was unnecessary because the assumptions were met to validate the affinity between the RHAs through ANOVA. The elements analysis established in this section was performed systematically in all the variables and the groups proposed.

The results of this study show that in most of the analyzed variables, it was possible to identify homogeneity conditions to be able to integrate groups of similar RHAs, which were formed from a maximum of 4 RHAs as in the Population variable (inhabitants), up to a minimum of 2 in most of the other variables treated. In addition, the maximum number of groups formed from the analyzed variables' type was a maximum of 4. Unlike the previous variables, the variables Precipitation per year, Renewable water per capita, Renewable water per capita by 2030, Agricultural production, Annual natural runoff volume, and Surface area were the only group of related regions that could be formed. This, shows that, although another way of integrating the regions according to the closest average value was considered based on the proximity of the averages per variable, there were still some cases in which the variables were not fully integrated.

Although in most of the variables, it was possible to form at least one group with a couple of regions in it, there were situations where the conditions were not conducive to it due to the heterogeneity of their observations. This occurred in the specific case of the variables Extraction, Total Renewable Water, Total Surface Average Natural

Table 8.2 Summary according to the confidence intervals by regions and groups conformed to a significance level of 95%

Variable analyzed	Group made up of	RHAs that make up the group	Average of the RHA	Confidence interval for the groups' medias
Availability (hm^3)	1	II	435.2	(426.8–485.8)
		III	495.6	
		VII	438.1	
	2	IV	810.9	(669.93–836.97)
		VIII	735.9	
		IX	713.6	
	3	VI X	1 123.5 1 244.9	(1 092.3–1 283.3)
Precipitation per year (mm)	1	II	424.6	(423.04–474.42)
		VI	477.2	
		VII	444.4	
	2	IV	917.4	(832.95–921.35)
		VIII	803.3	
		IX	910.08	
	3	V	1 186.3	(1 111.1–1 295.6)
		XII	1 220.4	
	4	X	1 792.4	(1 778–1 994.6)
		XI	1 980.2	
Deficit (hm^3)	1	III	83.3	(52.66–114.76)
		IV	84.15	
	2	VI	1 788	(1 610.2–1 982.8)
		VIII	1 803.8	
	3	VII	849	(790.24–859.17)
		XIII	800.5	
Average (hm^3)	1	II	3 169.7	(332.9–2 839.5)
		III	3045	
		IX	3044	
	2	VIII	2346.9	(2 227.8–2 354.2)
		XIII	2235.1	
Renewable water per capita (m^3/habs./year)	1	V	6 316	(5 607.9–7 091.2)
		XII	6 383	
Renewable water per capita by 2030 (hm^3/year)	1	I	873.93	(859.25–882.75)
		VI	868.07	

(continued)

Table 8.2 (continued)

Variable analyzed	Group made up of	RHAs that make up the group	Average of the RHA	Confidence interval for the groups' medias
Population (inhabitants)	1	VIII	2.26×10^7	(2.19×10^7–2.29×10^7)
		XIII	2.22×10^7	
	2	I	4.05×10^6	(4.14×10^6–4.33×10^6)
		III	4.29×10^6	
		VII	4.34×10^6	
		XII	4.26×10^6	
	3	IV	1.12×10^7	(1.11×10^7–1.17×10^7)
		VI	1.16×10^7	
Continental surface (km^2)	1	VII	1.94×10^5	(1.9×10^5–1.95×10^5)
		VIII	1.91×10^5	
	2	I	1.50×10^5	(1.49×10^5–1.52×10^5)
		III	1.52×10^5	
Population density (inhab./km^2)	1	VI	29,783	(29,228–30,803)
		XII	30,248	
	2	IV	95.23	(94,299–98,647)
		X	97.72	
Total irrigated area (ha)	1	VI	30 685	(30 109–3 757)
		X	31 001	
	2	VII	340,035	(315 571–343 501)
		IX	319 038	
Number of users	1	III	89 155	(84 874–92 775)
		IX	88 494	
	2	VII	31 229	(31 119–33 536)
		VIII	33 425.6	
	3	I	17 942	(17 671–18 978)
		V	18 707	
Agricultural production (thousands of ton)	1	I	1 219.5	(1 140.4–1 322.2)
		V	1 243.1	
Yield (ton/ha)	1	X	41.15	(39.6–42.9)
		XI	41.16	
	2	I	23.20	(21.99–25.13)
		IV	23.918	
	3	II	14.99	(13.79–15.45)
		III	14.77	
		V	14.10	

(continued)

Table 8.2 (continued)

Variable analyzed	Group made up of	RHAs that make up the group	Average of the RHA	Confidence interval for the groups' medias
NAMO Capacity (hm^3)	1	III	15 862.1	
		IV	14 022.9	(14 626–16 000)
		VI	15 120.3	
		VIII	16 247	
Stored volume (hm^3)	1	II	5849	(5087.5–6011)
		IX	5,250	
	2	III	10,713	(9560–11,591)
		VI	10,438	
	3	IV	11,940	(11,425–13,642)
		VIII	13,127	
Number of dams	1	II	8.93	(8.13–9.41)
		X	8.6	
	2	IV	20.87	(19.28–21.45)
		VI	19.87	
	3	IX	12.13	(10.40–12.40)
		XIII	10.67	
Vol. Esc. annual nat. (hm^3)	1	III	21 267	(19 282–23 008)
		IX	21 013	
Extraction (hm^3)	1	II	8373	(6789.2–8798.2)
		V	7938	
		IX	7070	
	2	III	22,622	(20,908–24,577)
		VIII	22,862	
Average annual availability (hm^3)	1	I	1267.8	(1230.3–1386.)
		VI	1356.8	
	2	V	58,544	(52,848–64,927)
		IX	59,231	
Area (km^2)	1	VIII	$1.03 \cdot 10^5$	(9.59×10^4–1.19×10^5)

Runoff, Average Renewable Water, Harvested Area, and Ordinary Maximum Water Level (NAMO Capacity).

The results previously presented reinforce this study's objective, which has been to demonstrate the homogeneity between some RHAs from related variables, even despite the transgressions in the statistical assumptions found.

The impact of the dispersion between the observations analyzed for the 26 variables extracted from the SINA platform was a frequent aspect in each step of the

Table 8.3 Summarizes the results obtained concerning the assumptions analyzed from group 2, where the regions III, VII, XII (Northeast, North Pacific, North Central Basins, and Yucatan Peninsula) converge concerning the Population variable

RHA	Group	Set of statistical tests performed on the conformed groups				
		ANOVA	Shapiro Wilk * Anderson Darling	Bartlett's *Levene	Point patterns in the graph	Kruskal-Wallis
Population (inhabitants)						
I, III, VII, XII	2	p = 0.134	◈I p = 0.12498 ◈III p = 0.05629 ◈VII p = 0.26137 ◈XII p = 0.53683 *p = 0.075	p = 0.057 *p = 0.012	A pattern in the residuals is hardly noticeable	×

development of the study. Its effect is evident in the analysis of the variable Harvested area (ha). The observations of the number of harvested hectares that make up the 13 regions showed an excellent dispersion. It becomes noticeable once the maximum value found is analyzed, equal to 8.51×10^5 ha. in region VIII and the minimum 3.68×10^4 ha. In region XI, both average observations are notoriously distant in magnitude, clarifying the significant difference between them. It can be seen in detail in the box plot of Fig. 8.4, where the heterogeneity of the RHAs is observed, and some outliers present between them.

Figure 8.4 conditions establish why the initial comparison did not work. All the regions were evaluated simultaneously, which answer was enough statistical clairvoyance to affirm that there was some similarity between the regions for each one of the 26 variables compared.

The transgressions that were detected in some established groups were considered necessary to eliminate considering severe implications evidenced. Even though

Fig. 8.4 Graph of the behavior of the values by region for the variable harvested area (ha)

ANOVA is a reasonably robust model against certain types of deviations (Rodríguez 2015), the Kruskal-Wallis test was implemented when the samples did not proceed with an average population and/or when the population variances were heterogeneous (Guillen et al. 2012). These issues were presented in specific variables case like Total irrigated area, NAMO capacity, and the number of dams, for which some groups with the problems referred to above that were related to them were discarded.

However, it is essential to emphasize that the groups established from the closeness of means between RHAs and not simultaneously or through the results of the post hoc tests reflected an adequate statistical consistency that was measured and verified through parametric tests non-parametric.

Figure 8.5 presents the analysis of the group 2 behavior, which was prepared with the information from regions I, III, VII, XII (Northeast, North Pacific, Central Basins of the North and Yucatan Peninsula), which belong to the Population variable (inhabitants). In this Figure, the similarity that group 2 of RHAs presents about the Population variable is evident since according to its average value (established with a line in the central part of the graph), all the data boxes of the regions are very close to it.

These results were obtained using the regional grouping approach; consider the closeness of their means. This way of integrating the regions improved the results, originating several groups that, in which case, also turned out to be significant due to the reduction of the dispersion between the observations.

Likewise, the groups formed could help understand the interaction between the regions based on the variables analyzed and effectively manage strategies that link the various regions and basins with similar conditions.

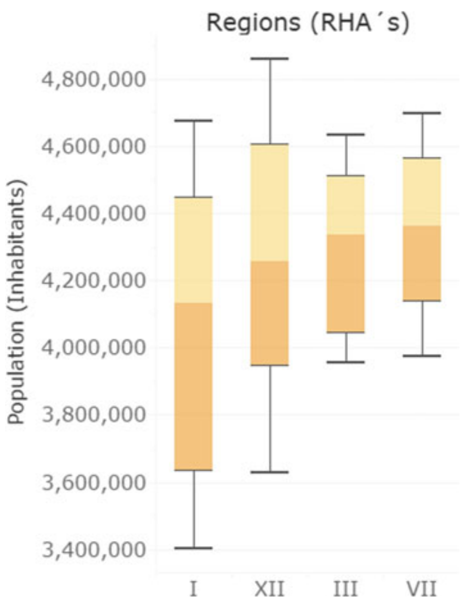

Fig. 8.5 Comparison between RHAs' group 2 regions I, III, VII, XII for the variable population (inhabitants) from a box plot

The future research questions from the results are how the regions can be reorganized according to the similarity between variables and regions. On the other hand, it is also implicit how the similarities between regions could improve the development of mechanisms of joint participation between RHAs from related themes derived from the analyzed variables.

8.4 Conclusions

The findings show that the similarities between the RHAs are present to a greater or lesser extent and depending on the type of variable analyzed. The analyzed variable defines the homogeneity between the RHAs yet to pass the territorial, geographical, demographic, structural, and agricultural differences between them.

On the other hand, it is essential to point out that the comparisons made through smaller groups of regions favored the analysis and the search for similarities between the RHAs. From this, it is concluded that as a whole, all the RHAs are so different from each other, but once they are analyzed carefully and in detail, it is feasible to group them and identify homogeneous conditions.

This way of reorganizing the RHAs has broad relevance in improving the understanding, performance, and implementation of strategies for access, distribution, and management of water and repercussions on the aspects related to the prevention, mitigation, and monitoring of the water. Drought at the national, regional, and basin levels.

In general, the search for similarities between RHAs is one more step in the comprehensive approach to understanding water-related problems and addressing their challenges in Mexico.

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Part II
Post-Disaster

Chapter 9
Optimising Distribution of Limited COVID-19 Vaccines: Analysing Impact in Argentine

Enrique Gabriel Baquela and Ana Carolina Olivera

Abstract Vaccination has become the most powerful tool to win the battle at COVID-19. Optimised distribution of the vaccines is crucial to provide a level of immunisation over a country that protects susceptible individuals from infectious diseases. However, the COVID-19 vaccines are recent, so manufacturing is slow. Consequently, its limited supply has a tremendous impact on the distribution policies in countries that depend on foreign supplies. In this chapter, a model of distribution of the COVID-19 vaccine is proposed, and several optimisation algorithms are tested. The proposal is tested in the Argentine scenario. It features an essential demonstration of the impact of an optimised distribution of the vaccine.

9.1 Introduction

Several pandemics have occurred during the last 20 years, such as the acute respiratory syndrome coronavirus (SARS-CoV) -2002 to 2003-, H1N1 influenza in 2009, and the Middle East respiratory syndrome coronavirus (MERS-CoV) in 2012. Since December 2019, the COVID-19 (Coronavirus Disease 2019) outbreak infected more than thousands of people. It killed more than hundreds in the first days of the outbreak in Wuhan city of southern China's Hubei province. Since that time, SARS-CoV-2 has infected more than 128,000,000 people, causing more than 2,800,000 deaths in 213 countries as of March 31, 2021. These facts indicate that the transmission rate of SARS-CoV-2 is higher than in other pandemics. With the rapid daily growth in the number of newly confirmed and suspected cases, vaccine immunisation has become

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a critical issue affecting the containment of the disease, especially in epidemic countries, which suffer from a lack of resources and low rates of detection (Chu et al. 2020). However, several vaccines have different profile characteristics (variations in the storage temperature requirements). Moreover, each country has a different infrastructure.

Currently, the COVID-19 outbreak is spreading rapidly, especially in cities with high population densities. Furthermore, people with minimal or no symptoms can also transmit the disease, making it difficult to control the outbreak. By using official information on the number of confirmed infected, vaccinated, recovered, and deceased, it is possible to use a modified SEIRV (Susceptible, Exposed, Infected, Recovered, Vaccinated) model to describe the dynamics underlying the progression of the disease shortly and to establish policies of vaccines distribution over a country to prioritise the immunisation of risk groups and cities with high infections minimising the cost.

In large countries with a low density of inhabitants per Km^2, but with a population mostly grouped in cities, the problem arises of distributing vaccines equitably while trying to reduce the total impact of the disease and take circulation into account between different urban. This applies to the case of many Latin American countries, such as Argentine, with cities that concentrate most of the population (in different jurisdictions) and a lot of interaction between them that cannot manage in isolation.

9.1.1 Literature Review

There exist several interesting works in the literature about optimising the distribution of vaccines. In Yang et al. (2021), the authors design the distribution network for WHO-EPI vaccines (World Health Organisation—Expanded Programme on Immunisation). The WHO-EPI was designed to provide universal childhood vaccine access for children across the world. The work is oriented to formulate the network design problem as a mixed-integer program (MIP) and present an algorithm for typical problems that are too large to be solved using commercial MIP software. The algorithm is tested using data derived from four different countries in sub-Saharan Africa.

Meta-heuristics have proven to be useful in different optimisation problems (Abdel-Basse et al. 2018; Baquela and Olivera 2019; Vidal and Olivera 2019; Rojas et al. 2020). Hu et al. (2014) introduce differential evolution to optimise the distribution of vaccines considering different ages groups of population and the impact in a SEIRV model. A classical infectious disease transmission model tested the proposed algorithm's performance, and a series of simulations have been made. The results showed that the proposed algorithm could obtain the best vaccine distribution strategy, minimising the number of infectious individuals during the epidemic outbreak.

Recently, Bertsimas et al. (2020) propose an epidemiological model to capture the effects of vaccinations and the variability in mortality rates associated with COVID-19. The authors integrate a predictive model inside the prescriptive model to optimise vaccine allocation. The authors propose a coordinate descent algorithm that iterates between optimising vaccine allocations and simulating the pandemic dynamics for the United States.

Matrajt et al. (2020) present an age-stratified mathematical model paired with optimisation algorithms to determine optimal vaccine allocation (COVID-19 vaccines) for four different metrics (deaths, symptomatic infections, and maximum non-intensive care unit and intensive care unit hospitalisations) under many scenarios.

Shim (2021) introduces the parametrisation of an age-structured model of COVID-19 spread in South Korea to understand the epidemiological characteristics of COVID-19. The model determines optimal vaccine allocation for minimising infections, deaths, and years of life lost while accounting for population factors, such as country-specific age distribution and contact structure and various levels of vaccine efficacy. A continuous-time age-structured ordinary differential equation (ODE) compartmental model simulates the progression of vaccines immunisation.

Concerning the ethics of the distribution of the vaccines, the WHO advised getting the vaccines equally distributed across all countries. Emanuel et al. (2020) present the Fair Priority Model (FPM), which explores the distribution in base of the Standard Expected Years of Life Lost indicator for each country.

In Jecker et al. (2021), several faces of the ethics about Covid-19 vaccines assignments are analysed. Global distribution and segmentation by risk, among others, are studied.

In this context, the chapter introduces a novel multi-objective optimising vaccines distribution approach that combines a modified SEIRV (Susceptible, Exposed, Infected, Recovered, Vaccinated) with multi-objective meta-heuristics to optimise the distribution of vaccines inside Argentine, taking into account the clusterised way in which Argentinian population is geographically distributed across the country, and proposing a measure to evaluate the equitably of the distribution itself.

The chapter is organised as follow: The Sect. 9.2 introduces the modified SEIRV build for the COVID-19 progression. Section 9.3 presents the multi-objective approach and multi-objective algorithms for its resolution. Section 9.4 presents the experimentation approach. Results are show in Sect. 9.5. Finally, in Sect. 9.6 conclusions are discussed, and future work is mentioned.

9.2 SEIRV Model

The Susceptible-Exposed-Infected-Recovered (SEIR) model became popular in the last year due to the possibility of shaping the dynamics of the epidemic (Mwalili et al. 2020; Yang and Wang 2020). With the second wave of COVID-19 on our doorstep, the governments worldwide destined their immunisation efforts of risk groups population. However, the vaccines are limited, so an analysis of immunisation's impact is crucial to take other policies like quarantine. Moreover, in countries with a large extension, the distribution of vaccines is an additional problem.

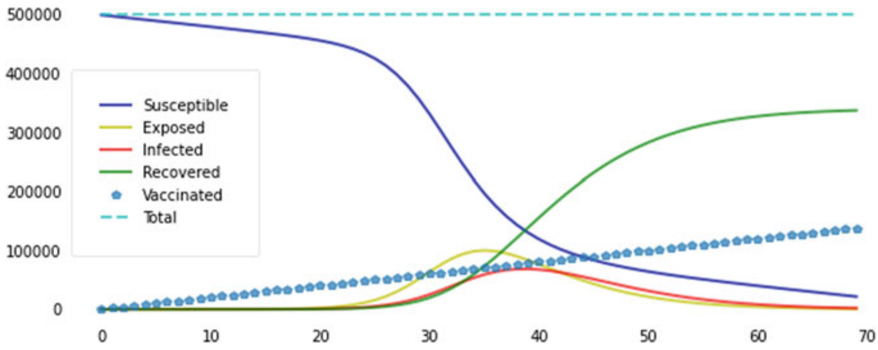

Fig. 9.1 Number of persons in each category as function of time

The SEIRV model presented in this chapter is an extension of SEIR in which individuals can be vaccinated. In this model, the whole population is split into categories: Susceptible, Exposed, Infected, Recuperated, and Vaccinated. Individuals flow from the Susceptible population to the exposed, then to infected, and finally to recuperate. The effect of vaccination, in this model, is to prevent that someone from a susceptible or exposed population can be infected. An example of how the number of persons in each category evolves in the SEIRV model is shown in Fig. 9.1. After a period of growth in the number of infected people, it tends to descent due to the combined effect of vaccinated and recovered persons (both immune, at least in the short term).

The SEIRV model presented in this chapter is based on the model proposed by Hu et al. (2014), in which the whole population is clustered into different groups, which some degree of interconnection. A low rate of interconnection means that the groups are more or less isolated, so can be handled separately. Conversely, a very high degree of interconnection means that all groups must be handled as a unique group. To handle these two situations and all intermediate scenarios, the model updates the infection rate with the information provided by an interconnection matrix. The whole formulation of the problem is shown in Eqs. (9.1), (9.2), (9.3) and (9.4).

$$\dot{S}_i(t) = -\lambda_i(t)(S_i(t) - v_i(t)) - v_i(t) \tag{9.1}$$

$$\dot{E}_i(t) = -\tau_i E_i(t) + \lambda(t)(S_i(t) - v_i(t)) \tag{9.2}$$

$$\dot{I}_i(t) = -\gamma_i I_i(t) + \tau_i E_i(t) \tag{9.3}$$

$$\dot{R}_i(t) = \gamma_i I_i(t) \tag{9.4}$$

$S_i(t)$, $E_i(t)$, $I_i(t)$, and $R_i(t)$ are the susceptible, exposed, infected, and recovered number of individuals in cluster i at time t. Differential Eqs. (9.1), (9.2), (9.3) and (9.4) model the variation of the number of individual in each cluster as a function of time. $v_i(t)$ is the vaccination rate in cluster i at time t, $\lambda_i(t)$ models the risk of any individual from cluster i to be infected at time t, $-\tau_i$ is the probability of exposed individual to be infected, and γ_i is the recovering rate. All clusters are interrelated by the $\lambda_i(t)$ factor, which takes into consideration the degree of interaction between members of different clusters. Its formulation is shown in the Eq. (9.5), where P_i is the total number of individual in cluster i, β_i is the vulnerability of the population in cluster i and $c_{i,j}$ is the rate of interaction between individual in cluster i and j.

$$\lambda_i(t) = \beta_i \frac{S_i(t)}{P_i} \sum_{j=1}^{n} c_{i,j} \frac{I_j(t)}{P(j)} \tag{9.5}$$

The $\lambda_i(t)$ calculation proposed by Hu et al. (2014) is modified in this work considering to work with rates of interactions.

The vaccines are received in batch, and the maximum number of people vaccinated in each cluster each day depends on the storage capacity and the vaccination service rate. Also, the best vaccination policy is to vaccinate as many persons as it is possible. We assume that $v_i(t) = v_i$ is a constant value.

The objective of a vaccination policy is to reduce the number of infected individuals. So, starting the vaccination at time t_{vacc}, the objective can be expressed by the Eq. (9.6)

$$Minimise f(V(t_{vacc})) = \int_{t=t_{vacc}}^{T} \sum_{i=1}^{n} I_i(t)\,dt \tag{9.6}$$

where T is the horizon of the analysis, and n the number of clusters.

Also, potential solutions are constrained to not distributed more vaccines than the available vaccines (Eq. (9.7)).

$$\sum_{i}^{n} v_i \leq \text{ Available vaccines per day} \tag{9.7}$$

9.3 Multi-Objective Optimisation

One way to cluster the population is based on the risk of disease in case of being infected. That is the criterion chosen for most governments to define priorities for vaccination in the COVID pandemic. But, in a wide country, like Argentina, there is a logistic problem to vaccine distribution and a legal and/or ethical one: you cannot give to some province or city many vaccines keeping another group without vaccines. This is, vaccines must be geographical-distributed based on equality considerations.

This enters into a conflict with the SEIRV model's optimisation because it tries to minimise the total number of infected without considering the interconnected groups. To consider both objectives and give a tool to evaluate the impact of distribution over the number of infected, the single-optimisation problem is expanded to a multi-objective one. The distribution of the vaccines across geographical groups is measured by the Gini coefficient (Mukhopadhyay and Sengupta 2021). So, the second objective is to minimise inequalities in vaccines assignment among clusters (Eq. (9.8)).

$$Minimise f(V) = \frac{\sum_{i=1}^{n}\sum_{j=1}^{n}\left|\frac{v_i}{P_i} - \frac{v_j}{P_j}\right|}{2n^2 v} \tag{9.8}$$

The Gini coefficient measures income distribution among individuals or households in a given country with respect to a perfectly equal distribution. A value of 0 represents absolute equality, whereas 1 would be the highest possible degree of inequality. This measurement reflects the degree of wealth inequality at a certain moment in time (Mukhopadhyay and Sengupta 2021). In this work, we use a Gini = 0 if all provinces receive the same number of dosses per inhabitant and 1 if only one province receive all the vaccines.

9.3.1 Multi-Objective Optimisation Algorithms

Multi-objective Evolutionary Algorithms (Deb 2001) (MOEAs) are specific Evolutionary Algorithms conceived to solve problems with many conflicting objective functions. MOEAs have obtained accurate results when solving difficult real-life optimisation problems in many research areas. This section introduces four multi-objective algorithms to generate a spectrum of possible solutions that consider both distribution policies over a country and SEIRV model impact.

NSGA-II (Non-Dominated Sorting Genetic Algorithm II) (Deb et al. 2002) is a popular MOEA that has been widely employed in different areas. NSGA-II begins creating random n solutions (initial population). In each generation, NSGA-II uses a selection operator that creates a mating pool by combining the parent and offspring populations and selecting the best n solutions (concerning fitness and spread). NSGA-II applies Pareto dominance for the fitness calculation, building fronts of solutions. The evolutionary search on NSGA-II overcomes the previous version (NSGA) by using: (i) a non- dominated, elitist sorting that reduces the complexity of the dominance check; (ii) a crowding technique for diversity preservation; and (iii) a fitness assignment that considers crowding distance values.

NSGA-III (Non-Dominated Sorting Genetic Algorithm III) (Deb and Jain 2014) is an extension of NSGA-II, which has been proposed to improve the performance of NSGA-II (i.e., the Pareto sets provided by NSGA-II). NSGA-III uses a predefined set of reference points to ensure diversity in obtained solutions. The chosen reference points can either be predefined in a structured manner or supplied preferentially by the user. In the absence of any preference, can adopt information predefined structured placement of reference points. NSGA-II not only emphasises non-dominated solutions, also emphasise population members that are in some sense associated with each of these reference points. Since the above-created reference points are widely distributed on the entire normalised hyper-plane, the obtained solutions are also likely to be widely distributed on or near to the Pareto-optimal front.

Li et al. (2019) introduces the Two-Archive Evolutionary Algorithm for constraints multi- objective optimisation (CTAEA). CTAEA is based on a parameter-free constraint handling technique that uses two co-evolving archives: the convergence archive and the diversity archive. The objective of the archives is to provide diversification information (convergence archive) whilst the diversity archive is used to explore areas under-exploited by the converge archive, including the infeasible regions.

Multi-objective Evolutionary Algorithm based on Decomposition (MOEA/D) (Zhang and Li 2017) employs a domain decomposition approach to solve several single-objective optimisation problems through a linear aggregation. The algorithm uses different weights for each objective function. A cooperation schema is also utilised: sub- problems are solved considering the information from neighboring sub-problems. The linear aggregation strategy is usually outperformed by Pareto-based methods when solving multi-objective optimisation problems. Still, it is a common approach in the literature mainly due to two main advantages: it is computationally efficient, so it is recommended when the time available for searching is short. MOEA/D is suitable for optimisation problems with a convex Pareto front (Coello et al. 2002).

Finally, the Adaptive weighted-sum method (AWSM) (Kim and De Weck 2005) is a bi-objective optimisation algorithm that determines the Pareto front that focuses on unexplored regions by changing the weights adaptively, specifying additional inequality constraints. The method was special designed for non-convex regions.

9.3.2 Solution Encoding

The solutions for the distribution of vaccines are represented as an array of n elements, in which each element *i* is the number of vaccines applied in each cluster *i* at each day. Each element *i* is bounded between 0 and the maximum number of available vaccines per day.

9.4 Experiments

Section 9.4.1, analyses the model implementation with five different multi-objective meta-heuristics, using a set of artificial model scenarios, which each cluster each one. Section 9.4.2 applies the model to real-world set of cases based on Argentinian demography.

9.4.1 Experiments Over Fictional Scenarios

To test our model, it was solved using five different meta-heuristics. Ten scenarios were defined, each of them with four clusters and using randomly generate interrelation matrices. Each value cell matrix was randomly selected to follow a uniform distribution with parameters 0 and 0.2 (except the diagonal, which is filled with 1). Each algorithm was executed 10 times in each scenario. The time horizon taken into consideration was 100 days. Results reached by the Adaptive Weighted Sum method were used as the benchmark Pareto Frontier, calculating the Dominated Hypervolume of the rest of the methods respects this one. The parameters values for each algorithm is shown in Table 9.1.

To compare the performance of all algorithms, three indicators for multi-objective algorithms are taken into account: the number of non-dominated solutions found (# NDS), Dominated Hypervolume (DH) concerning the Dominated Hypervolume generated by the AWSM, and the Additive Epsilon Indicator (EPS).

The Dominated Hypervolume (DH) is a well-known indicator that measures how much volume of the solution space is dominated by the curve evaluated (Zitzler et al. 2007). As bigger its value is, the more space the curve dominates. DH is calculated as is indicated in Eq. (9.9). A point outside the curve is used as a reference point. Then, |Q| hypercubes v_i are built, using opposite corners the reference point and the point i of the curve to evaluate. Then, all hypercubes are joined, and the total volume is calculated.

$$DH = volume\left(\bigcup_{i=1}^{|Q|} v_i\right) \tag{9.9}$$

The Additive Epsilon Indicator (EPS) is another well-known indicator that measures how similar a curve is to a benchmark curve (Liefooghe and Derbel 2016). Assuming that the benchmark curve is a real Pareto Frontier of a multi-objective problem or a good approximation to that, smaller values of this indicator mean a better match of the evaluated curve to the benchmark curve (a value of 0 means perfect match). It is calculated with the Eq. (9.10), A is the curve to evaluate, R is the real Pareto Frontier (or the approximation), and d is the number of objectives of the problem.

$$EPS_{(+)} = \max_{r \in R} \min_{a \in A} \max_{i \in \{1..d\}} (a_i - r_i) \tag{9.10}$$

Table 9.1 Parameters' configuration

Algorithm	Parameter	Value
NSGA-II	Population	100
	Generations	200
	Initial pop	Random
	Selection	Tournament
	Cross. prob	0.8
	Mut. prob	0.1
NSGA-III	Population	100
	Generations	200
	Initial pop	Random
	Selection	Tournament
	Cross. prob	0.8
	Mut. prob	0.1
	Reference points	Das-dennis
	Partitions	12
MOEA/D	Mattin prob	0.7
	Generations	200
	Reference points	Das-dennis
	Partitions	12
	Neighbour	15
CTAEO	Reference points	das-dennis
	k	5
AWSM	Weight	[0–1]
	Weights variation	0.01
	Solving each stage	Differential evolution

9.4.2 Experiments with Argentinian Data

The population distribution for each Argentine Province and the country's Capital is shown in Table 9.2. Considering the WHO recommendations and researchers' recommendations (Matrajt et al. 2020), Argentine establish three main risk groups for each province. The group with the highest risk, comprising the older people and medical workers, is around one-third of the total population. This group has the higher priority to get vaccinated, so we focus our study on this group.

To perform the analysis included in this paper, we estimated three different randomly generated interaction matrices. The values were sampled from a uniform probability distribution for provinces with a border in common, with parameters 0.05 and 0.2. For provinces without borders in common, the probability distribution parameters were 0.05 and 0.1. All elements in the diagonal were set to 1.

Table 9.2 Population distribution in Argentine

Province	Inhabitants	Km^2	Density
Ciudad Autónoma de Buenos Aires	2,890,151	200	14,450,8
Buenos Aires	15,625,084	307,571	50,8
Catamarca	367,828	102,602	3,6
Chaco	1,055,259	99,633	10,6
Chubut	509,108	224,686	2,3
Córdoba	3,308,876	165,321	20
Corrientes	992,595	88,199	11,3
Entre Ríos	1,235,994	78,781	15,7
Formosa	530,162	72,066	7,4
Jujuy	673,307	53,219	12,7
La Pampa	318,951	143,440	2,2
La Rioja	333,642	89,680	3,7
Mendoza	1,738,929	148,827	11,7
Misiones	1,101,593	29,801	37
Neuquén	551,266	94,078	5,9
Río Negro	638,645	203,013	3,1
Salta	1,214,441	155,488	7,8
San Juan	681,055	89,651	7,6
San Luis	432,310	76,748	5,6
Santa Cruz	273,964	243,943	1,1
Santa Fe	3,194,537	133,007	24
Santiago del Estero	874,006	136,351	6,4
Tierra del Fuego, Antártida e Islas del Atlántico Sur	127,205	1,002,445	0,1
Tucumán	1,448,188	22,524	64,3

Extracted from http://www.ign.gob.ar/NuestrasActividades/Geografia/DatosArgentina/DivisionPolitica on 2021-03-30

9.5 Results

The experiments were carried out over fictional scenarios and real-world Argentine scenario. The results of fictional scenarios were used to select the meta-heuristic applied over real-world scenario.

9.5.1 Results Over Fictional Scenarios

The algorithms were used for the ten fictional scenarios defined in Sect. 9.4.1. Table 9.3 resumes the comparison between each algorithm's results and indicators. For

Table 9.3 Comparison between algorithms

Scenario	Algorithm	# Non dominated	Avg compared DH	Min compared DH	Max compared DH	Avg epsilon
1	NSGA-II	98	1.375	0.891	1.561	5.63E-07
	NSGA-III	74	1.141	0.743	1.237	3.49E-08
	MOEAD	5	0.047	0.000	0.098	6.26E-01
	CTAEO	13	0.275	0.089	0.434	8.69E-04
2	NSGA-II	94	1.822	1.003	1.948	4.83E-07
	NSGA-III	87	1.263	0.862	1.514	2.30E-08
	MOEAD	12	0.228	0.077	0.398	5.72E-01
	CTAEO	16	0.741	0.097	0.797	4.27E-04
3	NSGA-II	94	1.515	1.255	1.741	3.09E-07
	NSGA-III	85	1.155	0.982	1.454	5.13E-08
	MOEAD	15	0.279	0.226	0.324	8.23E-01
	CTAEO	18	0.587	0.349	0.771	3.23E-04
4	NSGA-II	92	1.789	0.92	1.864	5.59E-08
	NSGA-III	78	1.431	0.947	1.63	1.12E-08
	MOEAD	17	0.352	0.236	0.475	7.11E-01
	CTAEO	24	0.434	0.337	0.452	9.10E-04
5	NSGA-II	89	1.493	1.043	2.039	1.09E-07
	NSGA-III	86	1.633	0.806	1.822	2.23E-08
	MOEAD	7	0.321	0.259	0.434	6.14E-01
	CTAEO	30	0.762	0.425	0.916	7.51E-04
6	NSGA-II	83	1.781	1.092	1.969	5.91E-07
	NSGA-III	86	1.595	0.774	1.715	5.99E-08
	MOEAD	6	0.413	0.127	0.499	3.66E-01
	CTAEO	23	0.701	0.211	0.794	6.32E-04
7	NSGA-II	91	1.762	1.011	2.054	2.82E-08
	NSGA-III	84	1.371	1.045	1.714	5.74E-08
	MOEAD	17	0.314	0.252	0.494	6.74E-02
	CTAEO	17	0.46	0.268	0.493	9.65E-04
8	NSGA-II	96	1.751	1.035	1.767	7.37E-07
	NSGA-III	88	1.338	0.891	1.42	2.29E-08
	MOEAD	11	0.458	0.14	0.496	8.67E-01
	CTAEO	26	0.692	0.532	0.823	2.28E-04
9	NSGA-II	97	1.640	1.099	1.766	4.09E-07
	NSGA-III	79	1.217	0.926	1.44	3.56E-07
	MOEAD	10	0.211	0.18	0.281	5.92E-01

(continued)

Table 9.3 (continued)

Scenario	Algorithm	# Non dominated	Avg compared DH	Min compared DH	Max compared DH	Avg epsilon
	CTAEO	29	0.487	0.286	0.546	9.47E-04
10	NSGA-II	87	1.508	1.351	1.856	7.69E-07
	NSGA-III	83	1.560	1.102	1.733	4.67E-08
	MOEAD	17	0.464	0.402	0.533	4.43E-02
	CTAEO	21	0.497	0.460	0.657	2.96E-04

*MOEAD does not converge in more or less 60% of the runs
**Best values are in bold

each scenario and algorithm (NSGA-II, NSGA-III, MOEA/D and CTAEO), the table shows the number of non-dominated solutions reached, the mean value, the minimum and the maximum of the Dominated Hypervolume compared with the AWSM, and the average epsilon indicator (using as reference the Pareto Frontier found by the Adaptative Weighted-Sum method).

Table 9.3 shows that both NSGA-II and NSGA-III obtain better results than the rest of the algorithm. NSGA-II performs better than NSGA-III in terms of the number of non-dominated solutions found and Dominated Hypervolume (for both, greater is better). Still, NSGA-III reaches better values than the Epsilon indicator (smaller is better).

Figure 9.2 shows an example of the shape of the Pareto Front found by the NSGA-II algorithm for a fictional scenario. Most of the results are concentrated in an interval between 7,000,000 and 8,000,000 infected, allowing to perform a very equitation

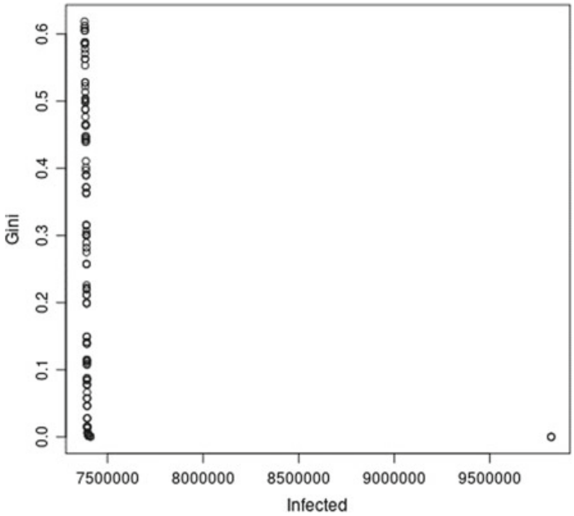

Fig. 9.2 Pareto Front found in one of the executions by the NSGA-II algorithm

distribution of vaccines keeping the number of infected almost constant. A detail of the range 7,000,000–8,000,000 is shown in Fig. 9.3. Clearly, if the distribution of vaccines is not the same for all provinces, immunisation provokes a reduction in the number of infected. In resume, the distribution of the number of vaccines for province made for the algorithm produces a positive result in the immunisation considering the impact in the number of infected.

Examples of how the NSGA-II evolves in one of the ten scenarios can be seen in Figs. 9.4 and 9.5. In these, the evolution of EPS and the number of non-dominated

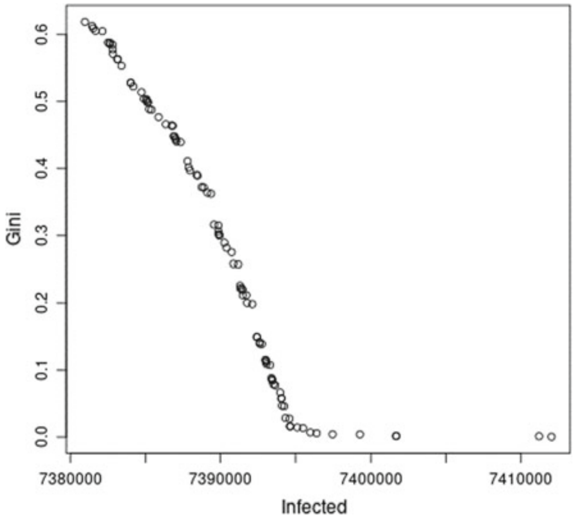

Fig. 9.3 The same Pareto Front than Fig. 9.2 with zoom in the region of 7,000,000–8,000,000 infected

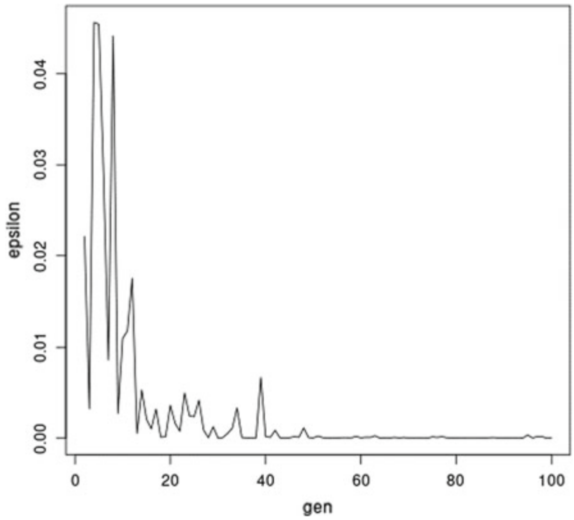

Fig. 9.4 Evolution of EPS for one of the executions of the NSGA-II algorithm over a fictional scenario

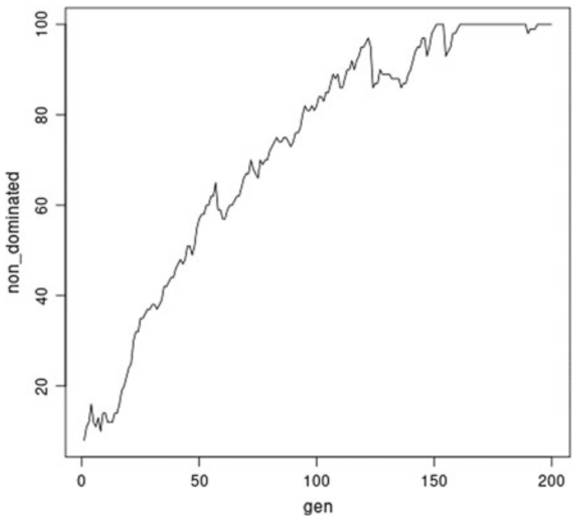

Fig. 9.5 Evolution of the number of non-dominated solutions found for one of the execution of the NSGA-II algorithm over one fictional scenario

solutions across generations are shown. In particular, EPS begins with a high value (near to 1), finalising with a value near 0.0000367(Table 9.4). Similarly, the number of non-dominated solutions increases considerably during the evolution, and it stabilises between the 150 and 200 generations that implying a variety of solutions alternatives for the decision-makers (Table 9.4).

9.5.2 Results with Argentinian Data

Considering the results reached in the previous section, Argentinian scenarios were run using the NSGA-II algorithm. Figure 9.6 shows the Pareto Frontier found for one of the scenarios. A wider trade-off between the number of infected people and the Gini coefficient can be found here. This can be caused for the disparity in population density in the country: *Ciudad Autónoma de Buenos Aires* and *Buenos Aires* have a big density, but provinces like *Santa Cruz* do not. Being the density not uniform, it has the sense to give more vaccines per inhabitant to provinces with more density. Despite this, good policies can be found keeping the Gini coefficient below 0.4. Above this value, there is not an important reduction in the number of infected individuals.

Table 9.5 summarises the result for two of the solutions in this Pareto Frontier. The first solution has a lower number of infected persons but a higher Gini value—the second one, a better Gini value but a worse number of infected people. The table shows the number of infected at the end of the evaluation period, the Gini value, and the minimum, median, mean and maximum number of vaccines assigned per 1000 inhabitants. It can be seen how the number of doses per inhabitant has a greater range of variation in solution 1 than in solution 2. Also, in solution 1, the median and the mean of the distribution of the vaccines is small than in solution 2, indicating

Table 9.4 Epsilon evolution in NSGA-II

# Generation	Non-dominated solutions	EPS
1	8	0.83439
10	14	0.010983564
20	24	0.003607091
30	38	2.06E-05
40	46	0.000171397
50	57	4.03E-05
60	57	4.51E-05
70	67	3.56E-05
80	72	3.48E-05
90	74	3.72E-06
100	82	2.18E-05
110	86	2.61E-05
120	95	2.04E-05
130	89	9.55E-07
140	90	9.19E-06
150	99	6.39E-05
160	99	5.44E-06
170	100	5.61E-06
180	100	5.18E-05
190	98	0.000186596
200	100	3.67E-05

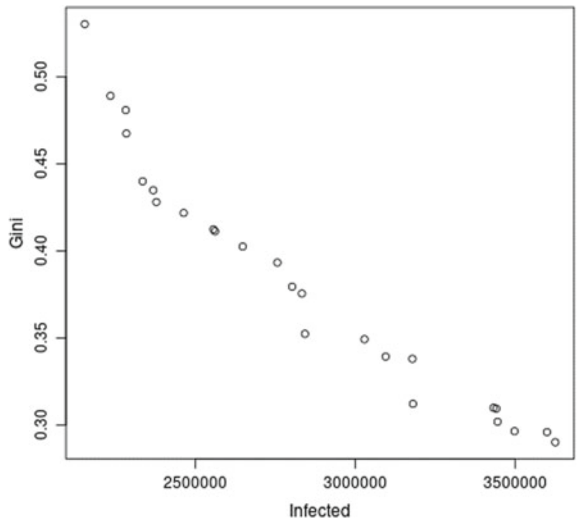

Fig. 9.6 Pareto Frontier for one of the randomly matrices generated for the Argentinian scenario

Table 9.5 Two examples of solution found with the NSGA-II algorithm for the Argentinian case

Solution	Infected	Gini	Min	Median	Mean	Max
1	2,687,940	0.403	0.019	3.421	3.711	9.439
2	3,426,289	0.305	0.260	4.298	4.104	7.999

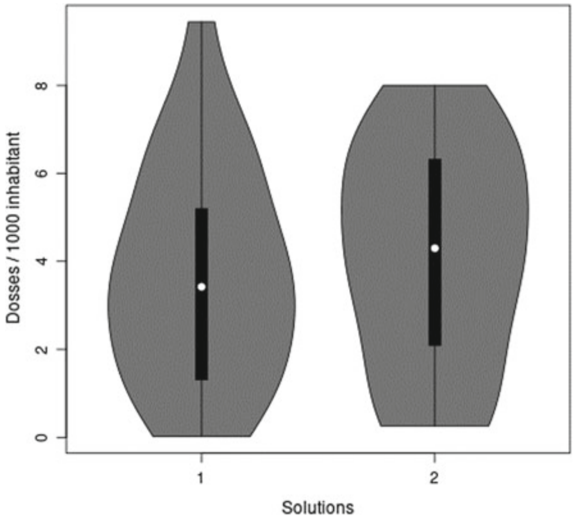

Fig. 9.7 Distribution of vaccines per province in solutions 1 and 2

that there are many states with few doses and few with a big number of dosses per inhabitants. These differences in distribution can be observed in Fig. 9.7, and the distribution of vaccines in solutions 1 and 2 can be seen in Figs. 9.8 and 9.9. The difference in the number of infected people is also important, more than 1,000,000 (approximately the 2.5% of the total population of Argentina).

9.6 Conclusions and Future Work

Vaccines distribution in geographically clusterised populations can be reached, obtaining good results concerning the number of infected people, assuring an equitable assignment to different clusters.

A significant result is that, at least in the studied cases, the trade-off between the number of infected and the Gini coefficient reduces the last a lot, keeping the first one in a small range of variation.

The most crucial point is to have a reasonable estimate of the interaction matrix (and the infection parameters).

NSGA-II gives us outstanding results. NSGA-III could need an improvement in its parameters, but it looks promissory. The adaptive weighted method is suitable but

Fig. 9.8 Distribution of vaccines per province in solutions 1. Darker means more vaccines per inhabitants

Fig. 9.9 Distribution of vaccines per province in solutions 2. Darker means more vaccines per inhabitants

consumes more time than the previous two algorithms. Anyway, the three look like good tools for providing helpful information about the possible ways to distribute vaccines.

As a future work, it will be interesting to evaluate the problem with different ranges of values in the interaction matrices to check if the behaviour related to the relative robustness of the number of infected people concerning Gini coefficient variation. Also, due to the isolation strategy has given good results in several countries (including Argentina), must evaluate its combination with the vaccination policy.

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Chapter 10
Location of Regional Humanitarian Response Depot (RHRD) in the Seven Regions in the State of Puebla

Carlos-Vicente Rascón-Limón, Diana Sánchez-Partida, José-Luis Martínez-Flores, and Santiago-Omar Caballero-Morales

Abstract For Humanitarian Logistics (HL), the management of supplies cannot be improvised at the time of an emergency. However, it must be incorporated as a planned activity. Organizations that attend emergencies constitute a chain whose segments are closely linked and where the management of each of them has an impact on the results of the others. This research has as its first the location of the municipalities where they can be established Regional Humanitarian Response Depot (RHRD) for the distribution of aid kits in the seven regions in which the State of Puebla is formed because each of these areas is exposed to both hydrometeorological and geological risks, which affect the general population. Therefore, it is mentioned that a location model was used, based on the Weber Problem, and that it is known as Attraction and Rejection, which aims to find desirable locations, rejecting the risk of a wrong location. This method was able to locate municipalities that meet both minimum distance conditions as well as risk reduction and consider them as feasible to host the RHRD.

Keywords Humanitarian logistics · Regional Humanitarian Response Depot (RHRD) · Weber problem · Attraction and rejection · Risk reduction

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10.1 Introduction

Currently, Logistics has been used to respond in natural disaster scenarios, which are very similar to military scenarios. Humanitarian logistics systems are compared to military systems, and potentially transferable quantitative models are identified between the two in their functional concepts, as well as their goals, necessary implementation capabilities, and various emerging concepts (González-Rodríguez et al. 2012).

Logistics is then presented as the art or strategy of achieving practical objectives in the quickest and organized way possible, making the most of the resources available, which in emergencies are often extremely limited, which is why two relevant considerations must be made.

In emergency operations, Logistics is required to support the organization and implementation of response actions so that they are not only fast, but also agile and effective. The mobilization of personnel, equipment, and material necessary for the work of organizations assisting and even activities related to the evacuation of wounded or the relocation of populations affected by the disaster, require a logistic system to be carried out efficiently, seeking the reduction of risks (Pan American Health Organization and World Health Organization 2001).

Humanitarian Logistics (HL) involves all actions aimed at risk mitigation, reducing the impact of the disaster, and returning to the state of normalcy (Hoyos et al. 2015). The phases of Humanitarian Logistics are divided into four stages: mitigation, preparedness, response, and recovery (Van Was-senhove 2006; FEMA 2010; Afsar et al. 2014; Anaya-Arenas et al. 2014; Rivera et al. 2015). This four-stage approach allows covering the planning of the system from the strategic, tactical, and operational levels (Rancourt et al. 2015).

The activities of the mitigation and preparedness stages are carried out before the occurrence of the disaster. The mitigation stage includes the risk study and structural analyses (Yi and Özdamar 2007), as well as the determination of possible land and infrastructure, uses to ensure accessibility to these areas (Kovács and Spens 2009).

In Mexico, the General Law on Civil Protection, and the State Civil Protection Laws, contemplate three phases: Prevention: These are all actions that are carried out before an emergency or disaster occurs. Aid or Assistance: These are the activities of assistance to the population affected by the presence of an emergency or disaster and should be timely and enough. Recovery: These are the actions that are taken to restore services and activities that have been affected by the presence of an emergency or disaster until it returns to normal.

Before disaster strikes, it is essential to have facilities to support the survival of people. Therefore, among the most critical decisions to assist communities is the location of RHRD. It will enable the protection and efficient and timely supply of products to meet the basic needs of people affected by accidents, reducing risks (Caballero-Morales et al. 2018).

For all the above, this research will be able to analyze how the preparation stage contributes through the development of a Logistics Decision Model to establish

RHRD in each of the Seven Regions of the State of Puebla using the Attraction and Rejection Problem that allow generation of optimal solutions to contribute to the anticipation of natural disasters that put the general population at risk.

10.2 Literature Review

The logistical management of disaster care operations, also called Humanitarian Logistics (Baldini et al. 2012), is a discipline that has developed in response to the increasing severity and frequency of disasters, both natural and human-made (Camacho-Vallejo et al. 2015). The effects of disasters are devastating on human and material losses (Barbarosoğlu and Arda 2004; Oloruntoba and Gray 2009; Kunz et al. 2014), and test the ability of nations to adequately protect their infrastructure and population and recover quickly (Altay and Green 2006).

Humanitarian Logistics is responsible for estimating, providing, storing, transporting and distributing the personnel and services required in the disaster-affected area (Sharif and Salari 2015), through a wide variety of activities carried out at different times, which aim to assist disaster survivors (Kovács and Spens 2007). The main objective is to provide emergency supplies quickly to affected areas, minimizing deaths and human suffering (Balcik and Beamon 2008).

The preparation stage includes all activities carried out by the population, local governments, and other organizations before the disaster occurred to reduce potential risks (Kunz et al. 2014). Preparation activities include: recruiting volunteers, training communities in the vulnerable area, acquiring emergency vehicles and equipment, purchasing and storing emergency supplies, and designing emergency plans (Altay and Green 2006).

For Ozguven and Ozbay (2015), the pre-disaster stages are the most important in logistics processes and must begin by establishing the necessary relations between governments, military forces, civilian agencies, and the private sector. Therefore, better preparation should lead to a much more efficient response phase, provided that Logistics is understood as an intrinsic element in emergency operations; that is, it must consider logistics as a bridge between disaster preparedness and response (Van Wassenhove 2006; Kovács and Spens 2007).

The literature shows that the mitigation and preparation stages serve, in the Humanitarian Logistics process, the purpose of designing the care chain, through actions such as identifying and preparing actors, selecting locations for RHRD, or charting aid distribution routes. Verma and Gaukler (2015) argue that the location of sites for the storage of emergency supplies is a critical factor for the quality of service provided after the disaster.

Optimal location of facilities is a problem that occurs in various areas and contexts, and for resolution, scientists have used operations research techniques (Owen and Daskin 1998). The first models were formulated in 1961 by Balinski and have been developing from then until now.

The problem of localization for RHRD has been studied and modeling for a few years now. In 1963, Cooper presented a method for deciding where to locate facilities to respond to emergencies, optimally allocating demand for aid from those facilities, and effectively using resources. Other authors propose models considering strategies to locate their RHDR is in some locations to address emergencies that arise in different parts of the world.

The diversity of the factors involved in the localization of industry has moved a good number of researchers to build theories and models, which try to explain the complexity of the real world through necessary simplifications of it, taking some factors as constants and others as variables. These theories tend to be deductive in the method and deterministic in the procedure. Its principles are related to the Theory of Localization and are based on alleged simplifications abstracted from real situations (Vallejo 2007).

These models are usually grouped into three or four schools or trends.

First group: Theory of Minimum Cost: includes mainly Weber's work. Based on the search for the optimal combination of production factors in each location, to obtain the minimum cost of transport. Weber also considers other aspects related to the cost of the hand and the effects of agglomeration.

Second group: Corresponds to the analysis of market areas. The aim is to find a location where a company can access the maximum number of consumers, to maximize its total income. The most representative authors are August Lush and Hotelling with the theory of location interdependence, which for some forms, a third group, and others are included within this group in the market areas.

Third group: incorporates the works of Greenhut, Isard, and Smith, can be encompassed under the theory name "Cost–Benefit," or also "Theory of substitution of factors." They are based on spatial variations in costs and revenues, considered simultaneously over time, also including the influence of the entrepreneur's decisions on localization, following a rational process of substitution of factors to obtain the most convenient combination. They have a more integrated structure than the previous ones and seem more applicable to reality.

For some, von Thünen (1783–1850) is recognized as the father of localization theories and is considered the author who initiated it. He used the construction of models to discuss the effect of different variables on the balances studied. Their models sought to explain the location of agricultural activities, unlike abstract interpretations of classical authors, based on empirical observations in their analyses, where it gave importance to cities, the influence of distance, transport costs, and itself, to the location of economic activities on market prices. His most crucial thesis is that distance and cost of transport determine the location of economic activities leading to the formation of economic zones around a city in a homogeneous space. It leads to the configuration of a single-center city whose concentric ring structure is created by leasing and transport costs, which would result in differential prices from the center floor to the periphery (Becerra Valbuena 2013).

Later, Weber (1929) would propose that distance to access the market and natural resources in anisotropic space is the primary factor that determines the location of an industry. For him, the industry seeks to locate itself where its transport costs are minimized, considering the proximity to the market and the factors of production, especially the work factor that is abundant. Finally, Weber added the concept of agglomeration that by being closer to others, industries benefit in terms of transportation costs, the proximity of skilled labor, access routes, and resources. This concept explains the spatial concentration of economic activities, the emergence of cities, and polarized regions. However, some criticize Weber for considering transportation costs only in terms of distance and for not considering the time it takes to arrive at a reasonable or production factor. Simplified the problem, he tried to establish the location where a company could produce with the minimum cost, through a geometric solution, the location triangle. The Optimum Location Triangle sought to explain that automated localization decisions would occur at the point of space that had the most favorable combination of Transport Costs with the three fundamental factors (raw materials, labor, and market).

Another precursor was Hotelling (1929), which introduced a more theoretical analysis using Cournot-type duopoly models. The author modeled competition in prices between firms that are subject to transportation costs and that look for location along a line of length that gives them higher demand from buyers. Consumers are rational and aim to buy from the firm that offers them the lowest total price (price + transportation costs). The remarkable thing about Hotelling is that it directly raised competition between two firms along a straight line, unlike von Thünen and Weber, who considered elements such as distance and proximity to production factors but in terms of a single firm. The optimal solution for duopoly occurs when each producer is at the midpoint of its market area, where the transport costs for consumers and maximum profits for the entrepreneur are minimal.

Previous authors can be noted as the forerunners of the Central Places Theory (CPT), ideas that were best developed by Walter Christaller in his doctoral thesis "Die Zentralen Orte in Süddeutschlan" (The central locations in southern Germany) (1933) and continued by Lösch (1954). Much of this structure was given by Christaller and refined by Lösch to find that the same proximity between central places makes the spatial distribution of them take on a hexagonal shape, which is the most efficient. The location depends on the production and transportation costs inherent with the central location. Perhaps the essential feature between these two authors is the idea that more significant central places supply services and goods to smaller places, thus creating a hierarchy of cities. In such city systems, population growth plays a crucial role in explaining the creation of these networks and in explaining post-industrial change where the service sector is beginning to be of greater importance. This model went from descriptive to predictive, and many cities interpreted as having lagoons and created gigantic state capitals to rebalance, others created central cities (Valladolid, Tarragona). They saw what they were missing and created cities that filled in those gaps. This model can be useful for the analytical study of those industries where products are standardized, and transport costs are high enough to represent a substantial part of the price. It is equally useful for analyzing procurement areas, where many raw material supplies cover ample space, selling identical products to a small number of producer-buyers, as in the case of agricultural industries.

Subsequently, other theorists emerge from analyzing the market area based on the spatial distribution of demand and how it influences the location (Greenhut 1956). The underlying assumptions they introduced in the classic model were (a) That the single market is a case. (b) That buyers are scattered in a market area. Therefore, if a buyer must choose between two competitive sellers, he will tend to orient himself towards the nearest one; therefore, the producer tends to get as close to the market as possible. Greenhut, too, thinks that deductive theories are intended for large companies and that for individual company's contacts are more important than factor substitutions. For Greenhut, economic forces can serve to determine the limits within which a location can be chosen.

Another significant contribution to the discussion is made by Walter Isard (1960), who was one of the forerunners in the inclusion of space to the theory of general equilibrium. In models of spatial and gravitational interaction, the Region is conceived as a mass, and the interregional relationships of such individual particles can be thought of as those made between masses. Isard provides a rigorous empirical analysis of regions and economic activity in the United States, where it widely applies the probattled by him. Isard overlays the modified landscape of Lush on the location of Weber's raw materials. From here, he began to investigate the formation of industrial complexes based on the creation of economies of scale, pointing to the dependence on localization against the regional economic space itself.

Finally, reference is made to the D. Smith model (1979), a conceptual schema in which new variables are introduced. At the center is the transformation of inputs, that is, laceration of the value-added. The transformation process is purely technical, defined as a productive function, which will vary according to the economic system and the technology adopted. Production caters to human needs and desires; the market points to individual preferences, and, increasingly, companies can create needs (advertising) by moving consumers towards a particular behavior concerning the product. Smith also introduces the concept of "subtracted value," which consists of the adverse effects (pollution) to be considered against positive ones and which can create negative externalities. In short, "the total contribution of industries should be assessed considering, in addition to technical, economic, social, and cultural factors, profits and disuse. The study of the industrial location should be considered as an interdependent part of the entire industrial system.

To talk about center-periphery models, one must first speak of the models of regional politics and development to which they belong. Regional policy and development models are divided into those that promote economic growth and the growth of less favored geographic areas through resources from other regions (exogenous development) and those that promote it through their entities. (indigenous development). Among the models of exogenous regional development is that of the development poles of Perroux (1964) in which there is an industrial complex chained to a central industrial dynamic where geographical concentration is the factor of development. In this, Boudeville (1966) oversees geographical contribution based on the thesis of the cumulative causation. Later, Berry (1972) determined the channels of diffusion of growth, and in the end, Friedmann (1972), with his center-periphery model, determines the stages of creation and geographical dissemination of economic dynamics. As noted above, there are also models of indigenous development and regional development, for which natural resources, transport and communications infrastructures, urban structures and physical capital (Wadley 1986), as well as human capital, organizational and business experience and innovative capacity, are fundamental to sustaining a development typical of each Region (Toral 2001).

Among the most recent contributions, Fujita and Thisse (2002) state that to understand the spatial distribution of economic activities (especially economic agglomeration, regional specialization, and trade) it should be assumed that (1) space is heterogeneous (which is characteristic of the neoclassical theory of international trade), (2) that there are externalities in production and consumption (what is taken from the urban economy) and (3) that markets are of imperfect competition (as they assume theorists of the new economic geography). If the FTA is analyzed, it is observed that the first of these assumptions is not taken into account, but the second, although not so explicit, is considered by some to be a compelling reason for studying the behavior between central places and its influence on production and consumption decisions on other central places. Compared to the third, although the FTA assumes perfect competition, the modeling that has achieved better results in the FTA such as Fujita et al. (1999) have made use of imperfect markets such as those of monopolistic competition, so it would be a point to consider for the development of this study.

On the other hand, authors such as Bogataj and Usenik (2005) have made contributions relevant to the modeling of spatial hierarchies in the market through games within fuzzy logic. In the same vein, Bogataj and Bogataj (2001) have made a slight exploration of the central places with the use of space games, but not so focused on Christaller's approaches. Bogataj and Bogataj (2001) present a quantitative method for building spatial hierarchies as a product of space games, in which the problem of consumer travel helps define the area of the market.

Knowing the cited literature, the objective of the research is to develop a logistic model to establish RHRD locations in each of the Seven Regions of the State of Puebla in the event of an eventual risk or natural disaster, thus allowing the generation of solutions optimal, and contributing to the stages of mitigation and preparation of catastrophes that put the population in general at risk, as part of Humanitarian Logistics, by applying the Problem of Attraction and Rejection, which allows the reduction of risks in choosing the ideal municipalities for the RHRD headquarters, and making use of literature on humanitarian logistics, emergency plans, risk atlases, emergency declarations, as well as databases of different government institutions.

10.3 Case Study in Puebla, Mexico

Mexico worldwide is located amid two zones of danger and risk, one by the presence of hurricanes and the second because of the seismic activity that affects it. Because of this, vulnerability and risk in urban areas have increased, fostered by the loss of natural areas, manifesting itself as deforestation that increases the risk of heavy rains and overexploitation of aquifers, causing sinking that damage the public infrastructure and housing of the population.

The State of Puebla (Fig. 10.1) is located in the central-southern part of the country (Mexico), between extreme geographical coordinates: to the north 20º50' and the south 17º52' north latitude: to the east 96º 43' and the west 99º 04' west longitude. It is bordered to the north by the states of Hidalgo and Veracruz, to the east by Veracruz and Oaxaca, to the south by Oaxaca, Guerrero, and Morelos and to the west by Guerrero, Morelos, Mexico City, Tlaxcala, and Hidalgo. It comprises an area of 34,280 km^2, representing 1.7% of the total territory of the country. Ranked in the twenty-first place in terms of extension and composed of 217 municipalities.

Fig. 10.1 Location of the State of Puebla

The main natural phenomena that affect the state are landslides and floods. These occur due to the characteristics of the rocks that constitute it offers little resistance and/or are easy to erode mainly by the storm-fluvial action. This erosion is favored by the indiscriminate logging existing in the state, mainly in the Sierra Norte and Sierra Northeast region of the state.

In particular, the geographical location of the State of Puebla makes it more vulnerable to disruptive agents of origin hydrometeorological, since, between May to November, it becomes prone to the destructive effects that cause cyclones, hurricanes, and tropical storms. Once extreme precipitation conditions occur can lead to flooding or overflows of channels (General Coordination of Civil Protection Puebla 2019).

Volcanism occurs in the center of the state mainly, since the poblano valleys (Region Angelopolis, Valle de Atlixco, and Matamoros and Valle Serdan) are located in areas covered with the contribution of pyroclasts of the Volcanoes Popocatepetl, Pico de Orizaba, and the Malinche. Based on geological studies, specialists have characterized volcanic threats that could offer an eruption of the Popocatepetl volcano. This threat characterization has been assessed in terms of the probabilities of occurrence of a specific type of magnitude of the eruption in primary danger zone, moderate danger zone, area of less danger. (Secretary of the Interior General Coordination of Civil Protection Puebla 2019).

Three seismic risk regions are identified in the State of Puebla:

High risk (113 municipalities) corresponds to the seismic zone where epicenters are frequent and comprises localities such as Tehuacan, Acatlan, Izucar de Matamoros, and other minors. Medium risk (53 municipalities): in these epicenters are less frequent and cover localities such as San Martín Texmelucan, Cholula, Puebla, Oriental, Lara Grajales, Ciudad Serdan, Tecamachalco, Acatzingo, Atlixco, and others of lower incidence. Low risk (51 municipalities): where epicenters are rare, such as the northern and northeastern mountains, Cuetzalan region, Teziutlan, and Zacatlan (Government of Puebla 2019).

The geographical location of the Mexican territory makes it vulnerable to disturbing agents of hydrometeorological origin since between May to November, it becomes prone to the destructive effects caused by cyclones, hurricanes, and tropical storms. About the State of Puebla (Fig. 10.2), critical points have been identified that range from irregular settlements and urban infrastructure that are located near or on riverbeds and ravines, as well as on slopes, which implies a permanent danger to the lives of the people who inhabit these places.

Mexico is in the most active seismic zone in the world called the "Ring of Fire" in the Pacific Ocean. There are seismic regions called "Mexican Volcanic Axis", located in the states of Veracruz, Puebla (Fig. 10.3), and the State of Mexico, which could cause serious damage because there, most of the country's population is concentrated.

Based on geological studies, specialists have characterized the volcanic threats that an eruption of the Popocatepetl volcano could offer. This characterization of threats has been evaluated in terms of the probabilities of occurrence of a certain type of magnitude of the eruption. The area considered most dangerous corresponds to the one that is most frequently affected by volcano eruptions. The moderate danger zone, which presents the same threats as the previous one, is usually affected by

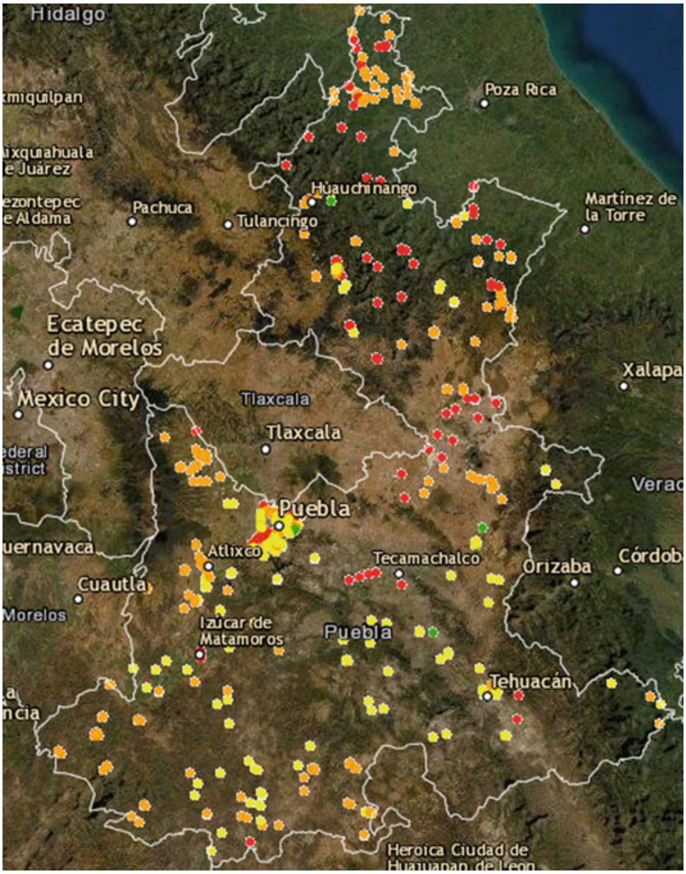

Fig. 10.2 Flood risk map of the State of Puebla

events that occur less frequently, while the lower danger zone corresponds to a large area that refers to very large volcanic manifestations considered relatively rare. The previous tables show, by volcanic danger zone, the disposition of the communities at risk, establishing the correspondence between the sectors defined by the National Civil Protection System to plan emergency actions, particularly in the State of Puebla (Fig. 10.4).

In Mexico, three levels of government are managed for disaster care, the National, State, and Municipal, and each of them performs specific functions in case of disasters, managing resources, declaring the disaster, giving information, implementing the collection centers, etc. In Mexico, the National Civil Protection System (SINAPROC) was created in 1986 to carry out actions to help reduce the impact of disasters caused by natural or human-made phenomena. Supplies to collection centers mainly come from three sources, the state (through the resources of the

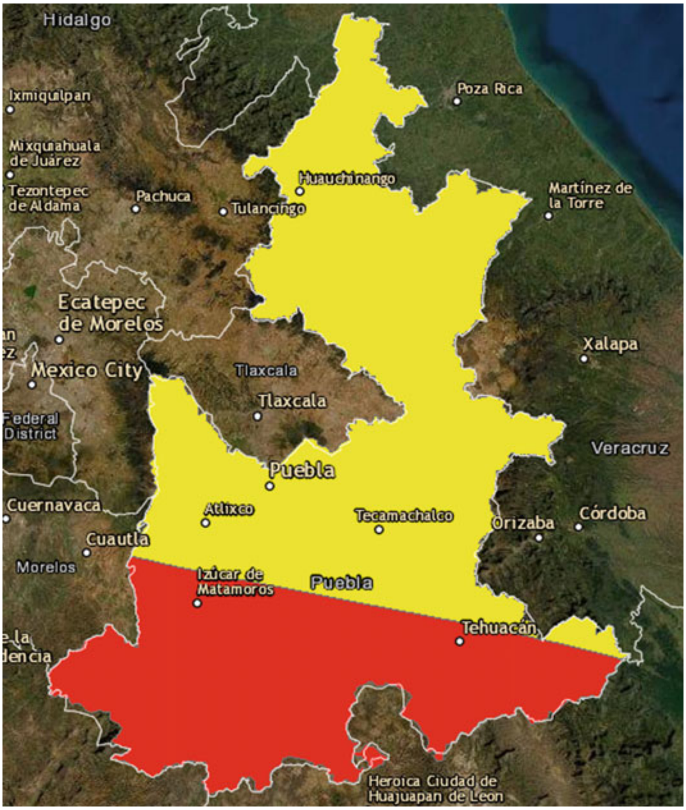

Fig. 10.3 Map of risk seismicity of the State of Puebla

Natural Disaster Fund), civil society donations, and contributions from international countries or organisms.

In the Mexican Republic, there is a National Risk Atlas containing information on the most occurring natural phenomena in specific regions and states, information that is taken as the basis for the prediction and planning of mechanisms and actions to mitigate the damage caused by the different types of disaster.

The Atlas of Risks of the State of Puebla was developed under the working agreement signed between the Mexican Geological Survey, the Constitutional Government of the State of Puebla through the Directorate General of Civil Protection of the State and Natural Disaster Prevention Fund (FOPREDEN) and the National Center for Disaster Prevention (CENAPRED) as the governing body, both belonging to the Ministry of Government.

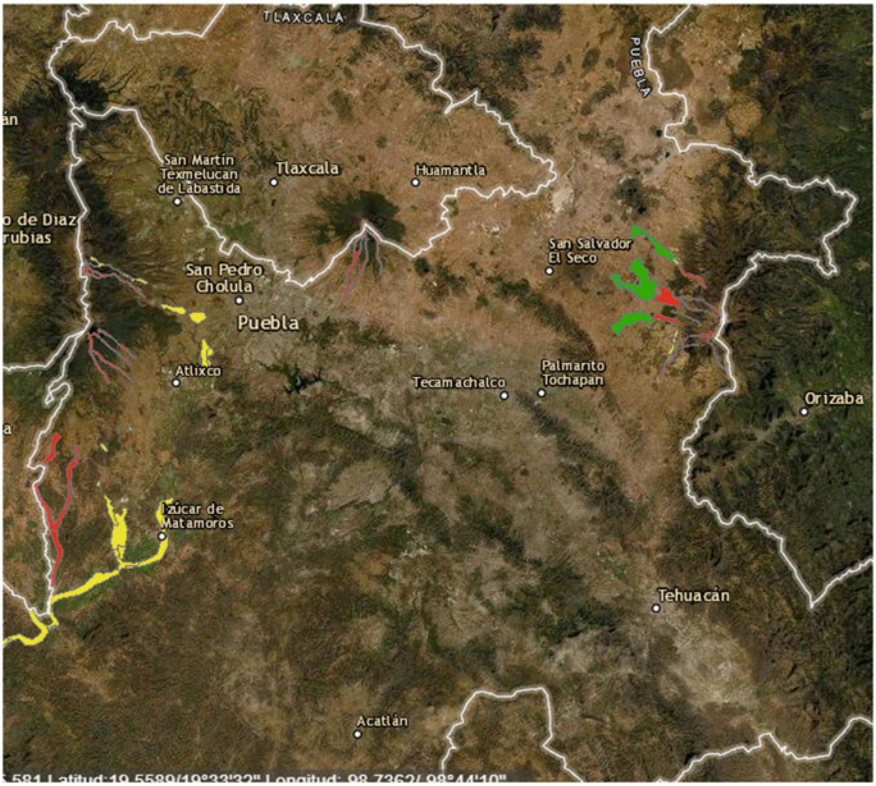

Fig. 10.4 Volcanic risk map of the State of Puebla

10.3.1 Methodology

Alfred Weber (1929) developed a theory on localization in which he relates four fundamental factors: distance to natural resources, distance to market, labor costs, and transport costs, giving greater importance to the latter, hence the proposed to find the place to minimize total transport costs. Weber sensed the beginning of a localization revolution, which would lead different industries to organize much more naturally in large-scale concentrations (1929:196). For the author, is located in the production plant, because he considers that the production costs are the same everywhere. With this assumption, it is ideal for the plant to be located where transport costs are minimized. Weber will represent their theory in a triangle, in which two vertices correspond to the products it needs in the elaboration, and another vertex is the place of market.

For this reason, it was based on the Original Weber Model, which tells us that if there are three sites, M1, M2, and M3, in a given space. The location is located at point K, which is distant from site M1, at d1, from site M2 to d2 away and from site

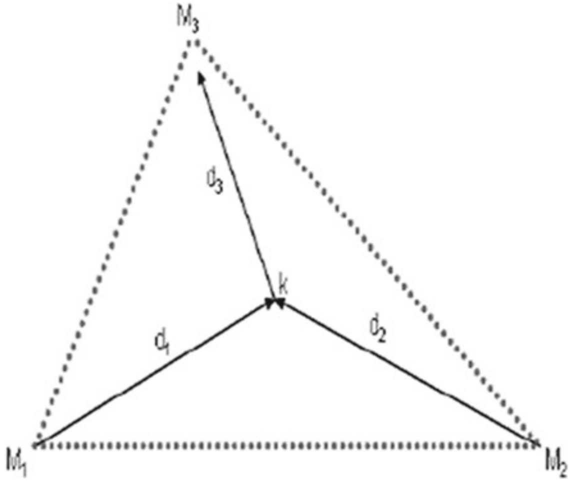

Fig. 10.5 Weber simple model (Weber 1929)

M3 to d3. Each site attracts the location according to the impact it has on maximizing its profit its possible relocation (Fig. 10.5).

For this reason, we started from the original model of Weber which indicates that, if in each space are three sites, M1, M2, and M3. The location is at point K, which is distant from the M1 site, at d1; from site M2 to d2 distance, and from site M3 to d3. The location is attracted by each site according to the impact that its eventual relocation has on maximizing its benefit (Fig. 10.5).

The usual thing, says Weber, is that in the elaboration of any product, more than one product is needed, even products made by other companies. Weber distinguishes between pure materials that are sold as they are found in nature, and on the other hand, the raw materials that have gone through some processing process and have lost weight.

The classic theoretical approach to the location of the company in the place of raw materials or the market of the final product was solved according to the proportion of weight between the two. Factories with a high location weight would minimize their cost of transport by focusing on the site of raw materials and, if low, in the product market. In pure materials, the result is 1. In gross materials, it will be greater than 1. The higher the material index, the more dependence the plant will have on the location of the resources, since the processed product loses weight, and therefore costs more transporting the raw material than the processed product. The lower the material index, the closer the plant will be. Weber considered the material index plus one as the location weight (PU-IM + 1). In a second model, Weber analyzes changes based on the cost of labor and agglomeration economies. He points out that these factors may cause the cost of production to fall, and the plant would tend to settle there, where producing will be cheaper, as long as the savings in production costs exceed the increase in the transport costs to be addressed, as the new location may not be the optimal reduction in transport costs.

The triangle that Weber used in the first model now appears surrounded by concentric circles that represent the cost of transportation in an area. Each circle is called isodapan, if a point is located at which the labor costs are less than the transport costs within the isodapan, the plant will be located at that point, but if the labor costs are outside the isodapan, the plant will not move. Weber called the limit between transportation costs and workforce savings critical isodapan. The cost of labor is a locational factor only does it vary between places. According to Weber (1929:95), in addition to this postulate that characterizes its methodology, only variables with regional differences can be location factors. Weber adds that the different salary levels are the result of differences in efficiency, motivated by subjective and objective reasons linked to the organization and the production technique. Only subjective reasons can be regarded as geographical peculiarities of wage differences since the second objective reasons are subsequently incorporated into the agglomeration factors (1929:96). Without introducing the remaining location determinants, the influence of the working factor on the geographic location will depend on the balance between the minimum cost of transport site, and the lowest wage site. Finally, Weber believes that technological development produces increasing losses of the weight of raw materials, so that, as a result, the industry must move decisively and continuously from consumer places to material deposits (Weber 1929:75).

Some problems are aimed, as in the Weber problem, finding the location of installation so that the weighted sum of its distances to the demand points is minimized. The difference with the traditional problem is that some of the points are given a negative weight. The first location problem that has to do with positive and negative weights is the so-called complementary problem. This problem was first proposed in the book “What is Mathematics?” which in 1941 wrote Courant and Robbins.

When it wanted to locate a facility and assign negative weights to some of the demand points, these weights can be interpreted as the degree of disapproval towards the facility. Claims with negative weights can thus be assessed by the risk it poses (Drezner et al. 2002).

The problem of attraction and rejection is related in some way to the location of semi-undesirable facilities, that is, facilities that, with some points, demand have positive interactions, so it wanted their location near them. However, on the other hand, there are other demand points, which have adverse interactions and want the location as far away as possible (Drezner et al. 2002).

10.3.1.1 Application of the Attraction-Reject Model

There are times when there is a set of demand points and the location for installation is sought, but the proximity of this installation to some of the demand points is favorable, while for other points the proximity is unfavorable. This situation gives rise to a variant of the Weber problem known as the Attraction and Rejection Problem (Torres-Díaz 2006).

Due to the above mentioned, the Risk Atlas of the State of Puebla was revised. In the same way, they were identified in the 217 municipalities that make up the state their respective coordinates (latitude and longitude) using the Google Maps tool. Commercial software was used to solve the problem, in which they introduced both the data of all the municipalities and regions, as well as the Attraction and Rejection Model, that would allow us to obtain the optimal results of the coordinates (latitude and longitude) with the decision on the best location could be made.

For the Law of Sustainable Economic Development of the State of Puebla, the State is divided into seven economic regions. These regions include the two hundred and seventeen municipalities of the State and are integrated as can be seen in Fig. 10.6.

There are municipalities in Regions of the State of Puebla with a high-risk rate due to natural phenomena that arise in them, in which the location of an RHRD would be unfavorable, compared to others, where the occurrence of disasters or natural risks is not so much or so frequent, thus becoming favorable locations, as can be seen in Table 10.1.

Not all regions of the State of Puebla present the same risks for natural disasters, but if it is notorious that there is an affectation in all regions, so it is more important to work in the stages of preparedness and mitigation, to facilitate risk reduction.

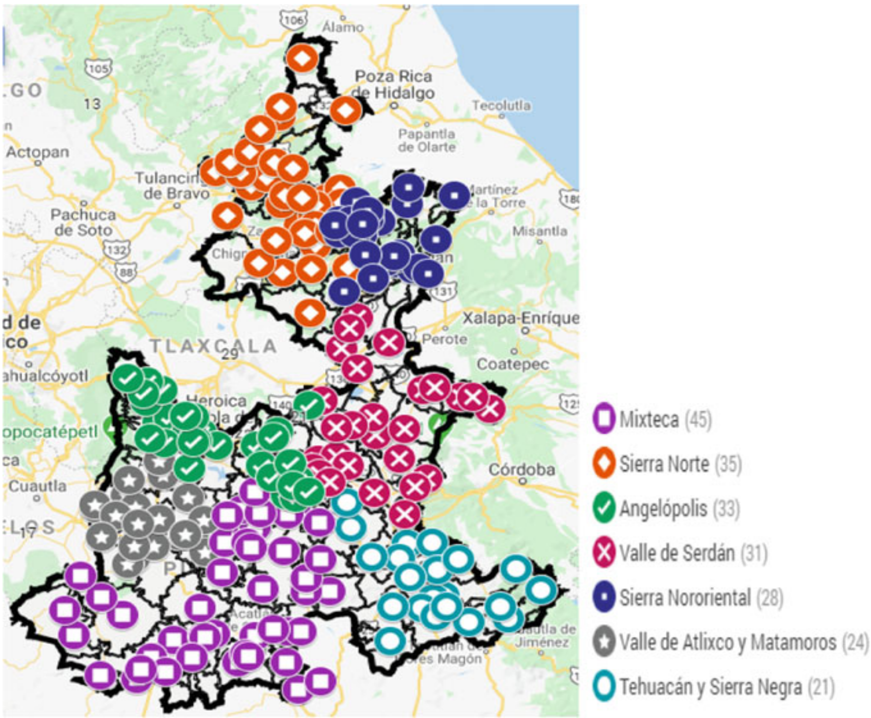

Fig. 10.6 The seven regions of the State of Puebla with their 217 municipalities. Own elaboration

Table 10.1 Regions of the State of Puebla with their kind of natural disaster risks

Puebla Regions	Landslides	Sinkings	Storms	Frost	Drought	Hailstorms	Erosion	Precipitation	Eruption	Seismicity	Flood	Total
Angelopolis	9	1		1	2	6	3	2	2	7	8	41
Mixteca	14				10		7	2		20	10	63
Sierra Nororiental	15	2				1	17	22			4	61
Sierra Norte	16	3	1	2			17	18			13	70
Tehuacan y Sierra Negra	11	4		1			3	5		11	3	38
Valle de Atlixco y Matamoros	10				1	1	4	1	2	5	3	27
Valle de Serdan	5			6		8	5	3	3	4	3	37
Overall Total	80	10	1	10	13	16	56	53	7	47	44	337

10.3.1.2 Mathematical Model of Attraction-Rejection

One way to model is to minimize the sum of the distances from the proposed location of the RHRD to each of the municipalities in its Region. However, it must be ensured that the new location is not located near municipalities that present risks of some kind. Therefore, a negative weight must be assigned to each of the municipalities with previously established risks and incorporate the resulting terms into the sum of distances that are intended to minimize. To identify the safe municipalities of each of the Seven Regions, where RHRD can be established, it was necessary to know what type of natural disasters have affected each of them, determining which ones should be considered harmful at the time of modeling.

This idea coincides with the approach of the problem of attraction and repulsion, as already mentioned, it is a variant of the original problem of Weber, and which mentions that may have a set of points in the continuous space which have associated weights, this points can be positive or negative. The objective is to find the point that minimizes the weighted sum of its distances to each of the demand points, as shown in Eq. (10.1).

$$min_{x,y}\left(\sum_{i=1}^{n} d_{A_i}(x, y) - w\sum_{j=1}^{m} d_{C_j}(x, y)\right) \tag{10.1}$$

Where:

$A_i = (a_i, b_i)$ = coordinates of the i-th client.

$C_j = (c_j, d_j)$ = coordinates of the j-th location.

w = negative value associated with each location.

$d_P(x, y)$ = distance from point P to point (x, y).

$_i\in \{1,2,\ldots, n\}$ y $_j \in \{1,2,\ldots,m\}$.

In the study problem, the ***n*** points that correspond to the municipalities are assigned a positive weight, while the points corresponding to the ***m*** municipalities at risk previously established are assigned a negative weight, which is equal for any installation.

10.3.2 Attraction and Rejection Model Solution

Once the problem was run the Attraction and Rejection Model with the coordinates of the municipalities of each of the Seven Regions, and having added the negative value to all those municipalities that were risky for natural disasters, the software presents optimal location solutions in the form of latitude and longitude, which were presented by Google Maps to visualize the surrounding municipalities. In six of the seven regions, the coordinates obtained were shown close to three municipalities of the Region, so to decide which would be chosen as the basis for an RHRD, the minimum distance in road kilometers obtained with the same Google Maps between the resulting coordinates and the nearby municipalities was taken, leaving the results as shown in Table 10.2.

An observing Fig. 10.7, generated from the model attraction and repulsion, it is appreciated that functions for each of the seven regions of the state of Puebla, giving optimal solutions for proposals RHRD, to facilitate the mitigation stage and preparation Humanitarian Logistics.

10.4 Discussion

10.4.1 Discussion for the Attraction and Rejection Model

For the solution obtained, where the Attraction and Rejection Model was used, it can be seen that the fact of adding a negative variable in the calculation, so that municipalities potentially prone to natural disasters were distanced from the optimal coordinates located if it affects the location results in search of the municipalities where to host the RHRD in the Puebla Regions (Table 10.3).

To understand why these differences exist, we will take as an example the Region of Angelopolis, as shown in Table 10.4.

In the solution, the coordinates were located close to the municipality of Amozoc, as indicated in Table 10.3, this can be understood because when the Attraction and Rejection Model was run, in addition to searching for the coordinates that met the principle from taking the shortest distances between municipalities, it also avoided the municipalities with the highest risks, thus complying with the 2 premises that seek a location of the municipality close to all the others, avoiding those riskier so that the location of the RHRD is effective and safe.

In Fig. 10.8 it can be seen how the municipality of Puebla is located in a central area of the Angelopolis Region of the State, which would make it an interesting proposal if only the factor of minimum distances between it and the rest were taken into account. However, the solution of the proposed method does not locate the RHRD proposal in the municipalities of the Region. To understand what happens, and how the Attraction and Rejection Model works, in Table 10.4 it can be seen that the municipality of Puebla is more likely to suffer some type of risk from the natural disaster, so it could not meet the conditions The model implies, for this reason then, that the location proposed by the model is close to the municipality of Amozoc, which has a low risk of suffering some type of natural disaster.

Although the Region of Angelopolis is presented, the solutions obtained through the proposed model, have the same impact in the rest of the areas of the state, so it proves its validity. Which creates certainty for the research carried out.

Table 10.2 Solutions with attraction and rejection method

Region	Atraccion y Rechazo		Distancia Km			
	Coordenadas X	Coordenadas Y				
Valle de Atlixco y Matamoros	18.73857	−98.52624	Huaquechula	Tepeojuma	Tlapanalá	
			4.6	12.7	5.9	
Tehuacán y Sierra Negra	18.46691	−97.31856	Ajalpan	Altepexi	Tehuacán	
			18.5	16.7	20.4	
Valle de Serdán	19.11283	−97.60705	Aljojuca	San Juan Atenco	San Salvador el Seco	
			9.1	10.1	4	
Mixteca	18.41	−98.17684	Acatlán	Santa Inés Ahuatempan	Tehuitzingo	
			60.2	35.9	20.1	
Angelópolis	19.01692	−98.09501	Amozoc	Puebla	San Andrés Cholula	
			10	24.3	39.4	
Sierra Norte	20.05566	−97.85832	Chiconcuautla	San Felipe Tepatlán	Tlapacoya	
			50.6	31.5	45.3	
Sierra Nororiental	19.86119	−97.63382	Cuetzalan del Progreso	Nauzontla	Zoquiapan	Zacapoaxtla
			43.6	31.1	39	10.5

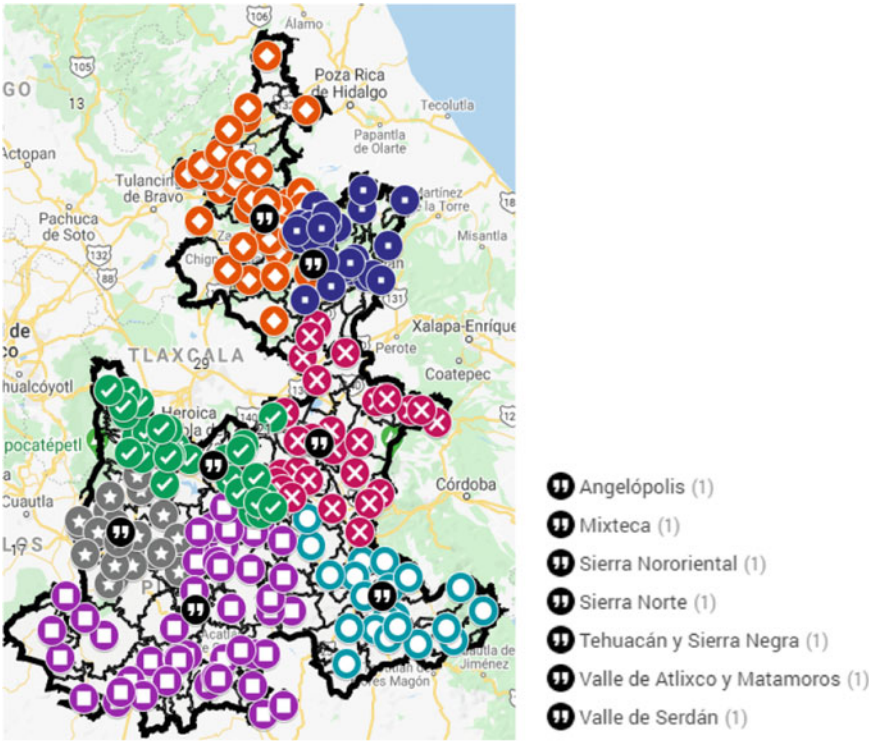

Fig. 10.7 Location of the RHRD obtained, in the Puebla regions. Own elaboration

Table 10.3 Selected municipalities in each region representing minimum distances and little risk

Region	Municipality	Coordinates X	Coordinates Y
Valle de Atlixco y Matamoros	Huaquechula	18.7706524	−98.5446545
Tehuacán y Sierra Negra	Altepexi	18.3693599	−97.2982224
Mixteca	Tehuitzingo	18.3297054	−98.2758531
Angelópolis	Amozoc	19.043829	−98.0437894
Sierra Norte	San Felipe Tepatlán	20.0908398	−97.7966913
Sierra Nororiental	Zacapoaxtla	19.8735055	−97.5887976

Table 10.4 Municipalities region Angelopolis and its risks

Angelopolis Townships	Landslides	Sinkings	Storms	Frost	Drought	Hailstorms	Erosion	Precipitation	Eruption	Seismicity	Flood	Total
Acajete							1	1				2
Amozoc	1											1
Calpan									1	1		2
Chiautzingo	1						1					2
Cuautinchán					1	1				1		3
Huejotzingo	1			1		1				1		4
Nopalucan						1						1
Ocoyucan	1											1
Puebla	1	1								1		3
San Andrés Cholula										1		1
San Felipe Teotlalcingo	1										1	2
San Martín Texmelucan						1					1	2
San Matías Tlalancaleca											1	1
San Nicolás de los Ranchos	1						1		1			3
San Pedro Cholula										1		1

(continued)

Table 10.4 (continued)

Angelopolis Townships	Landslides	Sinkings	Storms	Frost	Drought	Hailstorms	Erosion	Precipitation	Eruption	Seismicity	Flood	Total
San Salvador el Verde	1										1	2
Santo Tomás Hueyotlipan											1	1
Tecali de Herrera					1	1					1	3
Tepeaca						1		1		1		3
Tlahuapan	1											1
Tlanepantla											1	1
Tochtepec											1	1
Overall Total	9	1		1	2	6	3	2	2	7	8	41

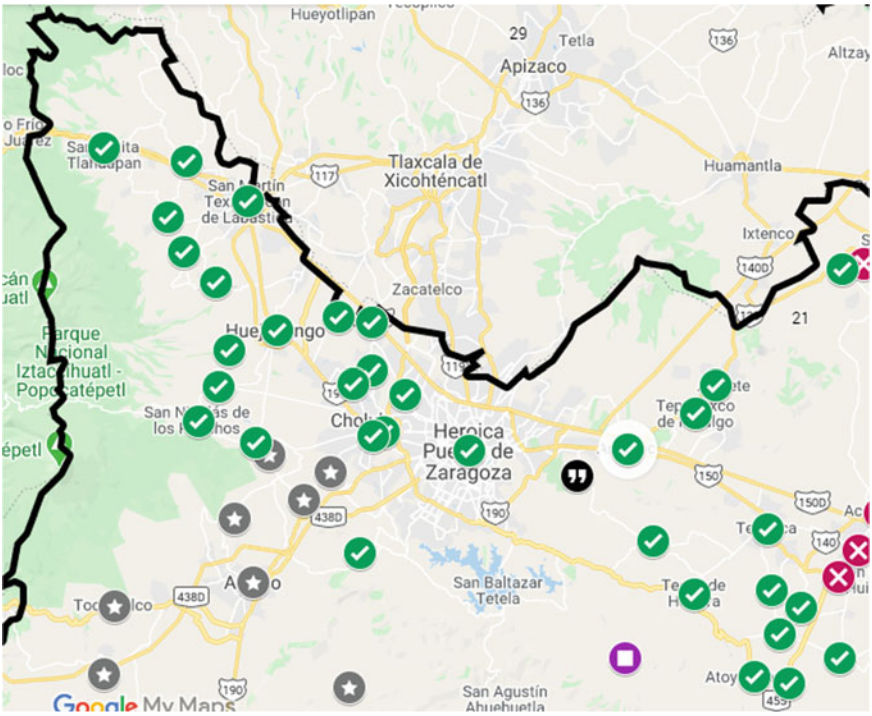

Fig. 10.8 Location of the proposed RHRD in the municipality of Amozoc (19.043829, −98.0437894) in the Angelopolis region. Own elaboration

As has been observed in each of the Seven Regions in which the State of Puebla is composed, there is a risk of natural disasters, it is true that not all produce the same consequences or generate the same type of needs and impacts, but it is vital that for to be able to generate an efficient Humanitarian Logistics, and above all to reduce the risk, counting on effective mitigation and preparation stages, we can support ourselves with this type of research whose purpose is to generate a culture of prevention.

10.5 Final Remarks

The world is continuously changing, and the effects that man has caused on nature are becoming increasingly noticeable, hence the increase in global disasters. These types of events are present in the State of Puebla, so the results obtained in this research are essential because it can be determined which municipalities are the safest in each of the Seven Regions for the establishment of an RHRD.

Among the most critical decisions in disaster situations is the location of RHRD, so localization issues provide certainty when determining which of the potential locations these centers should be established. Therefore, proper localization is key to acting on a preventive level, aimed at reducing risks, economic and social costs, and above all human losses that can occur accordingly.

It should be considered that the demands of the affected persons must be met by RHRD that is quickly operational, to avoid the lack of shelter, storage, and care, so they must be adequately located, close to concentrations of the population so that they are reached in the shortest possible time after a disaster has occurred.

The needs that are generated are changing, so a regular and frequent review is required to keep the information as up to date as possible. This review should include both the private sector and the public sector.

Another aspect of high relevance is the location of the danger zones and the level of risk identified in the different regions that make up the entity, thus constituting the first steps to reinforce the stages of mitigation and preparation involving Humanitarian Logistics.

The Attraction and Rejection model is very useful when it is required to establish safe locations, allowing the analysis of where the location of an RHRD is most convenient.

A systemic and global approach should be considered and taken, in which companies, government, academics, and society at large can achieve efficient Humanitarian Logistics that allow us to respond to the complexities generated by natural disasters and risks.

Currently, the leading natural phenomena affecting the State of Puebla are landslides, floods, frosts, erosion, sinking, volcanism, and seismicity, which are manifested in the different state regions. It is why the importance of having well defined where RHRD should be established to contribute to risk reduction. This type of research may have the scope in other states, and even countries, where natural disasters exist, considering an update in the information. It can also be further developed, considering other fundamental aspects of the supply chain such as routing, storage, capabilities, etc.

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Chapter 11
Location of Humanitarian Response Distribution Centers for the State of Chiapas

Ángel Alejandro Pineda-Figueiras, Diana Sánchez-Partida, Patricia Cano-Olivos, Erika Barojas-Payán, and José-Luis Martínez-Flores

Abstract Throughout history, we have witnessed major natural disasters, which have become more significant. In this chapter, we will talk about the state of Chiapas in Mexico, where natural phenomena substantially impact the state, such as heavy rains, cyclones, tornadoes, earthquakes, wildfires, floods, extreme temperatures, among others. These phenomena directly affect society in general, endangering the lives of the people affected and causing material losses; therefore, it is essential to establish logistics for humanitarian support to reduce health and meet the affected population's basic needs. This chapter aims to find the best location for Humanitarian Response Distribution Centers (HRDC's) to provide relief kits immediately after the occurrence of a natural phenomenon. For this study, a statistical analysis was carried out with information from the Centro Nacional de Prevención de Desastres (CENAPRED) for the emergency declarations that have occurred in Chiapas, review of the human development indexes on the website of the Instituto Nacional para el Federalismo y Desarrollo Municipal (INAFED), to identify the vulnerability of each municipality. Then, the P-median model was used to identify the optimal municipalities for the facilities and the distribution strategy to each affected municipality. Finally, the results obtained with the experimentation of two scenarios that reflect the best locations for installing the HRDC's were presented.

Keywords Humanitarian Response Distribution Center (HRDC's) · Humanitarian Logistics (HL) · P-median model · Vulnerability · Development indices

11.1 Introduction

Climate change is one of the critical factors driving and aggravating losses caused by disasters and development failures. It is a phenomenon that increases the intensity

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of risk. Predictions of climate change have occurred earlier than expected and on a catastrophic scale. In fact, by the late 2030s or early 2040s, it will exceed the pre-industrial level of 1.5 °C.

The threshold is an attempt to limit the extent of global warming through the Paris Agreement and, what is worse: The Intergovernmental Panel on Climate Change (IPCC) calculated that if countries limit their initiatives and efforts to the commitments made under the Paris Agreement, then we are talking about the temperature rising between 2.9 °C and 3.4 °C by the end of the century (GAR 2019).

Latin America and the Caribbean (LAC) is the second most natural disaster-prone region globally, with 152 million people affected by 1,205 disasters (2000–2019), including floods, hurricanes, storms, earthquakes, droughts, landslides, fires, extreme temperatures, and volcanic events.

The Center for Research on the Epidemiology of Disasters (CRED), located at the Catholic University of Leuven in Wallonia, Belgium, has been active since 1973 in the field of international disasters. In the CRED Report (2015) it promotes research, training, and expertise in humanitarian emergencies, focusing on public health and epidemiology. It provides an objective basis on the burden of disease and health problems arising from disasters and conflicts to improve the role of preparedness and response needs in humanitarian emergencies.

CRED has a long history of standardized data collection, validation, and analysis. It provides free and open access to its data through its website. One of CRED's core data products is the EM-DAT disaster database. EM-DAT contains data on the incidence and impact of natural disasters from 1900 to the present. According to an annual statistic conducted in 2015, it was estimated that 82 million people in Latin America and the Caribbean were affected by natural disasters, resulting in the death of more than 247,000 people in the last decade. The number of people at risk increases over the years, and the challenge for public health grows gradually.

In recent decades, natural phenomena in Mexico have caused damage with an average annual cost of 100 human lives and close to 700 million dollars. For this reason, the issue of disaster prevention has gained relevance in the civil protection agenda, recognizing that it is essential to establish long-range strategies and programs focused on preventing and reducing the effects of disasters and not only paying attention to emergencies and disasters (CENAPRED 2020).

The orographic and geographic conditions make Chiapas prone to natural disasters; the most recent are the earthquakes of September 7th and 19th, 2017, and this year the ravages caused by the rains caused by tropical storms "Amanda" and "Cristobal," where the latter left hundreds of damaged homes, collapsed roads, bridges and hundreds of victims.

Therefore, it is of utmost importance to be prepared with an efficient humanitarian response since the State of Chiapas does not currently have HRDC's. It would shorten distances and help the victims in time, and this will be achieved through the prior planning of the best location of the HRDC'S. The objective is to find the best locations for the HRDC's.

The objective is to find the most appropriate locations of the HRDC's to optimize the distribution of humanitarian aid kits immediately after the occurrence of a natural disaster in the State of Chiapas and thus minimize the impact on the victims' health in the affected municipalities.

For this research, LINGO software version 18.0 was used for solving the P-median model. Two solution scenarios were developed; in the first one, solutions were obtained taking into account distances and had an experimental assignment of four HRDC's; in the second one, solutions were obtained taking into account time and had an experimental assignment of four HRDC's.

11.2 Literature Review

In the multiple optimization models, authors carried out research obtaining similar advantages for the case study, for example, both Bermúdez-Arango and Garzón-Rueda (2016) and González-Lua (2015), the objective of the P-median model in the location models they used was to determine the location of facilities given a known finite demand, in turn, this model minimizes the costs related to travel times and distances between the nodes of the demand and the facility to which they are assigned.

Landa-Cruz et al. (2016) used the P-median model to find in the State of Veracruz optimal locations of distribution centers to provide the PROSPERA program's economic support to the localities of the municipality of La Perla since the distances to be traveled a maximum of 69.63 km.

Muñoz et al. (2011), Hakimi (1964), Daskin (1995), López-Monzalvo (2013), Bowerman et al. (1999), mention that the P-median model consists of finding and locating the optimal facilities depending on the given demand at *n* points by minimizing the sum of the weighted distances, times or transportation costs between the demand location and the selected facilities in a given region. The location problems aim to locate a server, optimizing the service provided to the demands, understanding demand as all the points that require the service.

Berger-Vidal et al. (2018) estimated the probability distributions associated with inventory systems' simulation process. With this, a model for locating safe locations of shelter-storage-care centers was developed, and a risk and vulnerability analysis was performed concerning the flooding phenomenon.

Mori-Villafranqui et al. (2017) developed a mathematical model based on demand estimation since it is focused on reducing the distance traveled by the victims to the donation delivery points, as well as for supplying the population affected by landslides in Chosica, Lima, a locality recurrently impacted by the El Niño phenomenon in Peru.

Fagueye-Niaye and Mbaye-Ndiaye (2012), conducted a study in the Guediwaye department, Dakar region, Senegal for the relocation and reconstruction of secondary schools considering a large number of students in the capacity of the facilities, so that the distance traveled by students who must attend schools is reduced since it covers 550 square kilometers. In 2002, Guediwaye became the fourth department of the Dakar region.

Barojas-Payán et al. (2019), the maximum coverage location problem involves locating a fixed number of facilities at existing stations to cover the maximum number of demand zones. A demand zone is covered when it can reach the cabinet installations within a predefined standard distance.

11.3 Description of the Problem

Chiapas is one of the ten states with the largest population in Mexico; its capital is Tuxtla Gutierrez. It has 124 municipalities and represents an extension of 3.74% of the national territory. It has a population of 5,217,908 inhabitants, which is 4.4% of the country's total. The population distribution is 49% urban and 51% rural; at the national level, the figures are 78% and 22%, respectively (see Fig. 11.1).

The number of indigenous language speakers aged three years and older is 28 for every 100 people; nationally, 7 out of every 100 people speak an indigenous language. The sector of activity that contributes the most to the state GDP is Commerce, contributing to the National GDP of 1.8% (INEGI 2017).

The State of Chiapas is in third place among the five states with the highest natural disasters (2000–2020). The CENAPRED is a decentralized administrative body hierarchically subordinated to the Secretary of Security and Citizen Protection.

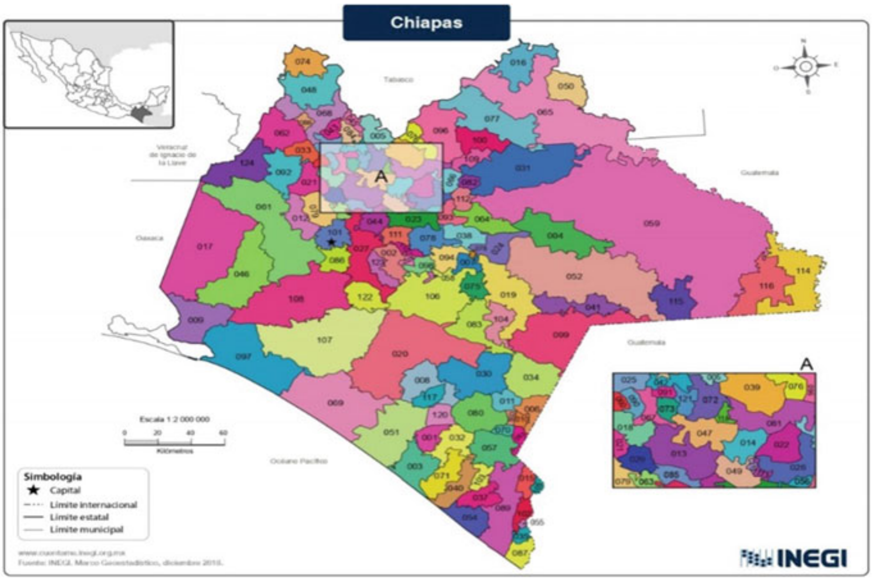

Fig. 11.1 The geographic location of Chiapas, Mexico. Instituto Nacional de Estadística y Geografía (2020)

Its primary responsibility is to support the Sistema Nacional de Protección Civil (SINAPROC) in the technical requirements of its operational demands.

CENAPRED carries out research, training, instrumentation, and dissemination activities on natural and anthropogenic phenomena that can lead to disaster situations and actions to reduce and mitigate the adverse effects of this type of phenomena to contribute to help a population better prepared to face such situations.

According to open access information from CENAPRED, there are three types of declarations: contingency, emergency, and disaster. On the one hand, the specific objective of the contingency declaration is to support low-income agricultural, fishing, and aquaculture producers to reincorporate them into their activities as soon as possible before the occurrence of an atypical, relevant, non-recurrent, and unpredictable climatic contingency.

On the other hand, the declaration of emergency is the recognition by the Secretary of Government that one or several municipalities or political delegations of a federal entity are facing the imminence or high probability of presenting a disturbing phenomenon of natural origin, which may cause an excessive risk to the safety and integrity of the population. The declaration of emergency is aimed at protecting the life and health of the population. The purpose of the disaster declaration is to provide resources to reconstruct damage to housing and public infrastructure.

In summary, the total number of natural phenomena presented in 20 years in Chiapas is 1826, of which 55% were emergency declarations, 6% contingency declarations, and 39% disaster declarations with a total of 1010, 108, and 708, respectively (see Fig. 11.2).

According to the data obtained from CENAPRED (2000–2020), we can observe the natural phenomena during these years, where the years 2006, 2010, 2014, and 2018 are the most representative of the different types of disasters present. In 2007, 432 declarations were recorded, of which 266 were emergency declarations, representing 61.57% of the total number of declarations; this year is the one with the highest number between 2000 and 2020.

In 2010 there were 153 declarations with 74 emergency declarations, representing 48.37% of the total declarations. In 2014, a total of 138 declarations were re-recorded, of which 88 were emergency declarations, representing 63.77% of the total number of

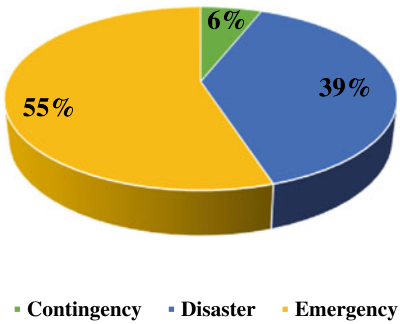

Fig. 11.2 Total, natural phenomena by type of declarations in the State of Chiapas 2000–2020. Own elaboration based on open access data from CENAPRED

declarations. Moreover, in 2017, 259 declarations were registered, of which 144 were emergency declarations, representing 55.60% of the total number of declarations (see Fig. 11.3).

From 2000 to 2020, 1010 emergency declarations have been recorded (see Appendix 11.A), of which the most occurred in 375 tropical cyclones, 258 rain, 174 earthquakes, 144 extreme temperatures, and 27 forest fires. Tropical cyclones were the most frequent during these 20 years (see Fig. 11.4).

In accordance with the privisions of the Diario Oficial (2010), The Fondo de Desastres Naturales (2020), is a financial instrument through which the National Civil Protection System, via the Fund's own Operating Rules and the procedures derived from there, integrates a process respectful of the competencies, responsibilities, and needs of the government levels, whose purpose, under the principles of

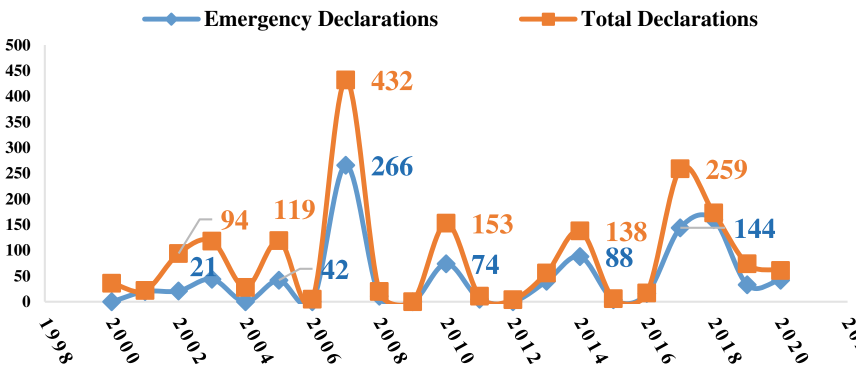

Fig. 11.3 Total events and emergency declarations by year from 2000 to 2020 in the State of Chiapas. Own elaboration based on CENAPRED open access data

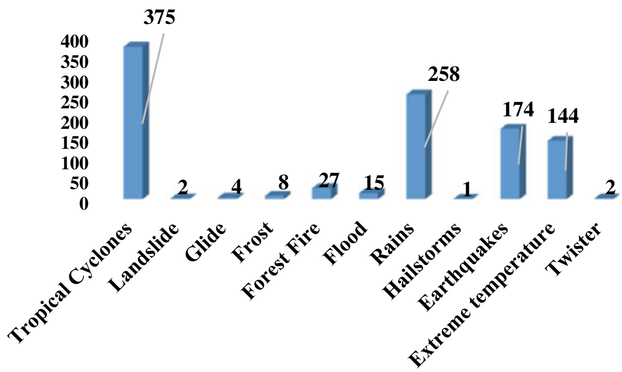

Fig. 11.4 Total emergency declarations between 2000 and 2020 in the State of Chiapas. Own elaboration based on CENAPRED open access data

co-responsibility, complementarity, timeliness, and transparency, is to support the states of the Mexican Republic.

As well as the agencies and entities of the Federal Public Administration, in the attention and recovery of the effects produced by a natural phenomenon, following the parameters and conditions outlined in its Operating Rules, its objective is to attend to the effects of natural, unforeseeable disasters, whose magnitude exceeds the financial response capacity of the agencies and parastatal entities, as well as the federal entities.

In the 2017 earthquake in Chiapas, it was reported that a total of 192 people were preliminarily injured, and 16 people died, 80,508 homes were affected, of which 58,168 were partially damaged, and 22,340 more were damaged. In the education sector, 1,534 schools were registered with partial damage and 86 with total damage, as well as 71 medical units, 194 public buildings, 411 churches, 658 businesses, 282 stretches of road affected and 67 bridges damaged by the state, 100 federal highways, 92 feeder roads, and four federal bridges.

There are no HRDC's or strategic points in the State of Chiapas to respond to these disasters in all affected municipalities. Analyzing these factors and the current situation in Chiapas, we see the importance and need to create HRDC's at strategic points in order to be able to attend to all the municipalities in the shortest possible time and efficiently with the supply of aid kits.

This work is supported by Chapter 4 Selection of Humanitarian Response Distribution Centers (HRDC) in Puebla, Mexico of Book Disaster Risk Reduction in Mexico pages 81–98, which takes as a starting point the results obtained from the research carried out by the authors Bello-Garduño et al. (2021). This research proposes a similar study but developed in the State of Puebla, Mexico, for the optimal location of HRDC's to safeguard the lives of those affected by natural disasters. Their work consisted of applying the P-median model taking the 114 municipalities most vulnerable to natusral disasters in the State of Puebla with information from CENAPRED according to the emergency declarations in the range from 2000 to 2019.

The timely delivery of humanitarian aid kits, tents, blankets, supplies, and heaters nearby is essential to reduce losses caused by disasters. Therefore, time and distance are critical factors in emergency management. Given the importance of choosing a distribution center, this article considers the P-median model, which selects the best HRDC locations that minimize total distance and total time, conducting experiments with 1, 2, 3, and 4 HRDC's, respectively.

The first step was to identify the municipalities with the lowest vulnerability to natural disasters, based on data provided by CENAPRED, taking the average number of declarations as five. In the range of study, 15 municipalities with declarations of less than five were reported, using this data for the elaboration of the matrix of distances and times to analyze these municipalities, with the objective that the candidate locations are municipalities with low risk of being exposed to a natural disaster (see Table 11.1).

For the candidate municipalities' analysis, a comparison was made with the 15 municipalities with the lowest number of emergency declarations presented in Table

Table 11.1 Table with the 15 municipalities with less than five emergency declarations in the State of Chiapas. Own elaboration based on CENAPRED open access data

#	SKU	Municipality	Geological	Hydrometeorological	Grand total
1	4	Aldama	1	3	4
2	5	Altamirano	2	–	2
3	8	Amatenango del Valle	1	3	4
4	12	Belisario Domínguez	–	1	1
5	22	Chanal	1	2	3
6	35	El Parral	1	1	2
7	44	Huixtán	1	3	4
8	55	La Independencia	1	1	2
9	58	Larráinzar	1	3	4
10	59	Las Margaritas	1	2	3
11	62	Maravilla Tenejapa	1	2	3
12	63	Marqués de Comillas	1	2	3
13	68	Mitontic	1	3	4
14	79	Pantelhó	1	3	4
15	94	Santiago el Pinar	1	3	4

11.1. Then five more municipalities were segregated, considering their human development and non-urbanization indexes and their degree of marginalization to ensure that they are facilities with more connections and road exits, based on the data reviewed in INAFED as well as what was analyzed in the databases of SNIM (2020) (see Table 11.2).

Figure 11.5 shows the 124 municipalities of the State of Chiapas geographic locations, making the distance analysis more intuitive. Here, the blue circles represent 114 municipalities with five or more emergency declarations. Similarly, the map shows the geographic locations of 10 municipalities with four or fewer declarations represented by the magenta circle, these after the analysis performed with INAFED (2010) data (see Fig. 11.5).

11.4 The P-median Model

The formulation of the problem from the application of the P-median is as follows:

Let be:

$J = \{1, ...n\}$ the set of indexes for customers.

N $= \{1.....m\}$ the set of indices for the potential locations of the medians.

$J = N$. For each (j, i), $j \in N, i \in J$

The following decision variables are defined. Typically:

Table 11.2 Table with the 15 municipalities and their levels of development, marginalization, and classification. Own elaboration based on INAFED open access data

Municipality	Grand Total	HDI	DHD	HI	Marginalization	Municipality classification
Aldama	4	0.514	BAJO	0.749	MUY ALTO	Rural
Altamirano	2	0.553	MEDIO	0.76	MUY ALTO	Rural
Amatenango del Valle	4	0.504	BAJO	0.653	MUY ALTO	Rural
Belisario Domínguez	1	NA	NA	NA	NA	Rural
Chanal	3	0.526	BAJO	0.738	MUY ALTO	Rural
El Parral	2	0.541	BAJO	0.52	ALTO	Rural
Huixtán	4	0.532	BAJO	0.729	ALTO	Semiurbano
La Independencia	2	0.529	BAJO	0.72	ALTO	Semiurbano
Larráinzar	4	0.522	BAJO	0.737	ALTO	Semiurbano
Las Margaritas	3	0.534	BAJO	0.689	ALTO	Urbano
Maravilla Tenejapa	3	0.506	BAJO	0.737	MUY ALTO	Rural
Marqués de Comillas	3	0.541	BAJO	0.761	ALTO	Rural
Mitontic	4	0.459	BAJO	0.663	MUY ALTO	Rural
Pantelhó	4	0.525	BAJO	0.683	ALTO	Semiurbano
Santiago el Pinar	4	0.522	BAJO	0.718	ALTO	Semiurbano

"HDI" = Human Development Index; "DHD" = Degree of Human Development; "HI" = Health Index

W_j = total demand to cover the node j; C_{ji} = distance from the node j to the node i; P = number of facilities to locate; X_{ji} = take the value one if the node j is assigned to the installation i y 0 otherwise; Y_i = takes the value one if an installation is located at i y 0 otherwise. The mathematical formulation of the problem is:

$$Min = \sum_{i \in J} \sum_{j \in N} W_j C_{ji} X_{ji} \tag{11.1}$$

Subject to:

$$\sum_{i \in J} X_{ji} = 1 \ \forall j \in N \tag{11.2}$$

$$\sum_{i \in J} Y_i = P \tag{11.3}$$

$$X_{ji} \le Y_i \ \forall j \in N, i \in J \tag{11.4}$$

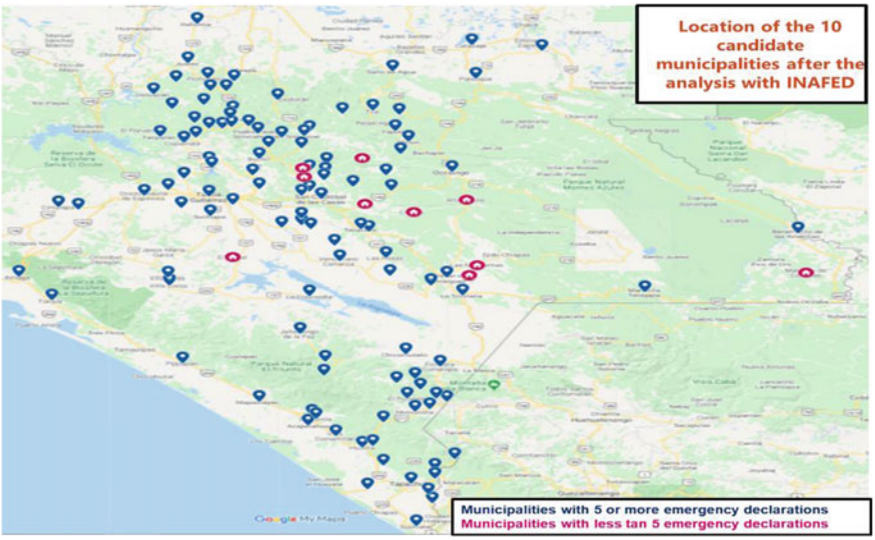

Fig. 11.5. 114 municipalities with five or more emergency declarations and ten municipalities with four or fewer emergency declarations. Own elaboration with Google Maps tool

$$X_{ji} \in \{0, 1\}, Y_i \in \{0, 1\} \ \forall j \in N, i \in J \tag{11.5}$$

The objective function (11.1) minimizes the weighted sum of the distances (or transport times) associated with the client municipalities' nodes assigned to the candidate municipalities' nodes. The set of constraints (11.2) ensures that all customer municipalities are assigned to precisely one location. Constraint (11.3) sets the number of facilities in P. Constraint set (11.4) prohibits any assignment to a site that does not have a facility, i.e., only nodes with a facility will supply the product. The set of constraints (11.5) reinforces the binary nature of the decisions to locate a faculty at a node and assign a client municipality node to an installation.

With the analysis performed on the historical information of emergency declarations, it was determined that a municipality has five declarations on average during the period 2000–2020.

The 124 municipalities are used to apply the P-median model in the development of this work. A more detailed investigation is made of the municipalities with less vulnerability and considering their level of development and urbanization to compare with the other vulnerable municipalities.

11.5 Scenarios Development

11.5.1 Scenario 1: Resolution with Distances

The data matrix is generated to develop the first scenario; the P-median model is used, assigning 1,2,3, and up to 4 HRDC's, the results obtained are generated and presented.

Work was done to generate the distances between each of the 124 municipalities to develop the project. For the compilation of this data, the Google Maps tool was used. In this tool, each place of origin (10 municipalities less prone to natural disasters after the analysis with INAFED) and each destination place (114 municipalities more vulnerable to natural disasters) was introduced, and several routes with the corresponding distances were shown. The distances that marked the shortest distance to travel were selected for filling out the matrix. The result is a matrix with dimensions of 124 by 10, with 1,240 data (see Appendix 11.B); the number of declarations of emergency per municipality is considered weight w, giving it a value of 1 to be used in the mathematical model.

According to the results of the first scenario, we obtain that the municipality selected as optimal was Larráinzar with a distance of 22,365.8 km; in the second run, the two municipalities selected are Larráinzar and La Independencia with a distance of 16,981 km; in the third run the three municipalities selected are Larráinzar, La Independencia and El Parral with a distance of 15,491.3 km. Furthermore, in the fourth run, the four municipalities chosen for installing the HRDC's in Chiapas are Larráinzar, La Independencia, El Parral, and Altamirano, a distance of 14,626 km (see Table 11.3).

In this scenario, the first result is resolved by assigning an HRDC in the optimal municipality chosen, Larráinzar, which should supply the humanitarian aid kits to the 124 municipalities. When the run is made by assigning 2 HRDC's, the municipalities that have been chosen are Larráinzar and La Independencia, with a distribution of 76 and 48 municipalities, respectively. When the run is made by assigning 3 HRDC's, the

Table 11.3 Result of the P-median model, taking into account the distances. Own elaboration

Runs	Minimum distance (Km)	Municipalities chosen for the HRDC's
1 HRDC	22,365.8	Larráinzar
2 HRDC's	16,981	Larráinzar y La Independencia
3 HRDC's	15,491.3	Larráinzar, La Independencia y El Parral
4 HRDC's	14,626	Larráinzar, La Independencia, El Parral y Altamirano

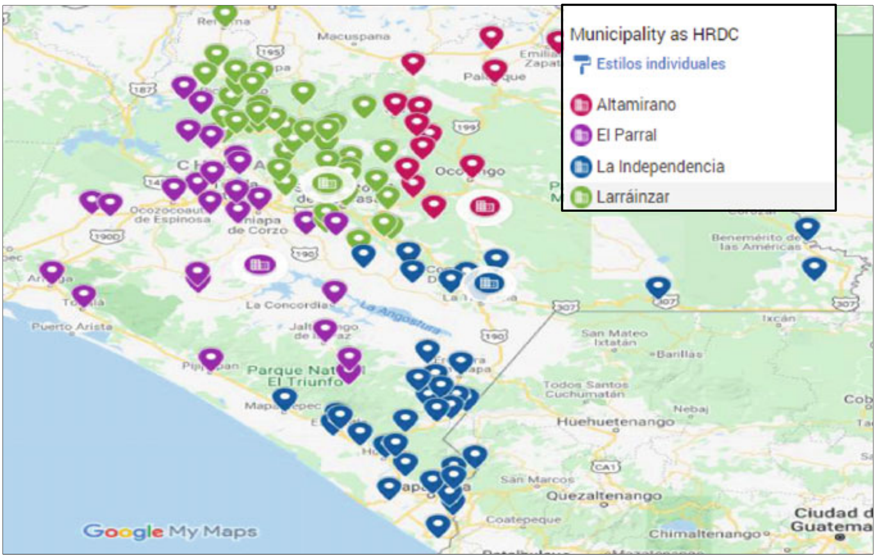

Fig. 11.6 Assignment of the 124 municipalities to the 4 HRDC's (considering distance). Own elaboration with Google Maps tool

municipalities that have been chosen are Larráinzar, La Independencia, and Parral, with a distribution of 48, 48, and 28 municipalities, respectively. Furthermore, when the run is made by assigning 4 HRDC's, the municipalities that have been chosen are Larráinzar, La Independencia, Parral, and Altamirano, with a distribution of 44, 38, 28, and 14 municipalities, respectively (see Appendix 11.D).

With the image of the building, we represent each HRDC, and with the dots representing the municipalities that are an allocation to each HRDC distributed with the respective colors, green for the municipalities supplied by Larráinzar, magenta for those supplied by Altamirano, blue for those supplied by La Independencia, and finally purple for the municipalities supplied by El Parral (see Fig. 11.6).

In the first scenario, we can see in race number four, four municipalities chosen as HRDC's, so these results confirm that they are the optimal points to generate a better humanitarian response to natural disasters in the State of Chiapas, considering the proposed scenario due to their distances between municipalities.

11.5.2 Scenario 2: Resolution with Times

A data matrix was generated to develop the second case, using the P-median model to assign 1, 2, 3, and up to 4 HRDC's. For the development of the project, the time matrix generation between 124 municipalities has been completed. For data collection, we used the Google Maps tool, in which we entered the place of origin (10 municipalities with fewer natural disasters after the analysis with INAFED) and destination (114 municipalities more prone to natural disasters) with the corresponding time.

The routes marked with the shortest travel time were selected, and these routes were selected to complete the matrix. It is worth mentioning that the time is expressed in hours and minutes, and the sum of the two is converted to minutes so that it is the same unit of time. The result is a matrix with 124 $\times$ 10, with a total of 1240 data (see Appendix 11.C. When using this mathematical model, the number of emergency declarations for each municipality is considered the weight w by giving it the value of 1 for the mathematical model.

The P-median model is solved using Lingo software version 18. According to the first scenario results, we can see that the results were different from the distance analysis since the municipality selected as optimal was Huixtán with a minimum time of 27,877 min. In the second run, the two municipalities chosen are Larráinzar and Las Margaritas with a minimum time of 23,638 Min; in the third run, the three municipalities chosen are Larráinzar, Las Margaritas, and El Parral with a minimum time of 21,601 Min. Furthermore, in the fourth run, the four municipalities chosen were Larráinzar, La Independencia, El Parral, and Altamirano, with a minimum of 20.389 min (see Table 11.4).

When making the first run considering one facility, this scenario is solved by selecting the municipality of Huixtán as the optimal municipality according to the time frame, which should supply the humanitarian aid kits to the 124 municipalities. When the run is made by assigning 2 HRDC's, the municipalities that have been chosen are Larráinzar and Las Margaritas, with a distribution of 74 and 50 municipalities, respectively. When the run is made by assigning 3 HRDC's, the municipalities that have been chosen are Larráinzar, Las Margaritas, and Parral, with a distribution of 40, 44, and 40 municipalities, respectively. Moreover, when the run is done by assigning 4 HRDC's, the municipalities that coincide with the distance analysis and chosen are Larráinzar, La Independencia, El Parral, and Altamirano, distribution of 35, 34, 40, and 15 municipalities respectively (see Appendix 11.E).

To make the assignment more intuitive, we take as an example the result of 4 facilities. The building's image is used to represent each HRDC, and with the dots,

Table 11.4 Result of the P-median model, taking into account the times. Own elaboration

Runs	Minimal time (Min)	Municipalities chosen for the HRDC's
1 HRDC	27,877	Huixtán
2 HRDC's	23,638	Larráinzar y Las Margaritas
3 HRDC's	21,601	Larráinzar, Las Margaritas y El Parral
4 HRDC's	20,389	Larráinzar, La Independencia El Parral y Altamirano

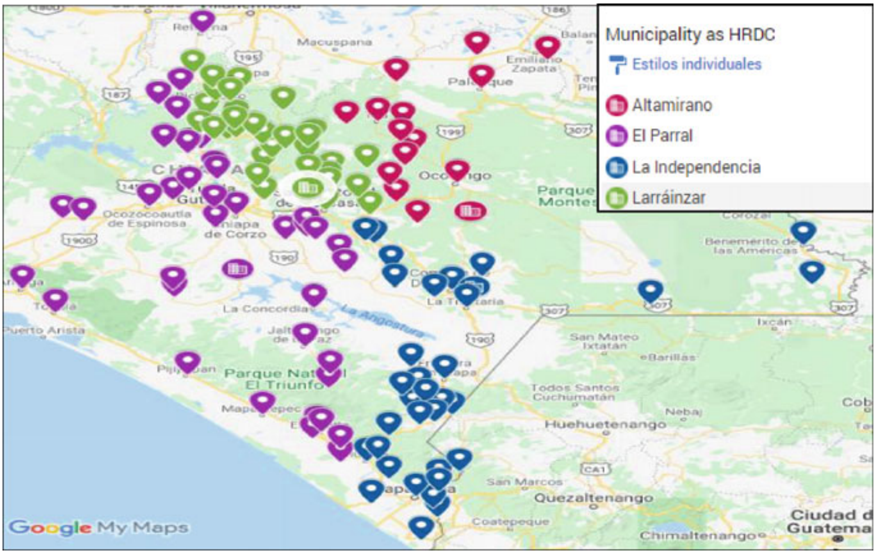

Fig. 11.7 Assignment of the 124 municipalities to the 4 HRDC's (considering time). Own elaboration with Google Maps tool

we represent the municipalities that are an assignment to each HRDC distributed with the respective colors. The municipality provided by Larráinzar is green, the municipality provided by Altamirano is magenta, the municipality provided by La Independencia is blue, and the municipality provided by El Parral is purple (see Fig. 11.7).

In the second scenario, we have the possibility of seeing in the fourth run four municipalities chosen as HRDC's, so that these results prove that they are the optimal locations to create a better humanitarian response to natural disasters in the State of Chiapas, taking into account the scenario proposed to address it at the time of the event.

11.6 Conclusions

After applying the P-median model in the first scenario, the minimum distance was 14,626 km; Altamirano, El Parral, La Independencia, and Larráinzar were the municipalities that were selected HRDC's. The minimum time was 20,389 min; Altamirano, El Parral, La Independencia, and Larráinzar were the municipalities selected as HRDC's. The localities of these municipalities are in the central part of the State of Chiapas to propose the 4 HRDC. In these four municipalities, because the minimum total distance and the minimum total time are maintained, it is worth mentioning that in the cases of 1, 2, or 3 HRDC is the selection of these municipalities was different

Table 11.5 Results of the P-median model for the 4 HRDC's, taking into account the distances. Own elaboration

SKU	MUNICIPALITY	#MATRIX	#MUNICIPALITIES	KM	MIN	HRS	DAYS
5	Altamirano	1	14	1316.4	2071.0	34.5	1.4
35	El Parral	3	28	3187.4	3664.0	61.1	2.5
55	La Independencia	5	38	6723.9	8875.0	147.9	6.2
58	Larráinzar	6	44	3398.3	5779.0	96.3	4.0

Table 11.6 Results of the P-median model for the 4 HRDC's, taking into account the times. Own elaboration

SKU	MUNICIPALITY	#MATRIX	#MUNICIPALITIES	KM	MIN	HRS	DAYS
5	Altamirano	1	15	1434.4	2291	38.2	1.6
35	El Parral	3	40	5249.8	6344	105.7	4.4
55	La Independencia	5	34	5492.8	7432	123.9	5.2
58	Larráinzar	6	35	2449.0	4322	72.0	3.0

since the times were the ones that made the difference, so when carrying out the exercise for four installations, these coincided perfectly being the optimal locations.

Besides, in order to make better use of the services provided to the municipalities, the distribution of the municipalities to be served by the 4 HRDC's should be taken as a reference, taking into account the time, giving a time of 5. 16 days to attend all 124 municipalities, which is the total simultaneous attention time for the entire State of Chiapas since these results vary in which HRDC would attend each municipality. The project's objective is to safeguard the health of those affected in the shortest possible time since the strategy of simultaneously assisting the affected municipalities is reduced by one day of attention (see Tables 11.5 and 11.6).

11.7 Closing Remarks

The priority of locating the HRDC's facility is to decide the safe site to provide relief kits to the municipalities most prone to natural disasters. The value of using inquiry techniques or procedures lies in finding accurate resolutions to complicated problems based on mathematical modeling where constraints have to be satisfied. In this situation, distances and times have been considered as part of the model.

The P-median model in applying this problem gave us satisfactory results to discover where the HRDC's have to be established. It is important to note that several routes have more designated municipalities than others. It is due to the total of distances, without losing sight of the satisfaction of all municipalities.

Organizing the HRDC's strategic location in the State of Chiapas will diminish the effect on the health of the victims of natural disasters and safeguard their lives. It is proposed to present the results to the state government to support decision-making to mitigate humanitarian aid response time to the victims.

An analysis of the number of transports to be housed in each HRDC should reduce multiple aid times throughout the state. It considers a scenario of multiple simultaneous natural disasters at the state, regional and national levels and analysis by region according to the type of phenomenon prevailing in that area.

Appendices

Appendix 11.A

SKU	Row labels	Geological	Hydrometeorological	Chemical	Grand total
1	Acacoyagua	3	9	1	13
2	Acala	1	4	–	5
3	Acapetahua	3	13	–	16
4	Aldama	1	3	–	4
5	Altamirano	2	–	–	2
6	Amatán	2	9	–	11
7	Amatenango de la Frontera	2	7	–	9
8	Amatenango del Valle	1	3	–	4
9	Angel Albino Corzo	2	8	–	10
10	Arriaga	2	12	1	15
11	Bejucal de Ocampo	2	8	–	10
12	Belisario Domínguez	–	1	–	1
13	Bella Vista	3	8	–	11
14	Benemérito de las Américas	1	4	–	5
15	Berriozábal	1	8	1	10
16	Bochil	1	7	–	8
17	Cacahoatán	3	6	–	9
18	Capitán Luis Ángel Vidal	–	–	–	0
19	Catazajá	1	12	–	13
20	Chalchihuitán	1	4	–	5

(continued)

(continued)

SKU	Row labels	Geological	Hydrometeorological	Chemical	Grand total
21	Chamula	1	5	1	7
22	Chanal	1	2	–	3
23	Chapultenango	1	9	–	10
24	Chenalhó	1	4	–	5
25	Chiapa de Corzo	1	6	1	8
26	Chiapilla	1	5	–	6
27	Chicoasén	1	8	–	9
28	Chicomuselo	3	5	1	9
29	Chilón	1	7	–	8
30	Cintalapa	1	8	2	11
31	Coapilla	1	9	–	10
32	Comitán de Domínguez	2	3	–	5
33	Copainalá	1	10	–	11
34	El Bosque	1	6	–	7
35	El Parral	1	1	–	2
36	El Porvenir	2	8	–	10
37	Emiliano Zapata	–	–	–	0
38	Escuintla	3	11	–	14
39	Francisco León	1	10	–	11
40	Frontera Comalapa	2	4	–	6
41	Frontera Hidalgo	3	7	–	10
42	Huehuetán	3	11	–	14
43	Huitiupán	1	7	–	8
44	Huixtán	1	3	–	4
45	Huixtla	3	10	1	14
46	Ixhuatán	1	8	–	9
47	Ixtacomitán	1	7	–	8
48	Ixtapa	1	4	–	5
49	Ixtapangajoya	1	7	–	8
50	Jiquipilas	1	8	1	10
51	Jitotol	1	5	–	6
52	Juárez	1	9	–	10
53	La Concordia	2	6	1	9
54	La Grandeza	2	7	–	9
55	La Independencia	1	1	–	2

(continued)

(continued)

SKU	Row labels	Geological	Hydrometeorological	Chemical	Grand total
56	La Libertad	1	7	–	8
57	La Trinitaria	1	3	1	5
58	Larráinzar	1	3	–	4
59	Las Margaritas	1	2	–	3
60	Las Rosas	1	4	–	5
61	Mapastepec	2	13	1	16
62	Maravilla Tenejapa	1	2	–	3
63	Marqués de Comillas	1	2	–	3
64	Mazapa de Madero	2	6	1	9
65	Mazatán	3	9	1	13
66	Metapa	3	7	–	10
67	Mezcalapa	–	–	–	0
68	Mitontic	1	3	–	4
69	Montecristo de Guerrero	2	5	–	7
70	Motozintla	3	9	–	12
71	Nicolás Ruíz	1	4	–	5
72	Ocosingo	1	6	1	8
73	Ocotepec	1	13	–	14
74	Ocozocoautla de Espinosa	1	8	1	10
75	Ostuacán	1	14	–	15
76	Osumacinta	1	5	–	6
77	Oxchuc	1	4	–	5
78	Palenque	1	7	–	8
79	Pantelhó	1	3	–	4
80	Pantepec	1	9	–	10
81	Pichucalco	1	11	–	12
82	Pijijiapan	2	10	1	13
83	Pueblo Nuevo Solistahuacán	1	8	–	9
84	Rayón	1	8	–	9
85	Reforma	1	10	–	11
86	Rincón Chamula San Pedro	–	–	–	0
87	Sabanilla	1	6	–	7

(continued)

(continued)

SKU	Row labels	Geological	Hydrometeorological	Chemical	Grand total
88	Salto de Agua	1	7	–	8
89	San Andrés Duraznal	1	5	–	6
90	San Cristóbal de las Casas	1	10	–	11
91	San Fernando	1	6	–	7
92	San Juan Cancuc	1	5	–	6
93	San Lucas	1	4	–	5
94	Santiago el Pinar	1	3	–	4
95	Siltepec	3	9	1	13
96	Simojovel	1	7	–	8
97	Sitalá	1	6	–	7
98	Socoltenango	1	4	–	5
99	Solosuchiapa	1	8	–	9
100	Soyaló	1	4	–	5
101	Suchiapa	1	5	–	6
102	Suchiate	3	7	–	10
103	Sunuapa	1	7	–	8
104	Tapachula	4	11	–	15
105	Tapalapa	1	10	–	11
106	Tapilula	1	10	–	11
107	Tecpatán	2	11	1	14
108	Tenejapa	1	4	–	5
109	Teopisca	1	4	–	5
110	Tila	1	8	–	9
111	Tonalá	2	7	1	10
112	Totolapa	1	4	–	5
113	Tumbalá	1	6	–	7
114	Tuxtla Chico	3	7	–	10
115	Tuxtla Gutiérrez	3	14	1	18
116	Tuzantán	3	7	–	10
117	Tzimol	1	4	–	5
118	Unión Juárez	3	7	–	10
119	Venustiano Carranza	1	5	1	7
120	Villa Comaltitlán	3	12	1	16
121	Villa Corzo	2	6	1	9
122	Villaflores	2	8	1	11

(continued)

(continued)

SKU	Row labels	Geological	Hydrometeorological	Chemical	Grand total
123	Yajalón	2	8	–	10
124	Zinacantán	1	5	1	7
	Grand total	180	803	27	1010

Appendix 11.B

SKU	5	22	35	44	55	58	59	63	79	94
1	310	408	349	386	250	380	257	473	423	388
2	188	143	68	121	142	116	148	385	159	124
3	312	411	352	389	253	384	259	476	427	392
4	132	87	136	65	136	9	141	386	51	10
5	0	39	201	66	78	125	64	335	107	133
6	280	198	224	177	248	118	252	406	110	125
7	200	221	273	227	140	244	147	363	278	253
8	120	68	141	46	65	64	70	315	97	72
9	294	249	98	227	284	221	285	528	265	230
10	284	238	180	217	288	211	292	538	254	219
11	206	226	279	232	146	250	153	369	283	258
12	249	269	406	275	189	438	196	412	326	301
13	205	226	278	231	145	249	152	368	283	257
14	325	363	458	357	277	402	305	37	339	410
15	177	132	80	110	181	104	187	431	148	113
16	186	141	125	119	190	41	196	440	98	48
17	335	501	442	480	275	474	282	498	517	482
18	361	316	165	294	352	289	353	472	332	297
19	176	215	418	208	254	273	240	261	191	280
20	107	98	151	77	147	39	153	398	25	46
21	110	64	115	43	114	17	119	364	60	25
22	39	0	157	44	98	80	85	356	87	88
23	313	235	236	214	285	155	290	439	212	162
24	128	82	135	61	132	24	137	382	33	30
25	149	104	62	83	153	77	159	404	120	85
26	189	89	80	68	138	62	145	382	105	70
27	199	154	103	132	203	126	208	453	169	134

(continued)

(continued)

SKU	5	22	35	44	55	58	59	63	79	94
28	192	213	265	219	133	237	139	356	270	245
29	73	111	240	105	150	163	136	331	68	171
30	231	186	127	164	236	159	241	486	202	167
31	245	200	150	179	250	117	255	500	216	124
32	74	95	178	101	14	119	21	262	152	127
33	224	179	128	157	228	151	233	478	194	159
34	173	127	153	106	177	47	182	427	71	54
35	202	156	0	135	192	129	199	436	172	137
36	224	245	297	251	164	268	171	387	302	277
37	190	145	64	123	195	117	200	435	161	126
38	307	410	351	388	247	383	253	470	426	391
39	326	280	224	259	330	253	335	473	296	261
40	168	189	241	194	108	212	115	331	246	220
41	340	506	447	484	280	478	287	503	522	487
42	291	457	398	436	231	430	238	454	473	438
43	196	151	177	130	201	71	206	453	63	78
44	67	43	135	0	111	58	116	361	73	66
45	277	443	384	422	217	416	224	440	459	424
46	226	181	207	160	231	101	236	431	158	108
47	293	215	241	194	265	135	270	420	192	142
48	153	108	92	86	158	42	162	407	124	49
49	272	214	240	193	264	134	269	398	174	141
50	227	182	123	161	232	155	237	482	198	163
51	168	123	149	102	173	43	178	423	100	50
52	325	332	276	311	358	170	387	451	207	177
53	280	235	85	214	267	208	272	514	251	216
54	212	233	285	238	152	256	159	375	290	264
55	78	98	187	110	0	128	13	255	162	136
56	191	230	455	223	268	310	255	258	206	317
57	88	109	189	115	29	133	35	250	166	141
58	126	80	130	59	130	0	135	380	57	8
59	64	85	191	115	13	133	0	282	166	141
60	105	92	138	70	51	88	56	300	122	96
61	426	381	322	359	280	354	287	503	397	362
62	198	219	299	225	118	243	145	137	276	251
63	335	356	436	362	255	380	282	0	413	388
64	212	232	284	238	152	256	158	375	289	264

(continued)

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SKU	5	22	35	44	55	58	59	63	79	94
65	314	480	421	459	254	453	261	477	496	461
66	332	498	439	477	272	471	279	495	514	479
67	224	179	129	158	229	152	234	479	195	160
68	123	78	131	57	128	19	133	378	39	22
69	326	280	131	260	313	254	318	437	297	262
70	219	239	291	245	159	263	166	382	296	271
71	156	97	103	75	110	93	107	353	126	101
72	30	68	198	63	107	121	93	331	69	130
73	265	220	170	198	270	126	275	493	236	133
74	188	143	84	121	193	115	198	442	159	124
75	320	275	219	254	325	248	330	505	291	256
76	197	152	102	130	202	125	207	451	168	133
77	48	28	154	19	130	77	135	380	59	85
78	149	187	316	181	226	239	212	233	163	247
79	107	86	168	73	166	57	171	415	0	63
80	213	168	179	146	218	88	223	455	145	95
81	284	228	299	206	278	148	283	410	186	155
82	380	335	276	313	385	307	389	634	351	315
83	185	140	166	119	190	60	195	473	117	67
84	208	163	189	142	213	83	218	449	140	90
85	292	326	270	304	375	201	380	419	227	208
86	193	148	174	127	198	68	203	465	125	75
87	129	167	224	160	206	118	192	380	110	125
88	163	201	387	195	240	243	226	289	162	250
89	192	147	172	125	196	67	201	446	76	74
90	99	53	106	32	103	26	108	353	69	34
91	176	131	81	109	181	103	186	430	147	112
92	67	47	162	38	150	70	155	358	32	76
93	132	87	86	65	144	59	151	388	102	67
94	134	89	138	67	138	8	143	388	60	0
95	233	255	306	260	173	277	180	396	311	286
96	188	143	169	122	193	63	198	463	57	70
97	79	118	192	68	156	100	143	338	47	106
98	125	109	137	88	65	106	72	309	139	114
99	285	201	227	180	251	121	256	412	178	128
100	165	120	105	99	170	48	175	420	104	55
101	175	129	45	108	179	102	184	419	145	110

(continued)

(continued)

SKU	5	22	35	44	55	58	59	63	79	94
102	359	525	466	503	299	497	305	522	541	506
103	311	303	247	281	353	176	358	437	213	183
104	313	480	421	458	254	452	260	477	496	460
105	263	218	167	196	268	99	272	466	156	106
106	219	174	200	153	224	94	229	439	151	101
107	244	199	148	177	248	171	253	498	214	179
108	80	54	135	30	126	45	131	376	45	51
109	108	63	136	41	71	59	76	321	92	67
110	109	148	276	141	186	200	173	343	105	208
111	303	258	199	236	308	231	313	557	274	239
112	191	160	85	139	141	133	148	385	176	141
113	108	146	275	140	185	198	172	300	103	206
114	327	493	435	472	267	466	274	490	509	474
115	155	110	60	88	160	82	164	409	126	91
116	273	443	384	422	213	416	220	436	459	424
117	86	107	166	112	27	130	33	270	163	138
118	359	525	466	504	299	498	306	522	541	506
119	143	127	102	105	92	158	99	336	156	166
120	292	422	363	401	232	395	239	455	438	403
121	246	200	58	179	244	173	255	488	216	181
122	238	193	65	171	243	165	248	479	209	174
123	84	122	251	116	161	174	148	343	80	183
124	111	66	107	44	115	24	120	365	67	32
w	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**

Appendix 11.C

SKU	5	22	35	44	55	58	59	63	79	94
1	414	376	299	338	326	341	327	589	439	369
2	240	176	81	136	178	142	179	456	222	161
3	423	379	300	341	335	345	336	599	442	372
4	213	149	174	110	202	21	201	482	112	22
5	0	68	256	103	121	198	98	422	210	216
6	386	355	336	316	409	221	407	453	219	235

(continued)

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SKU	5	22	35	44	55	58	59	63	79	94
7	268	299	338	282	179	327	180	440	392	337
8	155	110	174	72	77	116	76	364	183	130
9	353	292	119	249	333	257	331	608	338	274
10	298	233	155	195	288	198	287	571	280	219
11	303	333	372	317	214	361	215	475	426	371
12	346	377	358	360	258	401	259	518	470	415
13	305	336	375	320	217	364	219	478	429	374
14	372	438	513	413	329	487	342	70	470	495
15	226	162	85	122	214	128	209	496	206	145
16	250	187	154	146	239	82	234	520	190	97
17	451	465	387	426	363	429	366	623	529	461
18	484	424	250	381	464	388	462	672	470	406
19	253	318	370	293	368	351	348	291	350	372
20	205	170	204	131	223	75	220	507	56	89
21	172	108	133	69	161	32	156	441	114	49
22	67	0	194	73	152	136	129	453	195	153
23	424	394	333	355	443	260	442	491	368	274
24	206	143	177	104	194	46	193	481	62	62
25	192	129	73	89	182	95	178	467	175	113
26	249	158	99	118	173	123	174	449	204	142
27	252	188	124	148	241	152	235	524	232	170
28	259	290	328	274	170	316	172	428	380	328
29	117	182	308	158	235	251	212	394	183	267
30	265	201	122	162	249	165	249	540	246	184
31	326	262	198	223	309	202	309	598	305	217
32	114	145	205	130	28	172	29	311	237	183
33	288	224	160	185	271	188	271	560	267	206
34	293	229	211	190	277	95	277	562	162	109
35	246	183	0	142	225	150	226	502	229	167
36	346	376	416	360	258	402	259	517	469	414
37	227	164	74	122	210	130	210	501	207	398
38	413	379	300	339	325	344	327	585	443	371
39	429	365	287	325	413	330	412	582	411	348
40	217	248	286	231	128	273	130	386	339	286
41	453	466	387	427	368	431	369	627	533	482
42	404	417	339	378	317	384	318	574	485	411
43	341	277	259	238	325	143	325	529	141	157

(continued)

(continued)

SKU	5	22	35	44	55	58	59	63	79	94
44	103	71	156	0	143	97	143	431	141	115
45	392	405	327	365	304	370	305	561	472	398
46	367	303	284	264	351	169	351	480	277	183
47	383	352	333	312	400	217	399	447	325	231
48	208	145	114	107	195	83	194	483	191	97
49	363	354	335	315	402	219	401	426	315	234
50	262	197	119	158	246	223	245	539	243	180
51	278	214	195	176	262	80	261	545	188	94
52	400	363	285	323	405	265	410	462	353	279
53	335	274	101	232	314	243	313	592	321	256
54	318	349	388	332	230	375	231	488	442	387
55	120	151	225	145	0	186	23	320	255	201
56	275	341	404	315	393	385	370	283	372	408
57	128	159	214	144	41	185	42	300	252	197
58	201	137	162	98	185	0	184	467	110	19
59	99	130	225	145	24	187	0	337	256	201
60	151	144	158	106	73	148	72	360	217	163
61	422	358	281	319	362	324	365	618	422	349
62	259	290	346	276	163	317	174	161	386	329
63	417	448	504	434	321	475	333	0	544	487
64	286	317	356	300	198	342	199	454	410	354
65	423	435	358	396	335	402	336	590	504	429
66	445	457	380	420	359	424	360	614	527	454
67	290	227	163	188	274	192	273	563	270	208
68	196	134	168	94	184	37	183	469	76	46
69	432	371	198	330	411	339	410	616	418	353
70	299	330	368	313	210	355	212	466	423	368
71	223	168	122	130	154	172	143	430	241	187
72	48	116	247	94	169	189	146	392	186	205
73	368	304	242	265	351	227	351	596	347	241
74	234	170	93	131	217	135	217	509	214	151
75	375	311	234	272	358	276	358	543	356	293
76	251	188	126	148	235	153	234	524	231	169
77	79	63	183	28	169	115	168	455	132	140
78	221	285	411	261	338	355	314	258	317	370
79	210	194	241	144	256	112	255	542	0	125
80	351	287	248	247	335	153	334	520	261	167

(continued)

(continued)

SKU	5	22	35	44	55	58	59	63	79	94
81	372	370	319	330	418	235	417	436	324	250
82	380	317	240	277	374	284	376	666	376	304
83	306	242	224	203	290	108	289	547	216	123
84	339	275	257	236	324	141	322	508	249	156
85	366	346	268	307	394	296	394	429	374	311
86	316	252	234	212	300	118	298	533	226	132
87	220	285	368	262	338	251	315	485	250	266
88	248	313	356	289	366	336	342	334	333	354
89	330	266	248	227	314	132	312	598	197	146
90	153	89	119	49	137	53	136	423	136	71
91	227	163	100	124	210	128	209	499	207	145
92	131	116	223	82	222	137	220	467	100	151
93	216	153	109	114	181	118	182	460	199	137
94	219	155	181	116	203	19	201	486	119	0
95	372	402	441	386	283	428	283	541	497	440
96	328	264	247	225	313	130	311	550	136	145
97	131	197	290	148	250	204	226	409	139	218
98	174	175	161	137	88	180	88	367	248	194
99	387	330	313	292	379	196	377	450	305	211
100	223	160	129	121	208	87	206	496	185	101
101	213	151	61	110	198	115	197	487	197	133
102	467	480	403	444	383	446	383	635	549	473
103	420	355	278	317	403	285	403	483	372	300
104	419	433	356	394	333	398	333	589	502	426
105	350	287	224	247	333	176	332	546	285	191
106	357	292	275	254	341	159	339	490	267	173
107	322	259	195	218	305	223	303	595	303	240
108	139	110	178	56	180	95	178	467	93	109
109	164	99	163	61	86	104	84	374	173	119
110	182	247	374	224	300	318	277	419	248	333
111	314	250	173	211	300	216	300	600	305	234
112	252	202	105	163	174	167	174	451	248	184
113	180	245	372	221	298	315	275	360	246	330
114	438	452	375	413	353	416	353	606	519	446
115	201	137	72	98	184	102	182	473	182	119
116	386	405	329	366	299	369	299	555	470	396
117	128	159	191	142	40	186	41	319	251	196

(continued)

(continued)

SKU	5	22	35	44	55	58	59	63	79	94
118	488	503	427	465	403	468	404	656	570	496
119	202	190	117	150	123	186	123	400	263	203
120	402	386	309	346	316	350	317	570	449	375
121	294	232	70	191	283	197	276	559	279	215
122	283	222	84	181	269	187	267	550	267	203
123	139	204	331	180	257	275	234	416	205	289
124	172	108	123	70	157	39	154	438	121	59
w	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**

Appendix 11.D

SKU	Municipality	#Matrix	Destination-SKU	Destination-Municipality
5	Altamirano	1	5	Altamirano
5	Altamirano	1	19	Catazajá
5	Altamirano	1	22	Chanal
5	Altamirano	1	29	Chilón
5	Altamirano	1	56	La Libertad
5	Altamirano	1	72	Ocosingo
5	Altamirano	1	77	Oxchuc
5	Altamirano	1	78	Palenque
5	Altamirano	1	88	Salto de Agua
5	Altamirano	1	92	San Juan Cancuc
5	Altamirano	1	97	Sitalá
5	Altamirano	1	110	Tila
5	Altamirano	1	113	Tumbalá
5	Altamirano	1	123	Yajalón
35	El Parral	3	2	Acala
35	El Parral	3	9	Angel Albino Corzo
35	El Parral	3	10	Arriaga
35	El Parral	3	15	Berriozábal
35	El Parral	3	18	COBACH 132 Luis A. Vidal
35	El Parral	3	25	Chiapa de Corzo
35	El Parral	3	27	Chicoasén
35	El Parral	3	30	Cintalapa

(continued)

(continued)

SKU	Municipality	#Matrix	Destination-SKU	Destination-Municipality
35	El Parral	3	33	Copainalá
35	El Parral	3	35	El Parral
35	El Parral	3	37	Emiliano Zapata
35	El Parral	3	39	Francisco León
35	El Parral	3	50	Jiquipilas
35	El Parral	3	53	La Concordia
35	El Parral	3	67	Mezcalapa
35	El Parral	3	69	Montecristo de Guerrero
35	El Parral	3	74	Ocozocoautla de Espinosa
35	El Parral	3	75	Ostuacán
35	El Parral	3	76	Osumacinta
35	El Parral	3	82	Pijijiapan
35	El Parral	3	91	San Fernando
35	El Parral	3	101	Suchiapa
35	El Parral	3	107	Tecpatán
35	El Parral	3	111	Tonalá
35	El Parral	3	112	Totolapa
35	El Parral	3	115	Tuxtla Gutiérrez
35	El Parral	3	121	Villa Corzo
35	El Parral	3	122	Villaflores
55	La Independencia	5	1	Acacoyagua
55	La Independencia	5	3	Acapetahua
55	La Independencia	5	7	Amatenango de la Frontera
55	La Independencia	5	11	Bejucal de Ocampo
55	La Independencia	5	12	Belisario Domínguez
55	La Independencia	5	13	Bella Vista
55	La Independencia	5	14	Benemérito de las Américas
55	La Independencia	5	17	Cacahoatán
55	La Independencia	5	28	Chicomuselo
55	La Independencia	5	32	Comitán de Domínguez
55	La Independencia	5	36	El Porvenir
55	La Independencia	5	38	Escuintla
55	La Independencia	5	40	Frontera Comalapa
55	La Independencia	5	41	Frontera Hidalgo
55	La Independencia	5	42	Huehuetán
55	La Independencia	5	45	Huixtla
55	La Independencia	5	54	La Grandeza

(continued)

(continued)

SKU	Municipality	#Matrix	Destination-SKU	Destination-Municipality
55	La Independencia	5	55	La Independencia
55	La Independencia	5	57	La Trinitaria
55	La Independencia	5	59	Las Margaritas
55	La Independencia	5	60	Las Rosas
55	La Independencia	5	61	Mapastepec
55	La Independencia	5	62	Maravilla Tenejapa
55	La Independencia	5	63	Marqués de Comillas
55	La Independencia	5	64	Mazapa de Madero
55	La Independencia	5	65	Mazatán
55	La Independencia	5	66	Metapa
55	La Independencia	5	70	Motozintla
55	La Independencia	5	95	Siltepec
55	La Independencia	5	98	Socoltenango
55	La Independencia	5	102	Suchiate
55	La Independencia	5	104	Tapachula
55	La Independencia	5	114	Tuxtla Chico
55	La Independencia	5	116	Tuzantán
55	La Independencia	5	117	Tzimol
55	La Independencia	5	118	Unión Juárez
55	La Independencia	5	119	Venustiano Carranza
55	La Independencia	5	120	Villa Comaltitlán
58	Larráinzar	6	4	Aldama
58	Larráinzar	6	6	Amatán
58	Larráinzar	6	8	Amatenango del Valle
58	Larráinzar	6	16	Bochil
58	Larráinzar	6	20	Chalchihuitán
58	Larráinzar	6	21	Chamula
58	Larráinzar	6	23	Chapultenango
58	Larráinzar	6	24	Chenalhó
58	Larráinzar	6	26	Chiapilla
58	Larráinzar	6	31	Coapilla
58	Larráinzar	6	34	El Bosque
58	Larráinzar	6	43	Huitiupán
58	Larráinzar	6	44	Huixtán
58	Larráinzar	6	46	Ixhuatán
58	Larráinzar	6	47	Ixtacomitán
58	Larráinzar	6	48	Ixtapa

(continued)

(continued)

SKU	Municipality	#Matrix	Destination-SKU	Destination-Municipality
58	Larráinzar	6	49	Ixtapangajoya
58	Larráinzar	6	51	Jitotol
58	Larráinzar	6	52	Juárez
58	Larráinzar	6	58	Larráinzar
58	Larráinzar	6	68	Mitontic
58	Larráinzar	6	71	Nicolás Ruíz
58	Larráinzar	6	73	Ocotepec
58	Larráinzar	6	79	Pantelhó
58	Larráinzar	6	80	Pantepec
58	Larráinzar	6	81	Pichucalco
58	Larráinzar	6	83	Pueblo Nuevo Solistahuacán
58	Larráinzar	6	84	Rayón
58	Larráinzar	6	85	Reforma
58	Larráinzar	6	86	Rincón Chamula
58	Larráinzar	6	87	Sabanilla
58	Larráinzar	6	89	San Andrés Duraznal
58	Larráinzar	6	90	San Cristóbal de las Casas
58	Larráinzar	6	93	San Lucas
58	Larráinzar	6	94	Santiago el Pinar
58	Larráinzar	6	96	Simojovel
58	Larráinzar	6	99	Solosuchiapa
58	Larráinzar	6	100	Soyaló
58	Larráinzar	6	103	Sunuapa
58	Larráinzar	6	105	Tapalapa
58	Larráinzar	6	106	Tapilula
58	Larráinzar	6	108	Tenejapa
58	Larráinzar	6	109	Teopisca
58	Larráinzar	6	124	Zinacantán

Appendix 11.E

SKU	Municipality	#Matrix	Destination-SKU	Destination-Municipality
5	Altamirano	1	5	Altamirano
5	Altamirano	1	19	Catazajá

(continued)

(continued)

SKU	Municipality	#Matrix	Destination-SKU	Destination-Municipality
5	Altamirano	1	22	Chanal
5	Altamirano	1	29	Chilón
5	Altamirano	1	56	La Libertad
5	Altamirano	1	72	Ocosingo
5	Altamirano	1	77	Oxchuc
5	Altamirano	1	78	Palenque
5	Altamirano	1	87	Sabanilla
5	Altamirano	1	88	Salto de Agua
5	Altamirano	1	92	San Juan Cancuc
5	Altamirano	1	97	Sitalá
5	Altamirano	1	110	Tila
5	Altamirano	1	113	Tumbalá
5	Altamirano	1	123	Yajalón
35	El Parral	3	1	Acacoyagua
35	El Parral	3	2	Acala
35	El Parral	3	3	Acapetahua
35	El Parral	3	9	Angel Albino Corzo
35	El Parral	3	10	Arriaga
35	El Parral	3	15	Berriozábal
35	El Parral	3	25	Chiapa de Corzo
35	El Parral	3	26	Chiapilla
35	El Parral	3	27	Chicoasén
35	El Parral	3	30	Cintalapa
35	El Parral	3	31	Coapilla
35	El Parral	3	18	COBACH 132 Luis A. Vidal
35	El Parral	3	33	Copainalá
35	El Parral	3	35	El Parral
35	El Parral	3	37	Emiliano Zapata
35	El Parral	3	38	Escuintla
35	El Parral	3	39	Francisco León
35	El Parral	3	50	Jiquipilas
35	El Parral	3	53	La Concordia
35	El Parral	3	61	Mapastepec
35	El Parral	3	67	Mezcalapa
35	El Parral	3	69	Montecristo de Guerrero
35	El Parral	3	71	Nicolás Ruíz
35	El Parral	3	74	Ocozocoautla de Espinosa

(continued)

(continued)

SKU	Municipality	#Matrix	Destination-SKU	Destination-Municipality
35	El Parral	3	75	Ostuacán
35	El Parral	3	76	Osumacinta
35	El Parral	3	82	Pijijiapan
35	El Parral	3	85	Reforma
35	El Parral	3	91	San Fernando
35	El Parral	3	93	San Lucas
35	El Parral	3	101	Suchiapa
35	El Parral	3	103	Sunuapa
35	El Parral	3	107	Tecpatán
35	El Parral	3	111	Tonalá
35	El Parral	3	112	Totolapa
35	El Parral	3	115	Tuxtla Gutiérrez
35	El Parral	3	119	Venustiano Carranza
35	El Parral	3	120	Villa Comaltitlán
35	El Parral	3	121	Villa Corzo
35	El Parral	3	122	Villaflores
55	La Independencia	5	7	Amatenango de la Frontera
55	La Independencia	5	8	Amatenango del Valle
55	La Independencia	5	11	Bejucal de Ocampo
55	La Independencia	5	12	Belisario Domínguez
55	La Independencia	5	13	Bella Vista
55	La Independencia	5	14	Benemérito de las Américas
55	La Independencia	5	17	Cacahoatán
55	La Independencia	5	28	Chicomuselo
55	La Independencia	5	32	Comitán de Domínguez
55	La Independencia	5	36	El Porvenir
55	La Independencia	5	40	Frontera Comalapa
55	La Independencia	5	41	Frontera Hidalgo
55	La Independencia	5	42	Huehuetán
55	La Independencia	5	45	Huixtla
55	La Independencia	5	54	La Grandeza
55	La Independencia	5	55	La Independencia
55	La Independencia	5	57	La Trinitaria
55	La Independencia	5	59	Las Margaritas
55	La Independencia	5	60	Las Rosas
55	La Independencia	5	62	Maravilla Tenejapa
55	La Independencia	5	63	Marqués de Comillas

(continued)

(continued)

SKU	Municipality	#Matrix	Destination-SKU	Destination-Municipality
55	La Independencia	5	64	Mazapa de Madero
55	La Independencia	5	65	Mazatán
55	La Independencia	5	66	Metapa
55	La Independencia	5	70	Motozintla
55	La Independencia	5	95	Siltepec
55	La Independencia	5	98	Socoltenango
55	La Independencia	5	102	Suchiate
55	La Independencia	5	104	Tapachula
55	La Independencia	5	109	Teopisca
55	La Independencia	5	114	Tuxtla Chico
55	La Independencia	5	116	Tuzantán
55	La Independencia	5	117	Tzimol
55	La Independencia	5	118	Unión Juárez
58	Larráinzar	6	4	Aldama
58	Larráinzar	6	6	Amatán
58	Larráinzar	6	16	Bochil
58	Larráinzar	6	20	Chalchihuitán
58	Larráinzar	6	21	Chamula
58	Larráinzar	6	23	Chapultenango
58	Larráinzar	6	24	Chenalhó
58	Larráinzar	6	34	El Bosque
58	Larráinzar	6	43	Huitiupán
58	Larráinzar	6	44	Huixtán
58	Larráinzar	6	46	Ixhuatán
58	Larráinzar	6	47	Ixtacomitán
58	Larráinzar	6	48	Ixtapa
58	Larráinzar	6	49	Ixtapangajoya
58	Larráinzar	6	51	Jitotol
58	Larráinzar	6	52	Juárez
58	Larráinzar	6	58	Larráinzar
58	Larráinzar	6	68	Mitontic
58	Larráinzar	6	73	Ocotepec
58	Larráinzar	6	79	Pantelhó
58	Larráinzar	6	80	Pantepec
58	Larráinzar	6	81	Pichucalco
58	Larráinzar	6	83	Pueblo Nuevo Solistahuacán
58	Larráinzar	6	84	Rayón

(continued)

(continued)

SKU	Municipality	#Matrix	Destination-SKU	Destination-Municipality
58	Larráinzar	6	86	Rincón Chamula
58	Larráinzar	6	89	San Andrés Duraznal
58	Larráinzar	6	90	San Cristóbal de las Casas
58	Larráinzar	6	94	Santiago el Pinar
58	Larráinzar	6	96	Simojovel
58	Larráinzar	6	99	Solosuchiapa
58	Larráinzar	6	100	Soyaló
58	Larráinzar	6	105	Tapalapa
58	Larráinzar	6	106	Tapilula
58	Larráinzar	6	108	Tenejapa
58	Larráinzar	6	124	Zinacantán

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Chapter 12
Distribution of Personal Protective Equipment, Derived from the Presence of the COVID-19 Virus in Mexico

Erika Barojas-Payán, Miguel-Josué Heredia-Roldan, and Diana Sánchez-Partida

Abstract As a result of a wide variety of risks, diverse in scale, complexity, and consequences, countries must generate various strategies through which they can face them, protecting the population, the ecosystem, and the economy. The objective of the document to be presented is to help health organizations in decision-making in logistical aspects, specifically, in the location of facilities and distribution of supplies. This work proposes a logistic model that allows the location of a feasible municipality through the integration of the classic p-median problem and the Multiple Vehicle Routing Problem (MVRP). The goal is to determine a feasible location to establish a warehouse and the routes to supply Personal protection supplements for the health sector personnel to municipalities that host hospitals of different public institutions with COVID-19 patients. The model is evaluated in one of the states belonging to Mexico, making a typification of its municipalities. The results are obtained in four scenarios, showing both the host municipalities and the delivery routes. The results showed the municipalities of Cuitláhuac, Huiloapan de Cuauhtémoc, Huatusco, and Tlalixcoyan as feasible locations for the warehouse. From the information provided and through the *vehicle routing problem with time windows* (VRPTW), new delivery routes are established, showing a comparison of results. The total of established routes for delivery is seven. Due to the characteristics of the content, this research falls into the classification of case studies.

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Keywords Location · Multiple vehicle routing · Time windows · Health · Personal protective equipment

12.1 Introduction

According to international organizations, all countries of the world face a wide range of emergencies resulting from different risks in terms of scale, complexity, and international consequences, including (a) outbreaks of infectious diseases, (b) chemical and radiation contamination, (c) armed conflicts, and d) consequences of climate change. These can have profound political, economic, social, and public health repercussions and long-term consequences that can sometimes persist for several years (WHO 2015; Veracruz, State Government 2019).

In the area of emergencies derived from outbreaks of infectious diseases, an outbreak is defined as the occurrence of two or more similar cases, which are epidemiologically related (Government of Mexico 2018). In this same field, infectious diseases can be defined as those caused by pathogenic microorganisms such as bacteria, viruses, parasites, or fungi. These diseases can be transmitted, directly or indirectly, from one person to another (WHO, 2020a; IAEA, 2020). In this way, the term endemic is reached, which refers to the constant presence of cases of a disease or infectious agent in human populations within a given geographic area (Government of Mexico 2018). Moreover, the term epidemic refers to an unexpected or too high number of cases in a community or region derived from a disease's appearance. When an epidemic is described, the time, the geographical region, and the population group particularities in which the cases occur must be specified (BRÈS 1986) in (Beaglehole et al. 2003). A pandemic is defined as an epidemic disease that have spread to many countries or have attacked almost all the individuals in a community or region (Veracruz, State Government 2019).

It is worth mentioning that epidemics of highly infectious diseases represent a challenge for health workers, who face a higher risk of infection than the general population due to exposure during the performance of their activities work. Hence, knowledge about the type and correct use of Personal Protective Equipment (PPE) is essential. The use of such equipment should be done as part of prevention and control strategies. *PPE* is defined as any equipment, apparatus, or device specially designed and manufactured to preserve the human body, in whole or in part, from specific risks of accidents at work or professional diseases (Government of Mexico 2020a).

Figure 12.1 shows the chronology of some of the most lethal pandemics throughout history, including the one currently known as COVID-19.

In the same way, over the years, Mexico has been affected by infectious diseases, causing the infection and death of thousands of people. Figure 12.2 shows some of them.

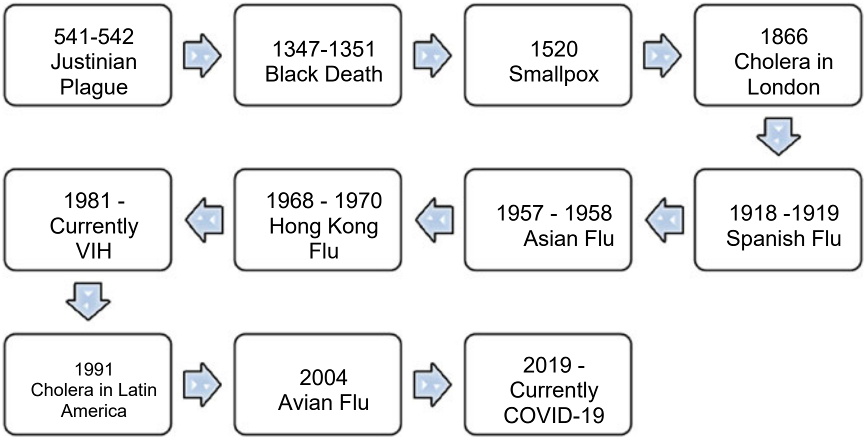


Fig. 12.1 Pandemic timeline. *Source* (Álvarez 2014; Barricarte 2006; WHO 2007; The Editors of Encyclopaedia Britannica 2020)

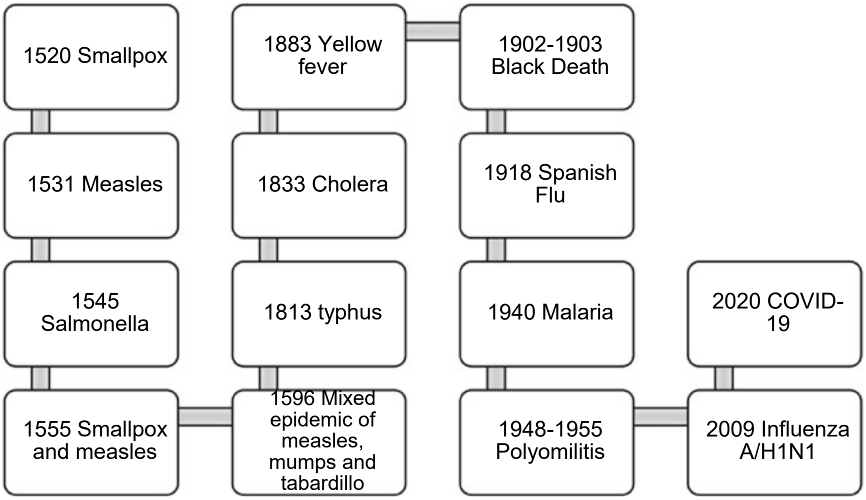


Fig. 12.2 Epidemics in Mexico. *Source* (SEGOB 2018)

12.1.1 COVID-19 Presence in the World

In late 2019, China reported a cluster of pneumonia cases in Wuhan, Hubei Province. Later it is determined that a new coronavirus causes them. Coronaviruses are a family of viruses that cause diseases ranging from the common cold to more serious respiratory diseases, circulating between humans and animals. Sometimes a new strain of coronavirus can emerge capable of causing disease in humans, such as *(a)* Severe Acute Respiratory Syndrome (SARS), in Asia in February 2003, and,

Table 12.1 Cases reported by region in the Americas. 2020 *Source* Authors with information on (PAO and WHO)

Sub-Region	Cases confirmed	Deaths confirmed	Recovered
North America	734,628	34,319	54,200
Central America	5,768	182	287
South America	73,553	3,362	20,768
The Caribbean and Atlantic Ocean Islands	7,911	395	1,038

(b) Middle East Respiratory Syndrome (MERS-CoV) in the Middle East in 2012. Moreover, since the end of 2019, COVID-19, a disease caused by the virus named SARS-CoV-2, is transmitted from an infected person to others when drops of saliva are expelled when speaking, coughing, or sneezing fall on the eyes, nose, or mouth of a healthy person. Since the virus survives on various surfaces, it is also transmitted by manipulating objects contaminated by the virus (hands, tables, cell phones, among others.) and then touching some part of the face such as eyes, nose, and mouth (WHO 2020b; Government of Mexico 2020b).

On April 18th, 2020, the Undersecretariat for Prevention and Promotion of Health in Mexico issued a New Coronavirus in the World Technical Report (COVID-19), which shows that 2,160,207 confirmed cases have been reported worldwide COVID-19 and 146,088 deaths with an overall case fatality rate of 6.8%. To date, 212 countries have reported cumulative cases in the six regions distributed by WHO: *(a)* America, 784,272 cumulative cases; *(b)* Europe, 1,086,889 accumulated cases; *(c)* Mediterraneo Oriental, 120,683 accumulated cases; *(d)* Southeast Asia, 25,291 accumulated cases; *(e)* Western Pacific, 129,968 accumulated cases, and *(f)* Africa, 13,104 accumulated cases (Secretary of Health 2020a).

The American continent has been considerably affected by the new coronavirus, and Table 12.1 shows the data belonging to the April 18th, 2020.

12.1.1.1 Mexico in the Face of the Pandemic

In Mexico, starting in 1997, the Action Program for Epidemiological Emergencies and Disasters was created, which has responded to the need of the Health Sector to have a response scheme for all kinds of health emergencies that may occur in said country, such as disasters caused by natural phenomena. The related risks for the occurrence of outbreaks due to communicable diseases, especially chickenpox, hepatitis A, dengue, or diarrhea, remain, the latter being the most frequent (Veracruz, State Government 2019).

At the end of February 2020, Mexico confirms the first case of infection with the new SARS-CoV-2 coronavirus. Derived from this, the Secretary of Health visualized three scenarios or phases for the new coronavirus spread, which emerged in China at the end of 2019.

- *Viral import*, where it is expected to detect the first cases from countries with the sustained local transmission;
- *Community dispersal,* once the virus is imported into Mexico, the presence of community outbreaks is expected, and;
- *Epidemic phase,* with the presence of the virus throughout the territory and the presence of outbreaks of COVID-19 in various regions of the country (Secretary of Health 2020b).

On May 31st, 2020, in Mexico, 90,664 confirmed cases and 9,930 deaths had been detected in 32 states. Indeed, Mexico City, Mexico, Baja California, Tabasco, Veracruz, and Sinaloa, are the states that have presented the highest number of positive deaths (Secretary of Health 2020b).

12.1.2 Importance of Logistics in Public Health

According to the International Health Regulations (IHR), an event is the manifestation of a disease or a potentially pathogenic event. In the same area, a public health emergency of international importance is called an extraordinary event that, by the IHR, has been determined to *(i)* constitute a risk to public health in other States due to the spread international management of disease, and *(ii)* could require a coordinated international response. While a public health risk refers to the probability of an event occurring that may adversely affect the health of human populations, considering, in particular, the possibility that it will spread internationally or could pose a severe and direct danger (Secretary of Health 2020c; WHO 2016).

Logistics for public health is an essential part of technical assistance delivered during a public health emergency. It covers a variety of functions, for example, inventory maintenance and distribution, handling and transportation management of infectious substances for laboratory tests, and the coordination of operations during epidemic outbreaks (WHO 2020d).

12.1.3 Problem Statement

Within the new social environment in which health organizations are immersed, they must adopt new strategies to manage their logistics activity more efficiently, thereby optimizing stock levels, delivery routes, and the required size by hospital warehouses (Ruiz 2005). Veracruz is one of the states that make up the Mexican Republic and is located on the Atlantic coast, in the Gulf of Mexico. To the north, it borders with Tamaulipas, to the south with Oaxaca and Chiapas, to the west with San Luís Potosí, Hidalgo, and Puebla the south-east with Tabasco. It has an area of 71,699 km^2 and around 8,112,505, according to the 2015 Intercensal Survey of the National Institute of Statistics and Geography (INEGI), making it one of the most populous states in the Mexican Republic (SECTUR 2020; SE 2019).

As a result of the increasing number of COVID-19 cases, in Veracruz, which is one of the six states with the highest number of deaths nationwide (until May 31st, 2020, having 3,717 confirmed cases, 1,524 suspected cases, and 538 deaths) (Veracruz, State Government 2020a). Parallel to this situation, health personnel assisting sick people is required, and these are those who have a higher degree of exposure to the SARS-CoV-2 virus. Motivated by the latter and to provide a support tool to health organizations in decision-making in logistical aspects, specifically in the location of warehouses and distribution of supplies, a logistics model is proposed that integrates the classic problem of the p-median and the multiple vehicle routing problems (MVRP). It allows proposing the location of a feasible municipality in which a warehouse is established that allows supplying personal protection implements for the health sector to the municipalities that host hospitals of different public institutions with people sick with COVID-19, in the state of Veracruz.

In order to obtain a municipality whose conditions allow proper warehouse management, a positional weight variable is established, which is made up of the level of compliance with a set of established characteristics *(1)* that does not have a presence or suspected coronavirus; *(2)* that it has the necessary services for the proper functioning of the warehouse (electricity, drainage, drinking water, telephone, and Internet); *(3)* that it has road access, and *(4)* that it has the necessary infrastructure—likewise, the establishment of delivery routes to municipalities with COVID-19 hospitals. Likewise, a comparison of routes is carried out between those obtained through the implemetation of the vehicle routing problem with time windows.

After the introduction, this document sets out the studies and research that have been done previously in health, humanitarian and environmental logistics, precise location, and vehicle routing. Subsequently, the methodology developed to meet the location and routing objectives in different scenarios are shown, ending with the authors' conclusions and the bibliographic sources used as the basis for the research.

12.2 State of the Art

Over time, many researchers have addressed logistics in various areas, including health, humanitarian, and environmental, to name a few. Either through a literary review, such as the research by Rahman and Smith (2000), in which they review the use of location and allocation models in health services. The purpose of the review is to examine the suitability of methods for designing health care systems and their relevance; or through applying of different methods, techniques, and tools that may include one or more logistical elements. As is the case, the article by (Castrellón-Tores et al., 2014) presents the results of the general modeling process for the logistics of drug distribution within the public health program in Colombia. The model is based on verifying the conditions on the actual information for the logistics distribution system for medicines in the six public health programs in Colombia.

The verification of the structure and robustness of the created model is carried out through an emulation system developed based on the actual information matrix, to be subsequently verified through discrete simulation using a program developed in visual. Net with input and output for Excel. The proposal is tested and validated through GAMS® (General Algebraic Modeling System), with the formulation of three operating scenarios that sequentially allow savings of up to 57.44% in the total cost of the logistics system for health drugs public.

Likewise, Talmor (2019) formulates a mathematical model to minimize the total logistical time required for medical prophylaxis for the urban population as a result of an anthrax attack in the air, balancing three cycles as follows: the cycle of loading, shipping cycle, and service cycle. Applying the model to two representative cases reveals the effect of various parameters in the process, such as the number of distribution centers and the number of servers in each center are critical parameters. In contrast, the number of central warehouses and the local shipping method are less critical. Similarly, Ceselli et al. (2016) develop an optimization model for the efficient distribution of vaccines or drugs through the simultaneous and coordinated use of distribution centers and vehicles. The authors present a Set Covering formulation with three types of columns and branching and price and cut algorithm to solve it. The model is tested on a set of 440 instances that demonstrate results that reach the optimal solution.

On the subject of routing, the authors Chowdhury et al. (2018) use a geographic information system (GIS) to design an emergency transport method for the rapid transfer of pregnant or postpartum women, newborns, and children under five years of age with suspected sepsis. The authors developed a travel time algorithm to incorporate the time taken by the different local transport modes to reach health complexes. The results yielded 15 pre-existing routes, and two new ones were identified as the shortest routes to the health complexes. Similarly, the article developed by Luan et al. (2019) presents a location routing problem model (LRP), which attempts to consider the relationship between the location of warehouses and delivery routes to maximize rescue efficiency. Researchers use the Hybrid Self-Adaptive Bat Algorithm (HSABA) to solve the deficiencies of the LRP; the model is evaluated in 20 coordinate data sets as demand points and four supply coordinate data sets due to the confidentiality of real data. Likewise, researchers Boyer et al. (2013) develop a mixed on-line programming model for the routing of waste, with two objectives: (*1)* to minimize the total cost, including transportation cost, operation cost, initial investment cost, and cost of waste sales. Furthermore, (*2)* minimize the risk of transportation. The authors use the GAMS software with CPLEX solver and apply it in the Markazi province in Iran.

The authors Landa et al. (2016), apply the classic p-median problem to identify a feasible municipality for providing support to low-income people in Mexico. Likewise, Caballero-Morales et al. (2018) provides a metaheuristic to determine the location of support centers in Mexico. The metaheuristic is based on an extension of the K-Means Cluster-ing (KMC) algorithm. This extension led to the GRASP-Capacitated-Means Clustering (GRASP-CKMC) algorithm. In the routing aspect, the researchers Barojas-Payán et al. (2018) address the problem of supplying necessities to people affected by a disaster. They use the heuristic technique of the nearest neighbor (NN) to establish delivery routes for these items in a municipality in Mexico.

Similarly, the research document by Barojas-Payán et al. (2019) shows a mathematical model that allows municipalities to be located for the installation of prepositioned warehouses and the calculation of inventory levels of products. According to the WHO, it allows supplying people affected by a natural phenomenon, said population is divided according to the stage of life of the human being according to the WHO, avoiding special situations such as the puerperium.

12.3 Methodology

The methodology is described in Fig. 12.3. It begins with the compilation of the information necessary for feeding the programs; programming with Lingo 18.0 software continues, and vehicle routing programming with time windows in commercial software is carried out, ending with evaluating different scenarios discarding municipalities obtained in previous runs.

12.3.1 Collection of Information

To evaluate the logistics model, the information contained in the following points is searched in databases and transparency pages of various institutions:

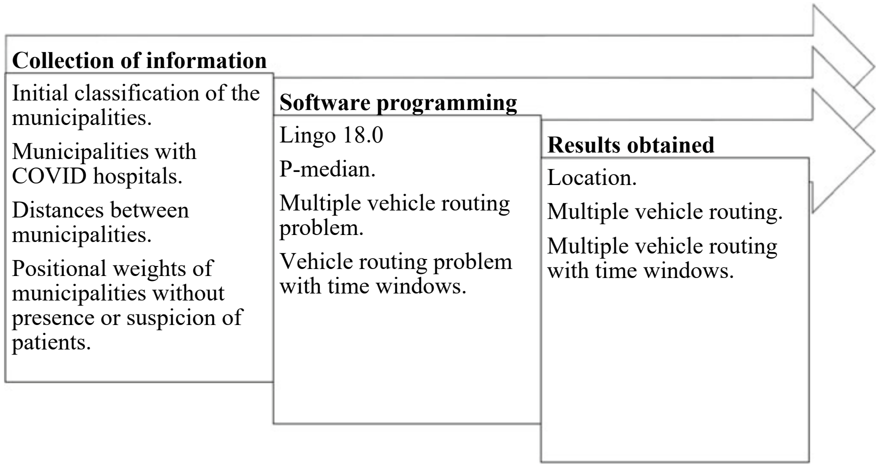


Fig. 12.3 Methodology to follow

12.3.1.1 Classification of Municipalities

With data published dated April 25th, 2020, a matrix is made, with the municipalities of the state of Veracruz that present suspected and/or confirmed cases of people sick with COVID-19 and the municipalities that have no presence or suspicion of cases (Veracruz, State Government 2020a).

Figure 12.4 shows a map of the state of Veracruz that shows the situation of each municipality it houses concerning the presence of confirmed cases (red color), suspicious cases (yellow color) without the presence or suspicion of cases (green color).

While in Table 12.2, it can be seen part of the matrix prepared (10 municipalities) from this selection. Said information would allow the municipalities that can reach the headquarters of the personal protection products warehouse to be identified and the first typification of the municipalities to be supplied.

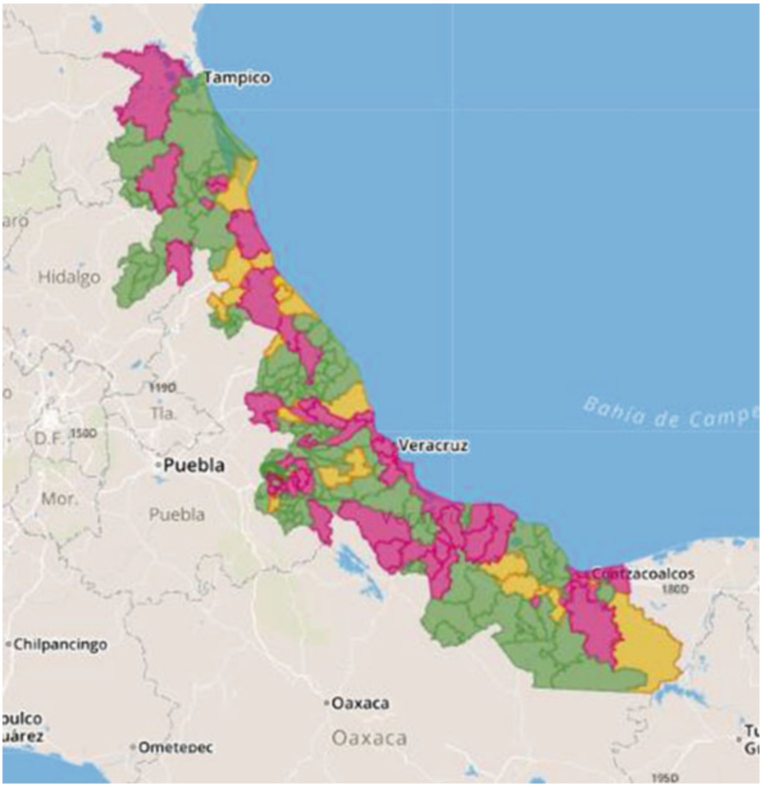


Fig. 12.4 Veracruz, municipalities with presence, with suspicion and without the presence and suspicion of people sick with COVID-19. *Source* (Veracruz, State Government 2020a)

Table 12.2 Municipalities with presence, with suspicion and without the presence and suspicion of people sick with COVID-19

Municipality	Presence	With suspicion	Without the presence and suspicion
Pánuco			
Jáltipan			
Banderilla			
Córdoba			
La Perla			
Orizaba			
Agua Dulce			
Misantla de Altamirano			
Tenampa			
Soledad Atzompa			

Source (Veracruz, State Government 2020a)

12.3.1.2 Municipalities with COVID-19 Sanitary Units

To provide care to Covid-19 sick people, institutions such as (*a*) SS (Secretary of Health); (*b*) IMSS (Mexican Social Security Institute); (*c*) ISSSTE (Institute of Security and Social Services of State Workers), and Pemex, to name a few, designated hospitals to carry out this activity efficiently (PR 2020; Veracruz, State Government 2020b).

And, in order to feed the logistics model, the municipalities that contain hospitals belonging to said institutions that could provide medical care to people with Covid-19 sicknesses and that present confirmed or suspected cases of sick people are identified, obtaining: (1) Boca del Rio; (2) Coatzacoalcos; (3) Córdoba; (4) Cosamaloapan; (5) Martínez de la Torre; (6) Minatitlán; (7) Orizaba; (8) Panuco; (9) Poza Rica; (10) Río Blanco; (11) San Andrés Tuxtla; (12) Tierra Blanca; (13) Tuxpán; (14) Veracruz, and (15) Xalapa (Veracruz, State Government 2020b; IMSS 2020; SCT 2020; PEMEX 2020).

12.3.1.3 Distances Between Municipalities

With the support of the Google Earth® application, a matrix of distances in km is made between municipalities with COVID hospitals and municipalities without

Table 12.3 Municipal attributes

Weight factor	Relative weight (%)	Description
Road access	50	State or federal terrestrial communication road
Services	30	Constructions with drainage service, piped water, energy, telephone, internet
Infrastructure	20	A number of classrooms built per school, this data is taken as a reference, since due to it being a new pre-positioned warehouse, there is no construction for it

Source (SCT 2016; INAFED 2010)

suspicion or confirmation of people infected by a said disease that allows the installation of a warehouse for safekeeping of personal protective equipment, said matrix has dimensions of 15 × 136.

12.3.1.4 Positional Weights

Once the municipalities were identified without the suspicion or presence of people sick with the COVID-19 coronavirus, a variable of the positional weight of each of them was determined, said weight is calculated from attributes, determined from the Authors' experience: *(1) services,* so that it can operate effectively in communication, cleaning, among others.; *(2) road accesses,* that allow a fast delivery in terms of distance traveled to the municipalities that are the headquarters of warehouses, and *(3) infrastructure,* that provides an adequate and safe space for the equipment to be supplied; this information is obtained from the transparency pages of government institutions. Table 12.3 shows a description of these characteristics.

12.3.2 Logistics Model

The model was implemented using Lingo 18.0, which is a comprehensive tool designed for the construction and resolution of optimization models, such as linear, nonlinear (convex and non-convex / global), quadratic, constrained quadratically, second-order cone, semi-defined, stochastic, and integer. The program allows the fast, easy, and more efficient implementation of an optimization model (Lindo Systems INC 2020).

12.3.2.1 Locating a Single Facility

To carry out the location of a feasible municipality to place a warehouse that allows the supply of personal protection items to municipalities with hospitals that care for people sick with the coronavirus COVID-19 in Veracruz. The following are established:

Municipalities with the presence or suspicion of COVID-19 are considered for their supply, as long as they have a health care unit belonging to any of the national health institutions immersed and cares for sick people with said coronavirus. While the municipalities are located, in addition to complying with the minimum distance traveled for the supply, they are evaluated according to their positional weight, which consists of *(1)* that it has the necessary services for the proper functioning of the warehouse (electricity), drainage, drinking water, telephone, and Internet); *(2)* that it has road access, and *(3)* infrastructure.

The mathematical formulation of the problem above is as follows:

$$\boldsymbol{Min}\sum_{i=1}^{n}\sum_{j=1}^{m} w_i d_{ij} x_{ij} \tag{12.1}$$

$$s.t.$$

$$\sum_{j=1}^{m} x_{ij} = 1, \forall_i, \tag{12.2}$$

$$x_{ij} \le y_j, \forall_{ij}, \tag{12.3}$$

$$\sum_{j=1}^{m} y_j = p, \tag{12.4}$$

$$x_{ij}, y_j \in \{0, 1\} \tag{12.5}$$

Where Eq. (12.1) represents the minimization of the product of the positional weight w of the municipalities that can become the headquarters of the supply warehouse due to the distances traveled between said municipalities and those with presence or suspicion of coronavirus; Eq. (12.2) ensures that municipalities with presence or suspicion of coronavirus are assigned to a facility located in a municipality without presence or suspicion of contagion if assigned; Eq. (12.3) makes sure that each client is attended by exactly one server; Eq. (12.4), sets the number of facilities to be located; Eq. (12.5) indicates that the variables are binary (Landa et al. 2016).

12.3.2.2 Vehicle Routing Problem

The vehicle routing problem (VRP) raises the search for the optimal solution with different restrictions such as the number of vehicles, their capacity, destinations (clients), and client demand, among others. The first VRP-type problem proposed was that of the traveling agent (TSP). It receives this name because it can be described in terms of a selling agent who must visit a certain number of cities in a single trip, in such a way that it begins and ends its journey in the “origin” city.

A variation of this is the multiple TSP (m-TSP), in which you have a warehouse and *m* vehicles, that is, *m* traveling agents. The stated objective is to build precisely *m* routes, one for each vehicle, so that each customer is visited once by one of the vehicles. Each route must start and end at the depot and can contain at most *p* customers. In the m-TSP problem, each customer is associated with demand and each vehicle has a specific capacity, which is why it is concluded that the travel agent problem gives rise to the routing problem.

Another variation of VRP appears in 1967, called the Vehicular Routing with Time Windows Problem (VRPTW), which is a VRP problem with the additional restriction of a time window associated to each consumer that defines an interval of time within a consumer must be served. The interval in the warehouse is called the programming horizon (DAAVEDRA. 2013; Rocha-Medina et al. 2011; Toth and Vigo 2002).

In this document, multiple vehicle routing and multiple vehicle routing with time windows are applied to distribute personal protection equipment to medical units in municipalities with hospitals belonging to public institutions that provide care to people sick with COVID-19. The mathematical model of the multiple vehicle routing problem is presented below.

$$Min \sum_{i=1}^{n} \sum_{j=i}^{n} c_{ij} x_{ij} \tag{12.6}$$

s.t.

$$\sum_{j=2}^{n} x_{1j} = m \tag{12.7}$$

$$\sum_{j=2}^{n} x_{j1} = m \tag{12.8}$$

$$\sum_{i=1}^{n} x_{ij} = 1, j = 2, \dots, n \tag{12.9}$$

$$\sum_{j=1}^{n} x_{ij} = 1, i = 2, \dots, n \tag{12.10}$$

$$+ \text{sub tour removal constraints.} \tag{12.11}$$

$$x_{ij} \in \{0, 1\}, \ \forall (i, j) \in A \tag{12.12}$$

Where Eqs. (12.7) and (12.8) ensure that exactly m sellers exit and return to node 1 (deposit). Equations (12.9), (12.10), and (12.12) are customary assignment constraints (DAVENDRA 2013). Equation (12.11) is used to avoid sub-tours, i.e., it degenerates tours that form between intermediate nodes and are not connected to the origin. These are:

$$\sum_{i \in S} \sum_{j \in S} x_{ij} \leq |S| - 1, \forall S \subseteq V \setminus \{1\}, S \neq \oslash \tag{12.13}$$

$$\sum_{i \in S} \sum_{j \in S} x_{ij} \geq 1, \forall S \subseteq V \setminus \{1\}, S \neq \oslash \tag{12.14}$$

$$u_i - u_j + p x_{ij} \leq p - 1 for 2 \leq i \neq j \leq n \tag{12.15}$$

Equations (12.13) and (12.14) avoid the formation of S cardinality sub tours without including the deposit (Dantzing et al. 1954 in DAVEDRA 2013). Unfortunately, both families of these constraints increase exponentially with an increasing number of nodes; therefore, they are not practical to solve the problem or its linear relaxation of programming directly. Miller et al. (1960) (DAVEDRA 2013) surpasses this. Hence the Eq. (12.15), the variable p denotes the maximum number of nodes that any vendor can visit.

Similarly, the mathematical model of vehicle routing with time windows is presented below:

$$\boldsymbol{Min} \sum_{k \in K} \sum_{(i,j) \in A} c_{ij} X_{ijk} \tag{12.16}$$

$$s.t.$$

$$\sum_{k \in K} \sum_{j \in \Delta^+(i)} x_{ijk} = 1 \forall i \in N \tag{12.17}$$

$$\sum_{j \in \Delta^+(0)} x_{0jk=1} \forall k \in N \tag{12.18}$$

$$\sum_{i \in \Delta^-(j)} x_{ijk} - \sum_{i \in \Delta^+(j)} x_{ijk} = 0 \forall k \in K, i \in N \tag{12.19}$$

$$\sum_{i \in \Delta^-(n+1)} x_{in+1k} = 1 \forall k \in N \tag{12.20}$$

$$W_{ik} + S_i + t_{ij} - W_{jk} \leq \left(1 - x_{ijk}\right) M_{ij} \forall k \in K, (i, j) \in N \tag{12.21}$$

$$a_i \sum_{j \in \Delta^+(i)} x_{ijk} \leq W_{ik} \leq b_i \sum_{j \in \Delta^+(i)} x_{ijk} \forall k \in K, i \in N \tag{12.22}$$

$$E \leq W_{ik} \leq L \forall k \in K, i \in (0, n+1) \tag{12.23}$$

$$\sum_{i \in N} d_i \sum_{j \in \Delta^+(i)} x_{ijk} \leq C \forall k \in N \tag{12.24}$$

$$x_{ijk} \geq 0 \forall k \in K, (i, j) \in A \tag{12.25}$$

$$x_{ijk} \in (0, 1) \forall k \in K, (i, j) \in A \tag{12.26}$$

Equation (12.16) represents the total cost, which can be interpreted as travel time or total distance traveled. Finding the minimum total travel distance using the fewest vehicles is required. Equation (12.17) restricts the assignment of each client to a single-vehicle route. Equations (12.18), (12.19), and (12.20) provide the characteristics of the route to be followed by each vehicle k. Equations (12.21), (12.22), (12.23), and (12.24) guarantee the feasibility of the sequence concerning time conditions and aspects of retrospective capacity. Equation (12.25) represent the non-negativity of variable x, and Eqs. (12.26) define the model as linear, integer, binary (Cruz 2018).

12.3.3 Results Obtained

The feasibility of the model is validated by running it on five occasions, discarding the municipalities obtained from a previous run, in order to provide possible additional locations for the installation of the personal protective equipment warehouse. The model results are presented in Fig. 12.5 and in Tables 12.4, 12.5, 12.6 and 12.7.

Figure 12.5 shows the host municipalities of the personal protective equipment warehouse, obtained in the following order: *(1)* Cuitláhuac; *(2)* Huiloapan de Cuauhtémoc; *(3)* Huatusco, and *(4)* Tlalixcoyan. Tables 12.4, 12.5, 12.6 and 12.7 show the delivery routes and some of the traveled circuits (i.e., the point of departure and return, the municipality where the warehouse is located, the municipalities where the hospitals to be supplied in order are located).

In the following paragraphs, more information is provided on the discarding of venues and the routes obtained to deliver the equipment to the Hospitals that could care for people sick with COVID-19.

12.3.3.1 Location One

Table 12.4 shows each route, the municipalities immersed in it, and the image obtained through Google Maps® of the supply circuits belonging to the first municipality derived from the programming of the model, which is called Cuitláhuac, with

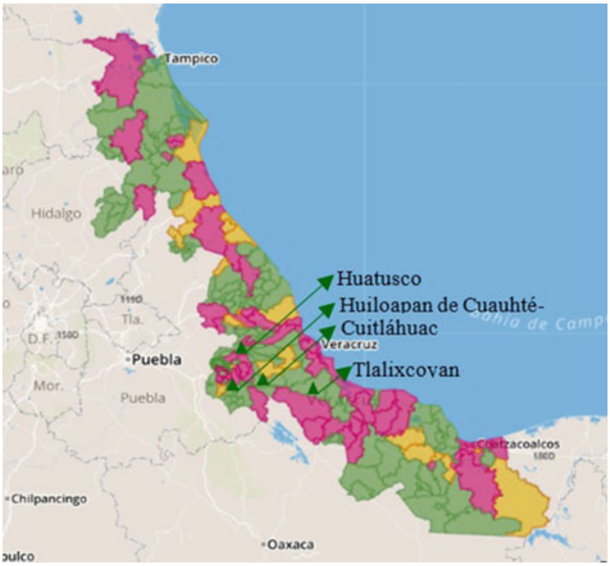


Fig. 12.5 Headquarters of the personal protective equipment warehouse. *Source* (Authors; Veracruz, State Government 2020a)

a total of 7 delivery routes to municipalities that host Hospitals that care for people sick with COVID-19.

12.3.3.2 Location Two

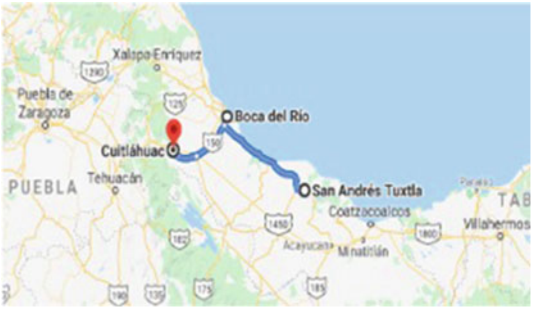
When discarding the first headquarters, the results of Table 12.5 are obtained, which shows the delivery routes belonging to the second municipality shown by the programming of the model, which is called Huiloapan, with a total of 6 routes. Likewise, the table shows a delivery circuit that involves a different delivery sequence (regardless of the location shown in Table 12.4) to municipalities that host Hospitals that care for people sick with COVID-19.

12.3.3.3 Location Three

By discarding the first and second headquarters, the results of Table 12.6 are obtained, which shows the delivery routes belonging to the third municipality thrown by the programming of the model, which is called Huatusco, with a total of six routes. Likewise, the table shows a delivery circuit that involves a different sequence (regardless of the locations than those shown in Tables 12.4 and 12.5) to municipalities that host Hospitals that care for people sick with COVID- 19.

Table 12.4 Routes are belonging to location one

<table>
<tr><th>NO.</th><th>MUNICIPALITY _1</th><th>MUNICIPALITY _2</th><th>MUNICIPALITY _3</th><th>MUNICIPALITY _4</th></tr>
<tr><td rowspan="2">ROUTE_1</td><td>Martínez de la Torre</td><td>Poza Rica</td><td>Tuxpan</td><td>Pánuco</td></tr>
<tr><td colspan="4">


</td></tr>
<tr><td rowspan="2">ROUTE_2</td><td>Boca del Río</td><td>San Andrés Tuxtla</td><td></td><td></td></tr>
<tr><td colspan="4">


</td></tr>
<tr><td rowspan="2">ROUTE_3</td><td>Veracruz</td><td></td><td></td><td></td></tr>
<tr><td colspan="4">


</td></tr>
<tr><td>ROUTE_4</td><td>Cosamaloapan</td><td>Minatitlán</td><td>Coatzacoalcos</td><td></td></tr>
</table>

(continued)

Table 12.4 (continued)

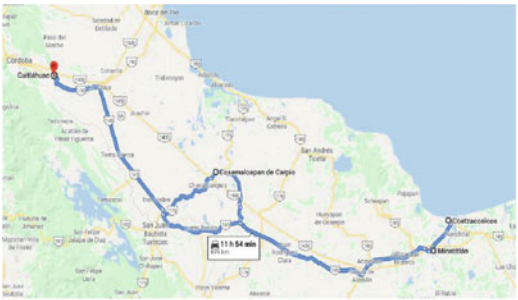
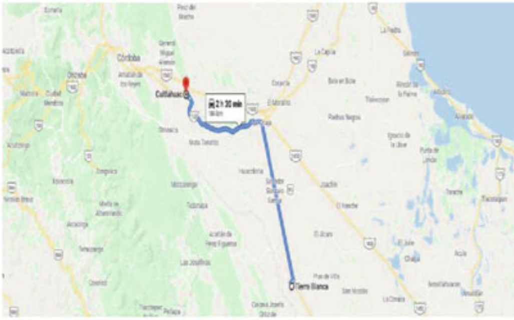
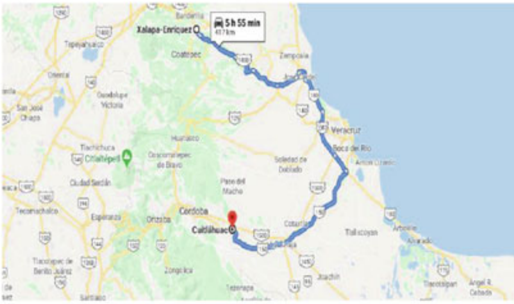
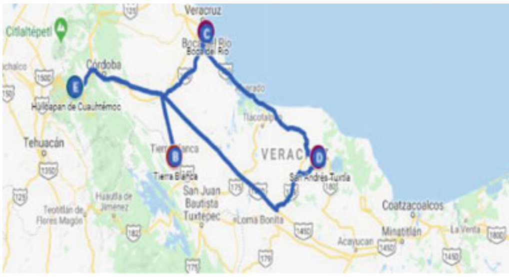
				
ROUTE_5	Tierra Blanca			
				
ROUTE_6	Xalapa			
				
ROUTE_7	Córdoba	Orizaba	Río Blanco	
				

Table 12.5 Routes are belonging to location two

NO.	MUNICIPALITY _1	MUNICIPALITY _2	MUNICIPALITY _3	MUNICIPALITY _4
ROUTE_ 1	Martínez de la Torre	Poza Rica	Tuxpan	Pánuco
ROUTE_ 2	Veracruz			
ROUTE_ 3	Cosamaloapan	Minatitlán	Coatzacoalcos	
ROUTE_ 4	Tierra Blanca	Boca del Río	San Andrés Tuxtla	
ROUTE_ 5	Xalapa			
ROUTE_ 6	Rio Blanco	Orizaba	Córdoba	



12.3.3.4 Location Four

A third evaluation is carried out without weighing the municipalities, that is, removing the positional weight of the municipalities. Based on this, the results of Table 12.7 are obtained, which shows the delivery routes belonging to the municipality shown by the programming of the model, called Tlalixcoyan, with seven delivery routes. In the same way, they show three delivery circuits to the municipalities to municipalities that host Hospitals that provide care to people sick with COVID-19.

Table 12.8 shows the comparison of the distances traveled in each delivery circuit with departure and arrival at the warehouse headquarters. As can be seen, the first location contains a more significant number of kilometers traveled for the supply; however, derived from the positional weight of the municipality of Cuitláhuac, compared to Huiloapan and Huatusco, allowed it to be the main campus. Unlike the municipality of Tlalixcoyan, which is the host municipality that would allow the least number of kilometers traveled if the characterization made for the municipalities will not be taken as a variable.

Table 12.6 Routes are belonging to location three

NO.	MUNICIPALITY_1	MUNICIPALITY_2	MUNICIPALITY_3	MUNICIPALITY_4
ROUTE_1	Martínez de la Torre	Poza Rica	Tuxpan	Pánuco
ROUTE_2	Boca del Río	San Andrés Tuxtla		
ROUTE_3	Veracruz			
ROUTE_4	Cosamaloapan	Minatitlán	Coatzacoalcos	
ROUTE_5	Xalapa			
ROUTE_6	Rio Blanco	Orizaba	Córdoba	Tierra Blanca

12.3.3.5 Vehicle Routing Problem with Time Windows

With the headquarters of the personal protective equipment warehouse in the municipality of Cuitláhuac, there are six delivery routes (see Table 12.9) with their respective traveled distances and their traveled time using normal-type traffic. At the same time, Fig. 12.6 shows the delivery routes from headquarters and their return to it.

Table 12.10 shows a comparison of travel distances between two types of VRP used. As can be seen, the distance between both options is only 19 km.

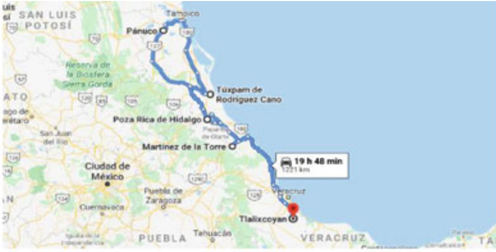
12.4 Conclusions and Future Work

Logistics is a critical aspect of assistance to different sectors, including health. It is because it facilitates critical processes for the material distribution, the deployment of qualified personnel, and the location of relief facilities and infrastructure.

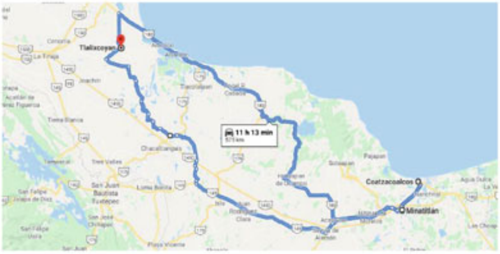
This document aims to help health organizations in decision-making in logistical aspects, specifically in the location of warehouses and distribution of supplies. By integrating the classic p-median problem and the multiple vehicle routing problem (MVRP), programmed in Lingo, a logistics model is proposed that allows the location of a feasible municipality. With that, a warehouse is established that allows supplying

Table 12.7 Routes are belonging to location four, municipalities without positional weight

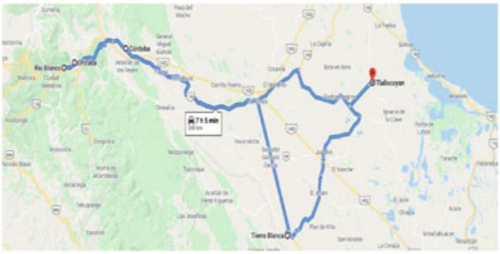
NO.	MUNICIPALITY_1	MUNICIPALITY_2	MUNICIPALITY_3	MUNICIPALITY_4
ROUTE_1	Martínez de la Torre	Poza Rica	Tuxpan	Pánuco



NO.	MUNICIPALITY_1	MUNICIPALITY_2	MUNICIPALITY_3	MUNICIPALITY_4
ROUTE_2	Cosamaloapan	Minatitlán	Coatzacoalcos	



NO.	MUNICIPALITY_1	MUNICIPALITY_2	MUNICIPALITY_3	MUNICIPALITY_4
ROUTE_3	Boca del Río			
ROUTE_4	Veracruz			
ROUTE_5	Tierra Blanca	Córdoba	Orizaba	Río Blanco



NO.	MUNICIPALITY_1	MUNICIPALITY_2	MUNICIPALITY_3	MUNICIPALITY_4
ROUTE_6	San Andrés Tuxtla			
ROUTE_7	Xalapa			

Table 12.8 Distances traveled from different headquarters to the municipalities

Routes	Cuitláhuac	Huiloapan	Huatusco	Tlalixcoyan
1	1331	1241	1229	1221
2	459	283	525	79.6
3	207	787	248	98.5
4	674	647	818	575
5	144	311	177	330
6	417	69.2	334	290
7	106			307
Total	3338	3338.2	3331	2901.1

Table 12.9 Vehicle routing with time windows, based in Cuitláhuac

No. Route	Municipality_1	Municipality_2	Municipality_3	Distance (km)	Time (Hr, Min)
1	Córdoba	Río Blanco	Orizaba	118	3,28
2	Veracruz	San Andrés Tuxtla		467	8,49
3	Boca del Río	Tierra Blanca		277	5,09
4	Cosamaloapan	Coatzacoalcos	Minatitlán	659	14.15
5	Poza Rica	Tuxpan	Pánuco	1230	21.49
6	Xalapa	Martínez de la Torre		606	22.21

personal protection implements for the health sector personnel to the municipalities that house hospitals of different public institutions with people sick with COVID-19 and the delivery routes of the same. For this, characterization of municipalities is carried out, the first based on whether or not these municipalities have confirmed or suspected cases of people sick with COVID-19, and later, with negative municipalities, weigh their attributes of *(1)* service; *(2)* highway accesses, and *(3)* infrastructure, to establish the warehouse headquarters in them.

For the evaluation of the model, four different scenarios are carried out, in the first, the headquarters obtained is the municipality of Cuitláhuac, with a distance traveled of 3338 km. In the second, the first location is discarded, and the municipality of Huiloapan is determined as the warehouse, with a traveled distance of 3338 km. The third scenario discards the first two, and the municipality of Huatusco is obtained, with a distance of 3331 km. The last scenario eliminates the positional weight, and as the headquarters of the warehouse, the municipality of Tlalixcoyan is obtained, with a distance traveled of 2901.1 km.

It is well seen that the first headquarters of the first three scenarios contain a more significant number of kilometers traveled for supply; however, due to its positional weight, it allows it to be the main headquarters. Unlike the municipality of Tlalixcoyan, the host municipality that would allow the fewest kilometers traveled, the characterization made for the municipalities will not be taken as a variable. A second

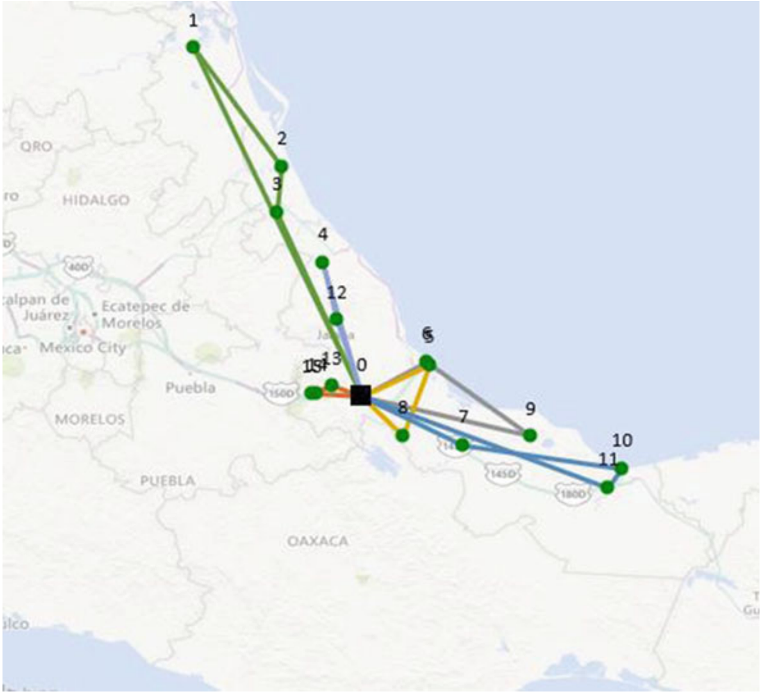


Fig. 12.6 Locations of the personal protective equipment warehouse

Table 12.10 Comparison of distances between routes based in Cuitláhuac

No. Route	VRP multiple Distance (km)	VRP Time window Distance (km)
1	1331	118
2	459	467
3	207	277
4	674	659
5	144	1230
6	417	606
7	106	
	3338	3357

comparison is made by applying the vehicle routing problem with time windows, six routes are obtained with a total of 3357 km and location of the warehouse in the municipality of Cuitláhuac, thus obtaining a difference of 19 km, with respect to scenario 1.

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Chapter 13
A Prediction Model to Determine a COVID-19 Patient's Outcome Based on Its Risk Factors

Linda Martínez-Fantini, Fabiola Regis-Hernández, and Irais Mora-Ochomogo

Abstract In December 2019, a new virus appeared in Wuhan, China. In a matter of weeks, this virus spread to all global regions, causing a pandemic. The first affected were the health systems globally due to the increasing demand of patients requiring hospitalization caused by the virus infection. This situation demanded national authorities to develop complex strategies to diminish the impact. One of the concerns to deal with this situation is an effective and equitable vaccination plan, effectively by attending ICU occupation and equity by prioritizing high-risk population. For this, we present a 5-step data analysis methodology for the calculation of a vulnerability index; considering comorbidities in the patients that enhance the risk of hospitalization. Four Machine Learning algorithms (i.e., Artificial Neural Network, C.50 Decision Tree, Logistic Regression and Naïve Bayes Classifier) were trained, and tested to predict a patients' outcome. The Decision Tree resulted with best performance both in accuracy (>95%) and computational time (<15 s). Finally, we provide an example of its application.

Keywords Vulnerability index · Risk · Machine learning · Data analysis · Pandemic

13.1 Introduction

In the last decade, the frequency and severity of disasters have increased remarkably, and authors suggest that this trend will continue (Leiras et al. 2014). A disaster has been defined as "*a sudden, devastating event that disrupts the functioning of a community causing human, economic or environmental losses that exceed the community's ability to cope using its own resources*" (IFRC 2021a).

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Disasters are classified based on two main characteristics: origin and onset speed. According to their origin, we can define *disasters* as natural (i.e., hurricanes or epidemics) or human-made (i.e., terrorist attacks or wars). As for the speed, we can find them as sudden onset (i.e., earthquakes or avalanches) and slow onset (i.e., droughts or famine). Finally, according to its management, a disaster can also be divided into two main stages: pre-disaster and post-disaster stages. The pre-disaster stages are those including activities that will prepare the communities to respond when a disaster strike. The pre-disaster stages comprise prevention/mitigation and preparedness. The post-disaster stages refer to the activities presented in the aftermath of a disaster and the ones involving the community's recovery. The post-disaster stages are known as response and recovery. More specifically, the response stage is the employment of emergency procedures and resources, and the recovery stage involves the actions taken after the disaster to stabilize the community and restore to normality (Altay and Green 2006).

Disaster Management is characterized by a high degree of complexity, uncertainty, and pressure to save peoples' lives. This type of situation requires efficient resource governance, meaning an adequate implementation of humanitarian logistics. Humanitarian Logistics has been defined as "*the process of planning, implementing, and controlling the cost-effective, efficient flow and storage of goods, materials, and information, from the point of origin to the point of consumption, to alleviate the suffering of vulnerable people*" (Thomas and Mizushima 2005).

One of the most recent humanitarian disasters is the COVID-19 pandemic. Pandemics are natural biological disasters that, unlike other types of disasters, are massive outbreaks of infectious disease that can promptly increase morbidity and mortality worldwide (Madhav et al. 2017, IFRC 2019).

The timeline of some emerging respiratory viruses that have caused pandemics in the last century starts with the appearance of Severe Acute Respiratory Syndrome coronavirus (SARS-CoV) in China in 2002. This SARS-CoV was followed by the 2009 H1N1 influenza pandemic and the 2012 Middle East Respiratory Syndrome coronavirus (MERS-CoV) in Saudi Arabia. Recently, the 2019 novel coronavirus (COVID-19) in China.

Novel viruses continue to emerge due to rapid globalization, food industrialization, among other reasons, posing challenges worldwide (World Health Organization 2020a). A pandemic's potential impact is described in terms of *clinical severity* and *transmissibility*. *Clinical severity* defines how significant is the illness associated with the infection, whereas *transmissibility* defines how quickly is the spread of the pandemic virus from person to person (CDC and NCID 2016). These two factors are measured through the Pandemic Severity Assessment Framework (PSAF) applied by public health officials in several countries. A preliminary assessment of the COVID-19 pandemic was developed by Freitas et al. 2020, revealing high transmissibility and clinical severity levels compared to historical outbreaks. The assessment results can be observed in Fig. 13.1 (Reed et al. 2013).

For this chapter's purpose, in the remaining sections, the context will be limited to the pandemic caused by the new coronavirus SARS-CoV-2 and the impacts that it has caused to society and its systems.

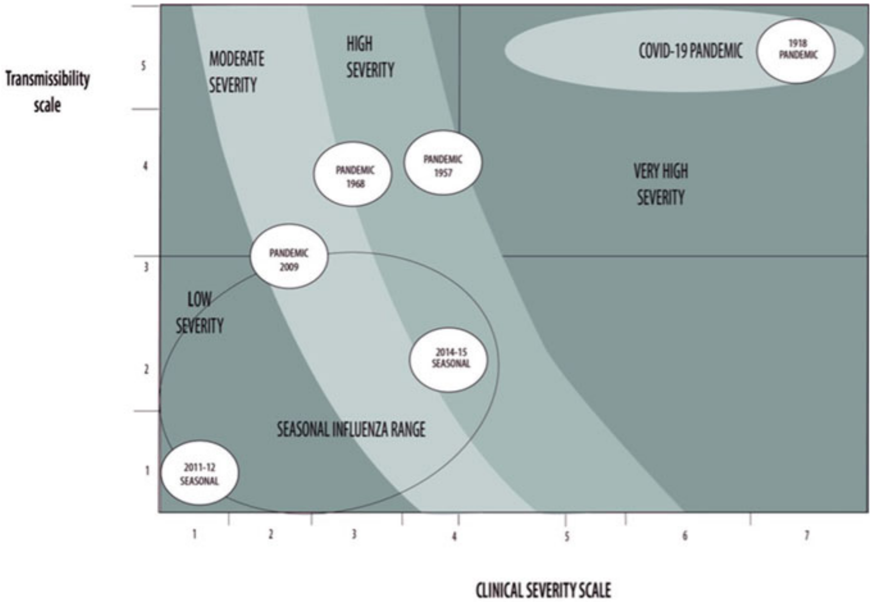

Fig. 13.1 Pandemic severity assessment framework

13.1.1 COVID-19 Pandemic

In December 2019 appears a novel virus that causes a disease known as COVID-19. This new virus spreads rapidly and reaches every continent in the world in a matter of weeks. On January 30th, 2020, the World Health Organization (WHO) declared the outbreak a Public Health Emergency of International Concern (World Health Organization 2020b). By March 2020, more than 214,000 confirmed COVID-19 cases, and more than 9,000 deaths were reported. Moving forward in time, by May 2021, the countries with the higher number of losses were the United States (>580 K), Brazil (>420 K), India (>240 K), México (>210 K), and the United Kingdom (>120 K) (Dong et al. 2020). Since the appearance of the virus, several experts worldwide have been working continuously to learn more about it, including high-risk populations, the spectrum of clinical disease, and the most effective ways to detect, interrupt, and contain human-to-human transmission.

This situation has been classified as a pandemic, demanding global organizations and federal authorities to mount complex and long-term response actions to eradicate it (World Health Organization 2020a). The WHO provided a framework that aids countries in incorporating new recommendations into existing national pandemic preparedness and response plans. In Fig. 13.2 the general framework includes the six-phase approach that can be implemented at any pandemic event (World Health Organization 2009). The phases from 1 to 3 include those decisions related to preparedness, capacity development, and response planning activities. Phases 4–6 involve

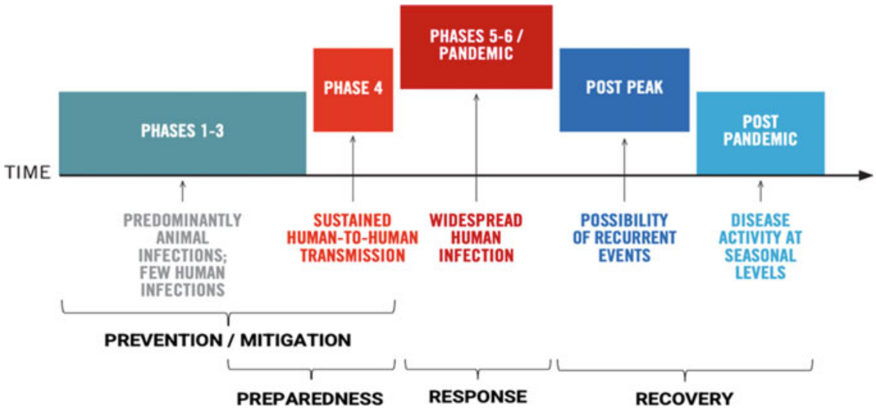

Fig. 13.2 Successive phases of a pandemic and disaster management phases

response and mitigation efforts because the virus has reached 3 to 5 global regions. Periods after the first pandemic wave are to facilitate post-pandemic recovery. The description of these phases resembles the disaster management phases in Humanitarian Logistics proposed by Altay and Green 2006. The activities involved in the pre-pandemic phases would correspond to mitigation and preparedness phases, the efforts to eradicate the pandemic assimilate actions taken in the response phase; finally, the post-peak and post-pandemic phases correspond to the recovery phase. This resemblance is as well depicted in Fig. 13.2.

Phase 6 is where the pandemic emerges. During this phase, the quick demand increase for healthcare attention and hospitalization causes several massive impacts on the healthcare system as well as in the social and economic sectors. For this reason, efforts worldwide to move forward in the vaccine development process were provided to attend to the pandemic. As it can be suspected, pharmaceutical interventions such as immunization and the development of antiviral treatment are the key to overpass the outbreak and restore normality (World Health Organization 2020c).

Immunization and the prior activities involved pose complex logistical challenges. For instance, the distribution and allocation of vaccines require adequate cold chain infrastructure, qualified personnel, lead times and vaccine expiration date control, and an effective network design. Furthermore, challenges regarding equity/fairness also emerge; due to the limited availability of doses at starting periods, it is necessary to identify the high-risk population groups to prioritize them in the vaccine administration as public health experts suggest (Lee et al. 2015; Duijzer et al. 2018). However, establishing an adequate definition of *risk* and *equity* has been a relevant challenge in the literature, especially in humanitarian logistics, where the decision-making process results in saving people's lives. Thus, this chapter provides an analysis of state-of-the-art regarding these topics and, as far as possible, focuses on those that present the limited vaccine allocation problem. The analysis enables us to propose a strategy to prioritize the COVID-19 vaccination in Mexico.

The remainder of the study is divided as follows. Section 13.2 presents the state-of-the-art. Section 13.3 explains the situation of the COVID-19 in Mexico. In Sect. 13.4, the methodology to determine the factors involved in the risk equation is defined. Section 13.5 provides the prediction model and an example of its application. Section 13.6 exposes the discussion derived from the results in Sect. 13.5. Finally, the conclusions and further research are presented in Sect. 13.7.

13.2 State of the Art

This section presents the state of the art. The objective is two-fold. The first objective is to acknowledge the several definitions proposed in literature for the concepts of "risk", "vulnerability", "equity", and "fairness". The second objective is to analyze the methods that have been proposed to define them. The 35 papers that encompass this section were obtained from past literature reviews and reference lists. The papers were classified according to their main topic, narrowing this to three categories related to the terms mentioned above. In this research, "equity" and "fairness" will be used interchangeably.

The scope is limited to identifying vulnerable groups in the Mexican population for their equitable prioritization in the allocation of vaccines; therefore, the definitions and measurement methods encountered will be narrowed to this.

There are several ways to view risk. According to Kumar and Havey 2013, one way to view it is as "a series of foreseeable events that cause a particular harm or a negative outcome". Although the literature about risk in humanitarian logistics and supply chain operations has increased in the last decade, it remains a small percentage compared to other areas (Regis-Hernández et al. 2017). Risk mitigation in humanitarian relief operations has been addressed by several authors considering dynamic response actions (Ben-Tal et al. 2011; Fiorucci et al. 2005). Regis-Hernández et al. 2017 present a multi-criteria framework that allows humanitarian stakeholders' interests to be quantified and integrated into optimization models that support the decision-making process. "Risk" and "Equity" are two of the seven criteria considered in their approach. Kumar and Havey (2013) also develop a methodology to identify and quantify different risks following a fault tree analysis.

In the context of pandemics, "risk" is perceived as the probability of disease aggravation in case of infection in a particular population group (Lee et al. 2015; Ompad et al. 2006); where a group can be associated to spatial proximity (i.e., communities, states, municipalities) or by some attribute of the individuals (i.e., age, gender, race, among others) (Marsh and Schilling 1994). Lee et al. (2015) introduce the concept of "switch trigger," which represents the proportion of vaccines used for the high-risk population before vaccination is opened to the general population. This concept aims to classify vaccination strategies into *full nonprioritized* where no distinction is made of the risk factors among the population, *full prioritized,* which means that all the vaccines available will be given first to high-risk individuals before the general population. A *mixed* strategy refers to the situation where a percentage is assigned to vaccinate the high-risk group first and the remaining to vaccinate the rest of the population.

The proximity of the factor risk with the concept of "vulnerability" is also observed in the literature. Vulnerability is defined as the weakened capacity of an individual or group to anticipate, resist, and recover from a hazard's impact (IFRC 2021b). Sodhi (2016) study the reinforcement loop created by a disaster's impact, economic growth, and vulnerability, establishing the transformation function where: $V(t)$ is the vulnerability measure which converts the input into disaster impact $D(t)$ as output. This output worsens the economy $E(t)$, which in turn increases $V(t)$.

Literature about the measurement of "vulnerability" is rare. Although publications include the term "vulnerability" or "vulnerable people," it is barely explicitly defined or measured. A generalized approach by Flanagan et al. (2011) is developing a social vulnerability index (SVI) that encompasses 15 socioeconomic and demographic factors that affect the community's resilience or ability to cope with adversity. Barzinpour and Esmaeili (2014) develop a specific approach that integrates population and damage severity measurement to assign a level of vulnerability to a particular urban area. Then, they integrate this measurement in a facility location model to cover the most vulnerable areas.

Furthermore, the literature on equity stresses the importance of the subject (Ares et al. 2016). To humanitarian interventions, equity or fairness is essential when seeking impartial access to assistance (Anaya-Arenas et al. 2018). However, disciplines have had the struggle with the complexity of the concept due to its subjectivity. Balcik et al. (2010) and others conclude that the definition of "equity" highly depends on the context.

Manopiniwes and Irohara (2017) refer to "equity" as allocating resources to recipients according to their demand rates. Young (1995) expose three equity concepts that rule resource allocation: "*parity* (individuals in need should be treated equally), *proportionality* (goods should be divided into proportion to differences among individuals in need), and *priority* (the person with the greatest claim to the good should get it)."

Marsh and Schilling (1994) establish that the fundamental process of evaluating equity involves comparing the effect of an action on two or more groups. For instance, in facility location, the action is the "sitting of facilities," while the effect is the negative or positive impact of the proximity to the facilities.

Authors agree that very few works explicitly mention fairness or equity as an objective when optimizing aid distribution (Anaya-Arenas et al. 2018; Regis-Hernández et al. 2017). In the evaluation of the common trade-offs in humanitarian operations made by Gralla et al. (2014), they concluded that "equity" is considered less important among effectiveness and efficiency objectives. This effectivity-equity trade-off was encountered frequently under different scenarios (Ares et al. 2016; Cho 1998; Sengul Orgut et al. 2017). Also, additional approaches that encourage equal service to all recipients included incorporating the min–max criterion as an objective in an optimization model (Mitropoulos et al. 2006). The development of performance indicators that relate to impartially and transparency, to measure fairness (Anaya-Arenas et al. 2018), or by incorporating the Gini coefficient as a measure of inequity

(Ares et al. 2016; Gutjahr and Fischer 2018; Williams and Doessel 2006; Khilji et al. 2013).

Finally, a publication that shares the context of vaccine distribution is the work by Enayati and Özaltın (2020). The authors propose an equity constraint to help public health authorities consider fairness when making vaccine distribution decisions.

This chapter presents a methodology that incorporates “risk”, “equity” and “vulnerability” by creating a vulnerability index based on population comorbidities. Then, this vulnerability index is utilized to identify the high-risk population and finally applied to develop a vaccine prioritization strategy. To the best of our knowledge, this has not yet been considered in the literature. Section 13.3 will present the context of the Mexican pandemic and the importance of incorporating equity in the allocation of vaccines.

13.3 Vaccines’ Allocation in Mexico

In the aim of this chapter, the following sections will be delimited to Mexico, which has belonged among the top ten countries with the highest number of confirmed cases globally and in the top five in the number of deaths (Dong et al. 2020). In March 2020, the national government and the Secretary of Health announced the consensus made about the population’s measures. These included confinement, economic pause for several industries, and social practices inhibition. Although initial measures yielded positive results in terms of numbers (Gobierno de Mexico 2021a), many families that gain their livelihood day by day are unable to comply with lasting such measures, entering a vicious cycle that led to powerful social and economic impacts. This effect shares similarities with Sodhi (2016) reinforcement loop explored in Sect. 13.2.

Following global organizations’ guidance and successive lessons learned, the Vaccine Supply Chain (VSC) was established in CeNSIA (2017) Protocol, by which vaccines go from the manufacturer to the patient. Figure 13.3 presents the VSC and decision levels (strategic, tactical, and operational) at each echelon, adapted to the COVID-19 vaccine distribution established by Instituto de Salud para el Bienestar (2021).

Vaccines arrive at the National Airport of Mexico City, where the National Warehouse is located. At this level, the vaccine distribution network is strategically designed to foresee the supply for subsequent echelons. Within hours, vaccines are transferred to Mexico’s Biological and Reagent Laboratories, S. A. of C. V. (Birmex) for storage and custody. Meanwhile, transport units, distribution routes, and regional warehouses are prepared for the arrival of vaccines. Once the vaccines are at the regional level, they are transported to the warehouses of each municipality. In each municipality, decisions consist mainly of establishing the vaccination points, determining the inventory levels, and coordinating the personnel and equipment required to administer vaccines to the population. The process for expired or leftover doses depends primarily on the vaccine type, although it must comply with each supplier or manufacturer’s disposal or return arrangements.

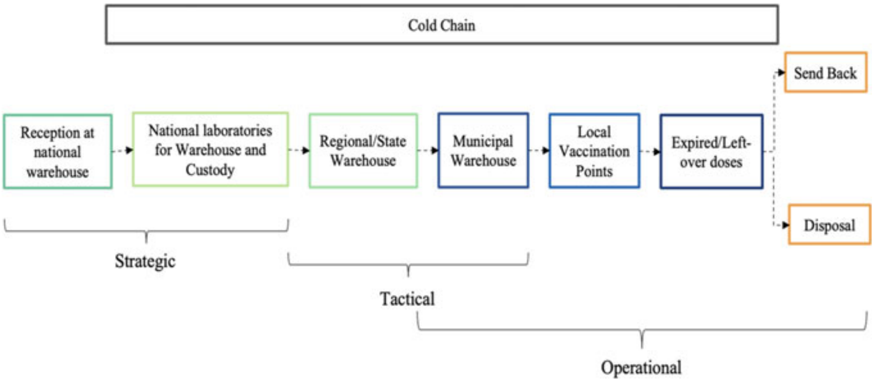

Fig. 13.3 Mexico's Vaccine Supply Chain

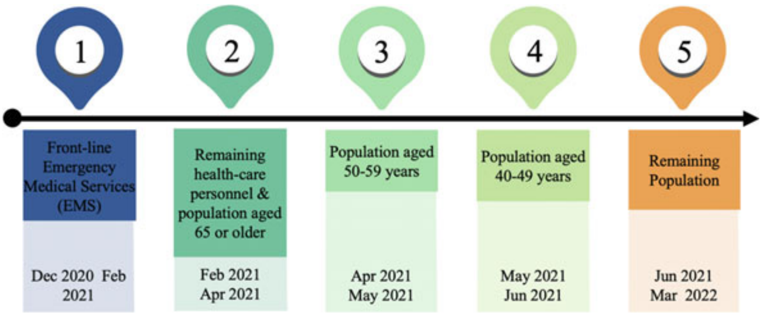

Fig. 13.4 Mexico's Vaccination plan against Covid-19

For the administration of vaccines, the Mexican government proposed the vaccination plan exposed in Fig. 13.4. Vaccine availability is one of the main concerns in the early stages of the pandemic due to the high demand and the manufacturer's capacity; thus, the government developed a strategy that prioritizes vaccination to reduce the mortality rate the quickest possible. Four priority axes were considered: (a) Population's age: Prioritizing the population aged 65 or older; (b) Medical conditions; (c) Prioritized attention groups: i.e., people with disabilities and (d) Epidemic Behavior: unlike the rest, this indicator is dynamic, since the behavior of the pandemic is considered independently on each state, the prioritization of entities may change during the plan execution. Also, population density is a critical factor in this axis since transmission is harder to mitigate and control in more densely populated areas; therefore, it must be prioritized (Gobierno de Mexico 2021b).

The vaccination started with the COVID-19 front-line health personnel in December 2020, followed by the population aged 65 or older, as established in the vaccination plan in Fig. 13.4; however, *age* has been the main prioritization criterion considered, with apparent disregard of the other prioritization axes such as comorbidities that aggravate the virus infection. Considering the vaccination strategies defined by the "switch trigger" concept (Lee et al. 2015), this vaccination plan falls into the *full prioritized* strategy.

The current proposal is a method to prioritize the population considering individuals' comorbidities and the population density as factors that enhance the probability of disease aggravation or hospitalization when infected. This probability will be denominated as *risk*. Currently, the National Center for Disaster Prevention defined *Risk* as the portion of the total cost of the systems foreseen to be affected by an event. Equation (13.1) shows how the risk is determined based on three factors: hazard, exposure, and vulnerability (CENAPRED 2001):

$$\text{Risk} = \text{Hazard (H)} \times \text{Exposure (E)} \times \text{Vulnerability (V)} \quad (13.1)$$

where *Hazard* defines the probability that a certain event happens. *Exposure* defines the number of people, goods, and systems likely to be damaged by an event in a certain location. *Exposure* is often determined in terms of costs; however, it may take other units according to the situation to be measured. Finally, *Vulnerability* is defined as the propensity of the population to be affected by the disaster.

For this research purpose, we defined the factors (i.e., hazard, exposure, and vulnerability) as follows:

- *Hazard (H)* takes the value of 1 since the pandemic is occurring, so the event occurrence probability is 100%.
- *Exposure (E)* is based on the population density of each analyzed location. This decision is derived from the fact that the probability that a person is infected is proportional to the population density where the person is, i.e., the higher the population density, the higher the probability a person gets infected.
- *Vulnerability (V)* will be represented as the portion of the vulnerable population of a given location (municipality or state). This value will be obtained by implementing a data analysis methodology. Section 13.4 presents the steps and arguments for applying it.

13.4 Methodology

The basic steps in data analysis include defining what will be analyzed, collecting data from sources, cleaning unnecessary data, analyzing the data by applying different tools and interpreting the results. The techniques used for the analysis vary according to the objective and context of each study (Kutner et al. 2005). Figure 13.5 presents the methodology steps implemented in this proposal.

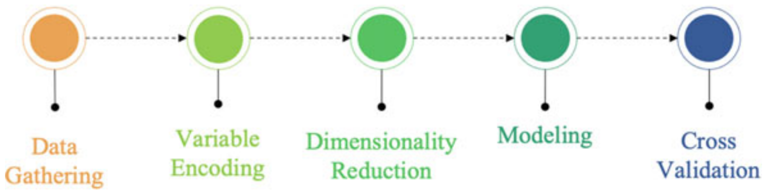

Fig. 13.5 Data analysis methodology

13.4.1 Step 1: Data Gathering

The database used for the analysis is an open-source database from Mexico's Epidemiological Center web page (Secretaria de Salud 2021). Each instance refers to a patient that has been attended at a healthcare unit in Mexico. The data collection started in January 2020, and it has been updated daily since then; therefore, the number of instances increases every day. From January 1st to December 31st, it overpasses 3 million instances. Figure 13.6 depicts the number of hospitalized patients (x-axis) in each month (y-axis) during this period.

The database includes 40 variables; these, as well, have been updated as the pandemic proceeded. The variables represent epidemiological and demographic facts about the patient, such as state of residence, age, and if the patient has comorbidities or not.

The first step was to align the database with the analysis objective by initial variable filtering. Variables related to locations, race, language, and dates were excluded from the analysis. Table 13.1 presents the remaining variables used in the proposed methodology.

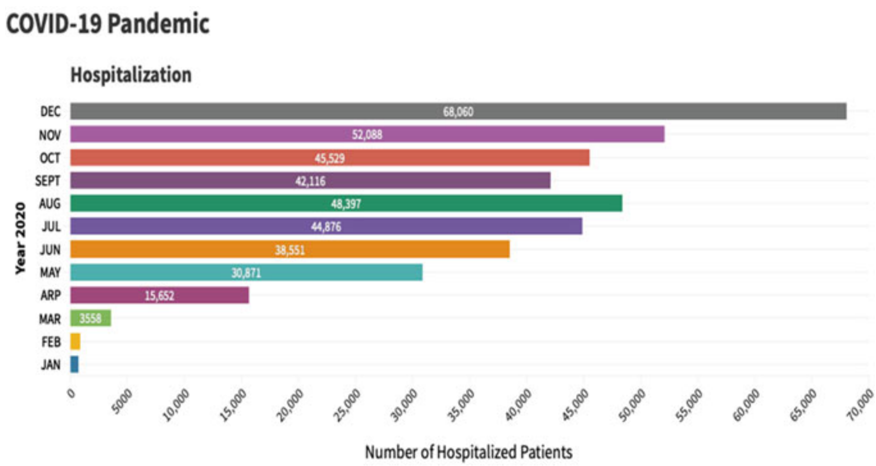

Fig. 13.6 Number of hospitalized patients plotted by month in 2020

Table 13.1 Variables included in the analysis

Variable name	Type of variable	Description [Variable value]
Age	Integer	Patient's age [0,..,100]
Gender	Binary	Patient's gender [Female or Male]
Type of patient	Binary	Type of attention required [Ambulatory or Hospitalized]
Pneumonia	Binary	1 if the patient suffers from this condition 0 otherwise
Diabetes	Binary	
Chronic Obstructive Pulmonary Disease (COPD)	Binary	
Asthma	Binary	
Immunosuppression	Binary	
Hypertension	Binary	
Obesity	Binary	
Cardiovascular diseases	Binary	
Other medical conditions	Binary	
Tabaquism	Binary	
Chronic renal failure	Binary	
Contact with a positive case of COVID-19	Binary	1 if the patient has been in contact with a positive case 0 otherwise

The data presents several characteristics that must be considered and treated before the appliance of subsequent steps. Firstly, the nature of most of the variables is dichotomous (17 out of 18 variables), which limits the techniques to apply for the analysis. Second, the high correlation between some of the variables is evident due to its definition, i.e., the variable *gender* is highly related to the variable *pregnant*; if the value of *gender* is male, the *pregnant* value will be No necessarily.

This aspect is known as multicollinearity, which refers to the existence of linear relation or dependency among two or more variables (Alin 2010; El-Habil 2012). Multicollinearity is not a matter of presence, but the degree, the higher the degree, the greater the likelihood of disturbing the solution of the models (El-Sibakhi 2016). It is considered a disturbance by several authors since it causes volatility in the data that complicates the interpretation of the results (Alin 2010; El-Habil 2012; Midi et al. 2010; Wissmann and Toutenburg 2007); therefore, it must be adequately attended. Among the techniques encountered in the literature to attend multicollinearity mainly apply to quantitative variables; thus, they are inappropriate for this case. Variable selection, shrinkage regression techniques (i.e., Ridge Regression), obtaining the Variance Inflator Factors (VIF), pairwise correlation coefficient, and eigenvalues are some techniques encountered in the literature regarding multicollinearity treatment with qualitative variables (Wissmann and Toutenburg 2007; Midi et al. 2010; El-Sibakhi 2016). Moreover, several issues are related to multicollinearity diagnostic measures, which are unexplored or partially explored in the literature (Wissmann and Toutenburg 2007). For this research, the Ridge Regression was applied.

Finally, there are 18 variables included in the study. Each added variable represents a dimension and produces an exponential decrease in predictive power. Therefore, reducing the dimensionality should be performed whenever possible (Berchtold et al. 1996). Section 13.4.3 explains the remedial measures taken to overcome the issues previously mentioned.

13.4.2 Step 2: Variable Encoding

As suggested by the literature, a key step of the pre-processing stage is the missing values treatment and variable encoding. The missing values (NA values) encountered in the database denoted three different meanings: (a) not applicable, (b) not enough information, or (c) not specified. Due to the low cost of elimination attained by the high number of instances presented in the database, the variables with missing values were indeed deleted. The numeric variable *age* was normalized by using a famous technique known as Min–Max Scaling. The min–max scaling rearranges values to go from 0 to 1 or –1 to 1 depending on the study (Patro and Sahu 2015). Also, the original values for the binary variables were 1 and 2; however, we encoded them into 0–1 values. The variable *gender*: 0 refers to female and 1 to male, and variable *type of patient:* 0 refers to ambulatory and 1 to hospitalized; for the remaining variables: 0 refers to no, and 1 to yes. This step aims to help the coefficients' interpretation.

13.4.3 Step 3: Dimensionality Reduction

This step proceeded to the modeling firstly to deal with the issues presented in Sect. 13.4.1. From the 40 variables, the first filter made in Sect. 13.4.1 left the analysis with 18 variables; an additional filter was held to exclude variables that were dependent on each other, where a clear example of this dependency is the variable *type of patient*, *intensive care unit*, and *required intubation*. By definition, when *type of patient* has the value of 0, it refers to an ambulatory patient; automatically, the variables *intensive care unit* and *required intubation* will take the value "not applicable" since the services were not provided to that patient. A similar case is the variables *gender* and *pregnancy* as if *gender* takes the value male, necessarily, the variable *pregnancy* will appear with the value "not applicable". Therefore, the variables *pregnancy*, *required intubation*, and *intensive care unit* shall be removed from the database for the remaining of the analysis. Also, we employed a Ridge Regression to aid the variable selection and gain better results in accuracy, however, the results obtained were not significantly different amongst the other algorithms (accuracy: > 90%, computational time: < 20 s).

To observe the models' performance, four samples were taken from the treated database, which corresponded to different months during the pandemic. The analyzed samples were April with 72 K instances, June with 284 K instances, August with 379 k instances, and December with 700 k instances. All the methods and techniques mentioned up to this step are part of the pre-processing of the data. This process is key to gain accuracy and reliability in the analysis. Section 13.4.4. will encompass the description of the techniques utilized for analyzing and interpreting the data.

13.4.4 Step 4: Modeling

A review of the literature was necessary to identify the state-of-the-art tools to deal with data with characteristics such as binary values and large sampling. Due to the latter characteristic, Machine Learning (ML) algorithms were included in the review. The search was limited to classification techniques since the response variable (*type of patient)* is binary. After the review, the models selected were:

- **Artificial Neural Network (ANN)**: It is a highly parameterized statistical model that has attracted considerable attention in recent years. ANNs input a combination of the predictor variables and transforms it by a nonlinear function to produce hidden outputs. The outputs from one layer, serve as inputs to the next layer. Each element forms a weighted sum of non-linear combination (Hand 2007).
- **Decision Tree**: Each internal node in the tree specifies a binary test on a single variable. A data vector x follows a single path from the root node to a leaf node depending on how the values match the binary tests of the nodes (Hand 2007). A final categorization is produced when a leaf node does not generate any more branches (Theobald 2017).
- **Logistic Regression**: It is one of the most important types of generalized linear model used when the response variable is binary. The aim is to formulate a model that links a linear combination with a non-linear probability (Hand 2007).
- **Naive Bayes**: It is a simple but powerful method that predicts the class probability based on conditional probability (Bayes Theorem), which states the probability of something to happen, given that something else has already occurred (Kassambara 2018).

Each of these models were trained and tested in each of the samples (recalling April, June, August, and December database division) using RStudio 1.3.1073 on MAC 11.1 with 4 G.B. memory. The R packages used were: (1) *neuralnet*, (2) *C50*, (3) *glm* from *stats*, (4) *klaR*. Alongside, *glmnet* package was used for the Ridge Regression mentioned in Sect. 13.4.3. The model accuracy and computational time were determined for each sample. The model accuracy is given in percentage, and it is measured as the proportion of the number of times that the response variable

Table 13.2 Models' accuracy and computational times at different instances

Models	April n = 72 K	June n = 284 K	August n = 379 K	December n = 700 K
Artificial Neural Network	> 85% < 100 s	> 90% < 400 s	> 90% < 2500 s	NA[a] > 14000 s
C5.0 Decision Tree	**> 85%** **0 s**	**> 90%** **< 5 s**	**> 90%** **< 5 s**	**> 95%** **< 10 s**
Logistic Regression	> 85% < 5 s	**> 90%** **< 5 s**	**> 90%** **< 5 s**	> 90% < 10 s
Naïve Bayes	> 85% < 10 s	> 85% < 30 s	> 90% < 40 s	> 90% < 70 s

[a] The accuracy for this instance was unattainable

matched the response variable *type of patient* (Kassambara 2018). Also, the computational time required by the algorithm to provide an input is given in seconds. These two metrics were considered to select the best model. As exposed in Table 13.2 accuracy values were very similar between models. In terms of computational time, the Decision Tree and Logistic Regression were the fastest models; however, the Decision Tree resulted with the best performance in all four instances. Therefore, the Decision Tree was chosen as the algorithm to continue with the reminder of the analysis.

13.4.5 Step 5: Cross Validation

For a final step of the data analysis, an external validation (also known as cross-validation) of the models was approached. This approach consists of splitting the database into two independent sets randomly and repetitively. Each time the database is split, an accuracy estimator is generated, so at the end, the unbiased estimators' average yields to an overall accuracy defining a more realistic performance of the model (Hand 2007). There are several methods to achieve cross-validation; a *K-Fold* Cross-Validation Method was applied in this methodology with a $k = 10$ as suggested in several publications reviewed. In Sect. 13.5, the Decision Tree appliance analysis and the results are presented.

13.5 Prediction model

To obtain the prediction model, we implemented the C5.0 Decision Tree in R with parameters "trials" set to 10 as a boosting procedure as suggested by Pandya and Pandya (2015). The model considers the instances for the twelve months of year

2020 (3 million observations) and the variables presented in Table 13.1. The plot of the final tree can be observed in Fig. 13.7.

Furthermore, the C5.0 includes a function *C5imp* with the parameter metric = ‘usage’, and pct = ‘F’ to obtain the Variable Importance Measures (VIMs) which are determined by the percentage of the training set that falls into the terminal nodes after the split; therefore, the predictor for the first split has automatically an importance measure of 100%, followed by the next predictor and so forth.

The variable importance measures alongside the variables are expressed as the linear Eq. (13.1):

$$y = \beta_1 x_1 + \beta_2 x_2 + \cdots + \beta_i x_i \tag{13.2}$$

where the β_i correspond to the VIM that applies to each of the variables and the x_i correspond to each of the variables.

Following the approach suggested in Eq. (13.2), the vulnerability level is determined by $\sum_i \beta_i x_i$. The sum is then evaluated against the sample median ($\tilde{x}$). If the vulnerability value is equal or above the median, the level “high risk”, represented by the value of 1, is assigned to the patient or “medium risk” represented by a 0 is assigned otherwise. The median estimator was considered as a threshold since the variables do not follow a normal distribution.

Once the β_i where estimated, the resulting prediction model can be expressed as Eq. (13.3):

$$\begin{aligned}\text{Vulnerabilityindex} = {} & 1 * \text{Pneumonia} + 1 * \text{Age} + 1 * \text{ChronicRenalFailure} \\ & + 1 * \text{ContactPositive} + 0.9959 * \text{Diabetes} + 0.9492 * \text{Immuno} \\ & + 0.6236 * \text{COPD} + 0.6182 * \text{OtherMedConditions}\end{aligned}$$

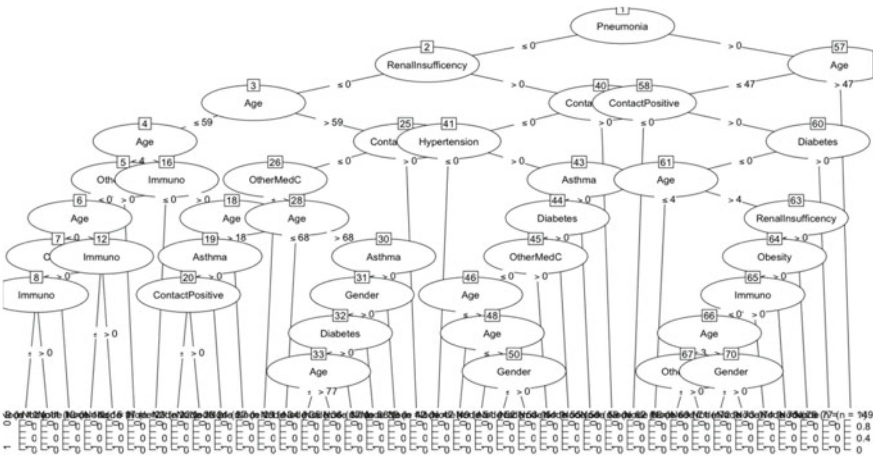

Fig. 13.7 Plot of 10th trial of the Decision Tree

$$+ 0.4149 * \text{Hypertension} + 0.4588 * \text{CardioDiseases} + 0.1922 * \text{Gender}$$
$$+ 0.573 * \text{Obesity} + 0.160 * \text{Tabaquism} + 0.058 * \text{Asthma} \quad (13.3)$$

where x_i are each of the comorbidities exposed in Table 13.1 that can take the values of 0 or 1, representing absence or presence respectively, of a comorbidity in the patient. Since the value of the VIMs are expressed as percentage, we divided them by 100 to keep the decimal form. Then, the VIMs were evaluated against each of the patients in the sample to obtain the median value. Applying Eq. (13.3) with an example of a 75-year-old male patient that presents hypertension, diabetes and has been in contact with a positive COVID-19 case, we obtain Eq. (13.4) that determines the patient has a vulnerability index of 2.228:

$$\text{Vulnerability index} = 1 * 0.6250 + 1 + 0.9959 * 1 + 0.4149 * 1 + 0.1922 * 1 \quad (13.4)$$

As a reminder, the age was scaled to 0.6250 using the min–max scaling. Since the value 2.228 is greater than $\tilde{x} = 1.308333$, this patient can be considered at "high risk".

To provide the population a prediction tool that, based on their comorbidities, helps them to estimate their risk index in case of contagion, various calculators were designed from different international organizations. One of the best known and used has been Johns Hopkins and University of Maryland Research Team (2020). However, in the specific case of Mexico, the Instituto Mexicano del Seguro Social (IMSS) developed one. Following, we provide a deeper description of each of them.

- **IMSSC:** ***The COVID-19 Health Aggravation Calculator developed by IMSS*** (2021) which, based on the person's comorbidities, estimates the probability of COVID-19 disease aggravation when infected. This estimation is only a preventive guide for the Mexican population, it does not replace in any way the medical evaluations made by medical experts (IMSS 2021).
- **JHC:** ***The Mortality Risk Calculator developed by Johns Hopkins and University of Maryland Research Team*** (2020) calculates the risk of mortality from COVID-19 in current uninfected individuals based on a set of risk-factors (Williamson et al. 2020), community-level pandemic dynamics, and the state of residence in the USA. The tool estimates an absolute mortality rate per 10,000,000 individuals in subgroups of the population with a similar risk profile, with a 95% confidence interval. For further information about how the calculator estimates the risk we refer the reader to Johns Hopkins and University of Maryland Research Team (2020)[1]

The list of comorbidities considered in IMSS (2021), Johns Hopkins and University of Maryland Research Team (2020), and the current proposal are presented in

[1] Kempler, A. W. A. C. (2020, December 11). Online COVID-19 mortality risk calculator could help determine who should get vaccines first. The Hub. https://hub.jhu.edu/2020/12/11/covid-mortality-risk-calculator-nilanjan-chatterjee/.

Table 13.3. For simplicity, the calculator created by IMSS (2021) will be referred to as *IMSSC***.** The calculator developed by Johns Hopkins and University of Maryland Research Team (2020) will be presented as *JHC*. Finally, the proposed methodology as *PMC***.** The main similarities remain in the comorbidities considered in each of the risk calculators, as exposed in Table 13.3. Although *IMSSC* considers only eight epidemiological factors, *PMC* includes 14 (6 additional factors than *IMSSC*), and *JHC* surpasses both quantities by considering 19 factors in total.

The variables list alongside the resulting importance measure of *PMC* is presented in Table 13.4. Some of the variables that appear with higher importance in *PMC* coincide with factors associated with high risk in the other calculators. Moreover, *IMSSC* considers the variable *gender* with high importance since the risk level increases when the value is *male*. Unlike the results on *PMC*, this variable resulted with a low importance measure. The strong influence of the *gender* variable may derive from statistics regarding the number of hospitalized patients in Mexico (59% of the

Table 13.3 Factors and comorbidities considered in the risk calculators

Factors	IMSSC	PMC	JHC
Gender	*	*	*
Age	*	*	*
Hypertension	*	*	*
Chronic renal failure	*	*	*
Chronic obstructive pulmonary disease	*	*	*
Immunosuppression	*	*	*
Diabetes	*	*	*
Weight	*		*
Obesity		*	
Pneumonia		*	
Contact with a confirmed case		*	
Asthma		*	*
Smoking		*	*
Other medical conditions		*	*
Cardiovascular diseases		*	*
Location			*
Height			*
Controlled or uncontrolled diabetes			*
Type of cancer			*
Years with cancer			*
Stroke			*
Race/Ethnicity			*

IMSSC: IMSS calculator; **PMC**: Proposed Methodology calculator; **JHC**: Johns Hopkins & University of Maryland Research Team calculator

Table 13.4 Variable importance measures

Importance	Variables
High (50–100%)	– Pneumonia – Age – Contact with a confirmed positive case – Chronic renal insufficiency – Other medical conditions – Diabetes – Immunosuppression – Chronic obstructive pulmonary diseases
Medium (0–49%)	– Cardiovascular diseases – Tabaquism – Gender – Obesity – Hypertension – Asthma

confirmed cases are male and 41% are female) (DataMexico 2021). Nevertheless, further research is required to confirm this theory (Kopel et al. 2020).

IMSSC reveals two levels of risk: Medium or High; to aid the comparison, the *PMC* risk values were defined as Medium and High too. Finally, *JHC* exposes five levels: (1) Close to or lower than average, (2) Moderately elevated, (3) Substantially elevated, (4) High, and (5) Very High.

To exemplify the use of the calculators and their performance, we evaluate of the calculators using randomly ten random patients from the database exposed in Sect. 13.4.1. The comorbidities and characteristics for each patient are presented in Table 13.5. Some variable names were shortened, i.e., "*Other Med C*" refers to "*Other medical conditions,*" and "*Contact*" refers to "*Contact with a confirmed case.*" The value of the *Ethnicity* variable was standardized to Hispanic since the database applies to Mexican citizens only. Also, the patients' height and weight are considered as the average weight and average height of Hispanic citizens (CDC/National Center for Health Statistics/Division of Analysis and Epidemiology 2016). The same logic also applies to those patients with obesity for which the assigned value was the average weight of obese Hispanic citizens. The variables included in Table 13.5 depend on the comorbidities presented on the patients chosen to run the trials; hence, some of them were excluded. In Sect. 13.6, we present the results obtained by the calculators along with the similarities and limitations encountered.

13.6 Example and Results

We performed the analysis firstly with the *JHC*. From the 10 patients, 9 resulted with the lowest risk level (Close to or lower than average), and only 1 resulted "moderately elevated". Moreover, the calculators' comparison against *JHC* is limited by several factors. First, the *JHC* was intended for the population of the 50 states in the United

Table 13.5 Patient information and outcome predictions

		Patients									
		P1	P2	P3	P4	P5	P6	P7	P8	P9	P10
Cormobidities	Age	65	49	69	49	83	57	47	38	39	32
	Gender	F	M	F	F	F	M	F	M	M	M
	Height (ft)	5.7	5.7	5.2	5.2	5.7	5.6	5.2	5.7	5.6	5.6
	Weight (lb)	230	348	160	120	160	128	120	280	130	129
	Pneumonia	*	*	*	*						
	Diabetes		*		*			*			
	Asthma						*				
	Hypertension	*	*	*			*				
	Other Med C									*	
	Obesity	*	*						*		
	Smoking	*									
	Contact			*		*	*				*
	Diabetes type[a]		1		1			0			
	Hospitalized	1	1	1	1	0	0	1	1	0	0
Risk[b] calculator	IMSSC	1	1	1	1	1	1	0	0	0	0
	PMC	**1**	**1**	**1**	**1**	**0**	**0**	0	0	**0**	**0**

[a]Controlled = 1; Uncontrolled = 0
[b]Risk Values for the calculators are: 1 = High, 0 = Medium

States; therefore, the results are highly affected by this. Further research must be employed to conclude the magnitude of such effect. Also, the *JHC* analyzes patient's risk of mortality, while the *IMSSC* and *PMC* considers risk of disease aggravation. Finally, the *JHC* assigns the patient a risk level considering a portion of the population that share the same characteristics and comorbidities as the patient. Unlike *PMC* and *IMSSC* the resulting risk level is calculated based on the whole population characteristics. Therefore, we decided to continue the comparison only considering *PMC* and *IMSSC* as presented in Table 13.5. It is worthy of mentioning that the predictions and accuracy may vary according to the random sample characteristics.

Both calculators share equal results on patients that were hospitalized. Furthermore, the Decision Tree accuracy obtained in Sect. 13.4.4 (>95%), the *PMC*'s prediction sustains the result by asserting in 8 of the 10 total cases. Unlike *IMSSC,* which presents a prediction accuracy of 60%.

There are few considerations for the appliance of this prediction model. One of them is that the classifier decision tree is highly susceptible to overfitting, which is a constant challenge in machine learning resulting on how closely the model follows the actual patterns of the dataset in the training process. An overfitted model will have accurate predictions from the training data but prove less accurate from the test data (Theobald 2017). The remedial measure for this issue was boosting, which main objective is to add weights to misclassified iterations in earlier trials, by selecting binary questions that improve prediction accuracy for each new tree (Theobald 2017). This measure was implemented by changing the "trial" parameter to 10 in the decision tree (Kassambara 2018). Also, resulting VIMs are highly sensitive to changes, therefore, the coefficients presented in Eq. (13.3) may not be the same in repeated experiments. However, the variables with high VIM remain from study to study. Furthermore, the data analysis methodology can be adjusted to obtain the vulnerability value of a municipality or a state, which will aid to identify the high-risk populations around the country, in such way that decision-makers can supply the vaccines more equitably.

13.7 Conclusions and Further Research

This work encompasses four global topics presented in each of the sections. (1) Humanitarian Logistics in pandemics. (2) The state-of-the-art in "risk", "vulnerability" and "equity". (3) The development of Data Analysis Methodology and (4) The use of Machine Learning algorithms for the prediction of an outcome. This chapter provides an overview of the importance of the disaster management in humanitarian logistics regarding a particular type of natural disasters which are pandemics. This subject includes the pandemic phases and the challenges presented in the decision-making to achieve an effective and equitable vaccine allocation. For the later, a state-of-the-art in the concepts of "risk", "vulnerability" and "equity" in humanitarian operations is presented, which seeks to analyze the established definitions and measurement methods regarding these concepts. In this analysis, a great stress was encountered within the authors that arises when establishing a correct definition and measurement of the terms due to their subjectivity. Publications that share the context of vaccine distribution and allocation to attend a pandemic encountered the importance of the prioritization of high-risk populations to achieve equity in vaccine administration, specially at starting periods, when the number of vaccines is limited. Thus, this work proposes a methodology to analyze and helps to identify high-risk population groups based on a Risk Equation built by three factors: hazard, exposure, and vulnerability. Four Machine Learning algorithms, i.e., Artificial Neural Network, C.50 Decision Tree, Logistic Regression, and Naïve Bayes Classifier, were trained, and tested to predict a patients' outcome. The C5.0 Decision Tree resulted in the best performance (>95%) and revealed Pneumonia, Age, chronic renal insufficiency, Immunosuppression, and Diabetes, among the variables with high importance measures. These results share similarities with other risk calculators that measure disease aggravation or patient mortality applied in Mexico and worldwide, alongside some discrepancies which require further analysis. The implementation of this methodology and the Machine Learning algorithms resulted in an effective tool to equitably prioritize the population at higher risk of hospitalization due to COVID-19 infection, based on their comorbidities (vulnerability index). Further research leads to implementing the proposed methodology in developing predictive models to be used as a tool to improve the decision-making process.

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Chapter 14
Application of a Markov Decision Process in Collection Center Operations

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Abstract With the increase of disasters around the world, the need to improve the response becomes crucial. In many countries worldwide, this response arrives in for of in-kind donations. This chapter presents two numerical applications of a Markov Decision Process. In the first one, the existence of a Monotone Optimal Non-Decreasing Policy is tested under the five conditions defined by Puterman. The second is a case study of a hurricane Katia in Mexico where the behavior of the policy is evaluated, and a sensitivity analysis of the operating costs is performed.

Keywords Disaster relief · Humanitarian logistics · Collection centers · Donations management · Markov decision process

14.1 Introduction

Donations represent the fuel of most humanitarian organizations; cash or in-kind are the main ways to receive these donations. In many countries worldwide, due to cultural or social beliefs, or the distrust in cash management, the proportion of in-kind donations is much higher than cash. Therefore, collection centers become

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Fig. 14.1 General representation of the flow of donations in a disaster relief supply chain

a crucial point on the disaster relief supply chain. Figure 14.1 presents a graphic representation of an example of a supply chain operated with material donations.

The material flow starts on the left with the donors, who can be the general population, organizations, or even smaller collection centers. The donations are received as individual items of different nature; this can include food, medicines, clothes, and hygiene products. Each collection center decides the type of items that they will be receiving. This can be decided according to their assessment of needs, their ability to manage, or other policies previously defined.

Once they arrive at the collection center, donations are sorted, classified, and packed to be ready to send to the affected area. Collection centers are usually located outside the affected area, so shipments must be made with a certain frequency to reach the people in need. When donations reach the affected community, they can be received in a distribution center, sent to distribution points, and finally to recipients. In this chapter, the frequency of shipment decisions are addressed.

Mexico is an example of a country where in-kind donations are received more commonly than cash. When a disaster occurs and the affected community requires national assistance, collection centers are one of the first actions taken to help. The biggest collection centers and the ones that are enabled more frequently are operated by humanitarian organizations with a nationwide presence, for example, Mexican Red Cross and local and federal governments. But, when the disaster is close or big enough, collection centers operated by the general population have also been shared. In the earthquake of September 19th, 2017. over 900 collection centers were accounted for only in Mexico City (Verificado 19S 2017).

This chapter presents a case study applying a Markov Decision Process (MDP) that models the operations of the collection centers and seeks to decide the frequency of the shipments to the affected area. To make this decision, we previously mathematically verified the existence of a Monotone Optimal Non-Decreasing Policy (MONDP) (Mora-Ochomogo et al. 2021, p.). This chapter aims to validate numerically the conditions under which this policy is present in the results.

The remainder of this chapter is structured as follows. Section 14.2 presents the description of the MDP, the MONDP, and the Matlab program used to solve the model. Section 14.3 presents a small numerical instance to prove the conditions of existence of the MONDP. Section 14.4 provides a case study, including the results, and a sensitivity analysis that test the impact of the costs on the policy. Finally, Sect. 14.5 presents the conclusions of the case study presented.

14.2 Methodology

Collection centers' operations face uncertainty on the donations and demand. This makes the deterministic methods less likely to represent the real operations. In this case, they were modeled as a Markov Decision Process where the uncertainty can be incorporated into the model.

14.2.1 Markov Decision Process

An MDP is a model for sequential decision-making under uncertainty, taking into account both the short-term outcomes of current decisions and opportunities for making decisions in the future (Kallenberg 2009). The elements that conform an MDP are decision epochs, states, actions, rewards, and transition probabilities. Figure 14.2 presents a graphical representation of how these elements interact.

Each box represents a decision epoch, where the state variables define the system's current state. With the information of the present states, an action is taken, and a reward or cost is generated from the chosen action. Once the action is taken, the transition probability defines the state of the subsequent decision epoch.

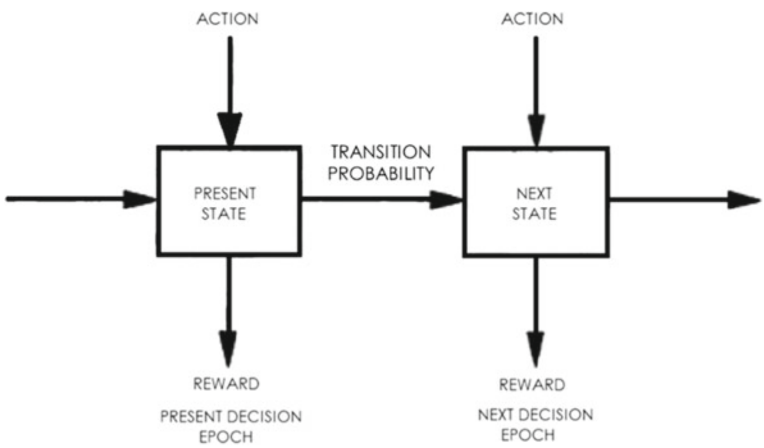

Fig. 14.2 Representation of a Markov decision process. Modified from: Puterman (1994)

Table 14.1 Description of the elements of the collection centers' MDP

Element	Description
Decision epoch	The decisions are made each day of the operation of the collection center
States	The state of each decision epoch is defined by two variables: the number of kits available to send (inventory on hand) and the accumulated demand (number of kits)
Actions	The two possible actions at each decision epoch are: to wait for another decision epoch to send a shipment or to send a shipment of size Q_t The shipment size is defined as the minimum value between the available inventory on hand or the sum of the accumulated demand and the expected demand for the next period
Costs	For the collection center model, the costs used for the value function are: • deprivation cost • fixed shipping cost • variable shipping cost • holding cost • salvage value
Transition probabilities	The transition probabilities define the next state of the inventory on hand and the accumulated demand in the collection center model The increase of the inventory on hand is modeled as a Compound Poisson Process. The process combines the number of donors in each epoch and the number of kits each donor is expected to donate The increase of the accumulated demand is modeled as a binomial distribution where the number of affected families and the probability a family requests a kit are considered

The description of the elements for the MDP developed for the collection centers is shown in Table 14.1.

In this model, we seek to minimize its value function. The value function is defined by the immediate costs of the action taken in a period and the expected costs of the following periods. The expected costs are computed with the transition probabilities and future costs of the feasible states.

One of the main uses of Markov Decision Process methods is to establish the existence of optimal policies with a special structure. According to Puterman (1994), the importance of results regarding the optimality of structured policies lies in their appeal to decision-makers, their ease of implementation, and their enabling efficient computation.

A control limit policy is a deterministic Markov policy composed of decision rules of the form:

$$d_t(s) = \begin{cases} a_1 & s < s^* \\ a_2 & s \geq s^* \end{cases}$$

If we establish that such policies are optimal, the problem of finding an optimal policy reduces to that of determining s*.

Monotone policies (non-decreasing or non-increasing) control limit valuable policies when there is a natural ordering in the state space. Once the states are ordered, the monotone policy identifies the optimal threshold for the corresponding action.

In the proposed model for collection centers, the states are grouped according to the inventory level and partially ordered by the level of accumulated demand. This means that each inventory level will present a monotone non-decreasing behavior where there will be a threshold defining when to start sending. Identifying this helps the decision-makers minimize the total costs.

A Monotone Optimal Policy is desirable for:

- The dynamic environment.
- Heterogeneity of input data at each stage.
- Appeal to decision makers.
- Ease of implementation.
- Enabling efficient computation.

The Monotone Optimal Policy corresponds to a threshold level of inventory and demand such that shipping kits is optimal for (partially ordered) states beyond this threshold.

Theorem 4.7.4 of Puterman (1990) provides conditions under which there exist monotone nondecreasing optimal policies in all the states for all periods. These conditions are the following:

1. $r, (s, a)$ is nondecreasing (nonincreasing) in s for all $a \in A'$
2. $q, (k|s, a)$ is nondecreasing (nonincreasing) in s for all $k \in S$ and $a \in A'$,
3. $r, (s, a)$ is a superadditive (subadditive) function on $S \times A'$,
4. $q, (k|s, a)$ is a superadditive (subadditive) function on $S \times A^{'}$ for all $k \in S$, and
5. $r_N(s)$ is nondecreasing (nonincreasing) in S.

The authors have mathematically validated these conditions in the context of the collection centers. They will be numerically verified in this chapter with a small instance.

14.2.2 Matlab Program

The numerical instances to test the MDP performance and the existence of the Monotone Optimal Non-Decreasing Policy numerically were performed through a backward induction program in MATLAB. This program establishes all the feasible states in all the periods considered in the time horizon. Then it computes the size of the possible shipment and the value function for the two possible actions, to send the corresponding shipment or not to send it. Finally, it chooses the best action comparing the two costs and proposes the optimal policy.

The data needed to run the program are some parameters that, in the case of a real event, can be estimated with information about the affected population, real-time data available, or expertise from previous experiences. The parameters requested are:

- Estimated number of families in the affected area.
- Capacity of the collection center (number of kits).
- Number of days the collection center is expected to operate.
- Proportion of families that will demand a kit in one period.
- Average number of donors each period.
- Average amount of kits donated per donor.
- Penalty cost for each unit (kit) of unmet demand one period.
- Fixed shipping cost.
- Variable shipping cost.
- Holding cost at the collection center for one period.
- Salvage value of the kits left in the collection center on the last period.

The program results are displayed in a table that includes the period, the current inventory level, the accumulated demand, the size of the shipment to be made in case the best action is to send, the cost of both alternatives, and the action to be taken. The goal of these tables is to identify the compliance of the MONDP and identify the threshold that states when the decision-maker should start making shipments.

Two numerical instances were developed for this chapter. The first one seeks to prove the conditions of the MONDP, and the second one is based on hurricane Katia that stroke Mexico in September 2017. This disaster was a hurricane category 2. It impacted the states of Veracruz and Puebla in México. More than 900 people of low-income communities were affected by the intense winds and flooding. This case study to prove the model is presented in the next section.

14.3 Numerical Instance

For this section, a small instance has been developed. It allowed verifying that the MATLAB program worked properly and helped identify the policy's proper behavior presented in Sect. 14.2.1.

The parameters used for this numerical instance are shown in Table 14.2.

In this example, the probability of a family requiring a kit decreases as time passes. This means that it starts with 0.85 and reduces 20% each period. Therefore, for period two, the probability drops to 0.68 and 0.64 for period three.

14.3.1 Results

The solution of the numerical instance stated in the previous section is presented in Table 14.3. The instance was solved by backward induction, finding with this the optimal policy for this case.

Table 14.2 Parameters set for the numerical instance

Parameter	Value
Number of families in the affected area	3
Maximum number of kits that can be managed at the collection center at any given stage	4
Length of the decision-making time horizon	4
Probability a family requiring a kit in a period	0.85
Average number of donors that donate each period	2
Average amount of kits donated per donor	1
Penalty cost for each unit (kit) of unmet demand one period	20
Fixed shipping cost	52
Variable shipping cost that depends on the number of kits sent	10
Cost for holding inventory at the collection center for one stage	20
Salvage value of the kits left in the Collection Center on the last period	10

For each period, the states were grouped by level of available inventory to be shipped and partially ordered according to accumulated demand. This generates 20 different possible states per period.

The results show the period, the state variables, the shipment size to be sent if action 1 is chosen, the cost of both actions, and finally, the action to choose. For example, a shipment should be made in action 1 while in action 0, the shipment is not required.

In Table 14.3, we can see that from periods 1–3, a particular action is chosen for each state. For example, in period one and inventory of one, it is never optimal to make a shipment; however, when two kits are available to send, the threshold appears once they have a demand of one kit. Thus, from that point on, the optimal action to take is to send whenever we have two kits in inventory and one or more kits demanded. The same behavior is observed for inventory levels of three and four kits.

For time two with an inventory of one as well, there is no level of demand for sending a shipment, and level two of inventory has similar conduct as in period one. But when there are three or more kits in inventory, it is always optimal to send a shipment size of three or four respectively, even if there is no demand at that point.

As stated previously, there is no decision to make in the fourth period; therefore, the action will always be not to send, and the cost function will include the rescue value of the remaining kits for the case of inventory level 1–4.

This instance presents a clear example of the MONDP presented in Sect. 14.2.1, showing that the presented data fits the policy's requirements. For each group with an equal available inventory level, there is a threshold that indicates the point from where from then on, the optimal action is to send a shipment. Before that point, it is optimal not to send.

Table 14.3 Results of the numerical instance

Period	Inventory	Demand	Shipment	Cost not send	Cost send	Action
1	0	0	0	139.53	0	0
1	0	1	0	162.01	0	0
1	0	2	0	184.62	0	0
1	0	3	0	207.37	0	0
1	1	0	1	154.36	185.82	0
1	1	1	1	175.89	187.51	0
1	1	2	1	197.56	209.25	0
1	1	3	1	219.4	231	0
1	2	0	2	168.97	185.03	0
1	2	1	2	189.55	186.24	1
1	2	2	2	210.25	187.66	1
1	2	3	2	231.05	209.33	1
1	3	0	3	187.65	188.18	0
1	3	1	3	207.61	188.18	1
1	3	2	3	227.61	188.18	1
1	3	3	3	247.61	188.18	1
1	4	0	3	211.01	221.62	0
1	4	1	4	230.94	198.18	1
1	4	2	4	250.94	198.18	1
1	4	3	4	270.94	198.18	1
2	0	0	0	75.169	0	0
2	0	1	0	100.72	0	0
2	0	2	0	126.57	0	0
2	0	3	0	153.23	0	0
2	1	0	1	92.48	120.59	0
2	1	1	1	115.6	125.37	0
2	1	2	1	139.01	150.29	0
2	1	3	1	163.43	174.43	0
2	2	0	2	110.26	117.4	0
2	2	1	2	131.08	120.44	1
2	2	2	2	152.04	124.91	1
2	2	3	2	173.9	151.49	1
2	3	0	3	131.85	120.94	1
2	3	1	3	151.25	120.94	1
2	3	2	3	170.57	120.94	1
2	3	3	3	190.57	120.94	1

(continued)

Table 14.3 (continued)

Period	Inventory	Demand	Shipment	Cost not send	Cost send	Action
2	4	0	3	155.95	152.04	1
2	4	1	4	174.93	130.94	1
2	4	2	4	193.9	130.94	1
2	4	3	4	213.9	130.94	1
3	0	0	0	14.545	0	0
3	0	1	0	43.665	0	0
3	0	2	0	72.785	0	0
3	0	3	0	101.9	0	0
3	1	0	1	26.851	58.441	0
3	1	1	1	55.971	65.665	0
3	1	2	1	85.091	94.785	0
3	1	3	1	114.21	123.9	0
3	2	0	2	40.64	57.125	0
3	2	1	2	69.76	59.823	1
3	2	2	2	98.88	64.785	1
3	2	3	2	128	93.905	1
3	3	0	2	55.973	73.905	0
3	3	1	3	85.093	63.905	1
3	3	2	3	114.21	63.905	1
3	3	3	3	143.33	63.905	1
3	4	0	2	72.64	86.211	0
3	4	1	3	101.76	83.905	1
3	4	2	4	130.88	73.905	1
3	4	3	4	160	73.905	1
4	0	0	0	0	0	0
4	0	1	0	20	0	0
4	0	2	0	40	0	0
4	0	3	0	60	0	0
4	1	0	0	−10	0	0
4	1	1	0	10	0	0
4	1	2	0	30	0	0
4	1	3	0	50	0	0
4	2	0	0	−20	0	0
4	2	1	0	0	0	0
4	2	2	0	20	0	0
4	2	3	0	40	0	0

(continued)

Table 14.3 (continued)

Period	Inventory	Demand	Shipment	Cost not send	Cost send	Action
4	3	0	0	−30	0	0
4	3	1	0	−10	0	0
4	3	2	0	10	0	0
4	3	3	0	30	0	0
4	4	0	0	−40	0	0
4	4	1	0	−20	0	0
4	4	2	0	0	0	0
4	4	3	0	20	0	0

14.3.2 Numerical Verification of MONDP Conditions

Condition 1

This condition states that the value function is non-decreasing in demand for each level of inventory and action a = {0}. Table 14.4 presents an example of the results in period 3 and inventory level 2. This condition can be verified in column 5, where the cost of the chosen action increases for each level of inventories as the accumulated non-satisfied demand increases.

Condition 2

Condition 2 focuses on the transition probabilities. It states that it should be a non-decreasing function. This means that for all inventory groups and when action a = {0} is chosen, the transition probability is a non-decreasing function.

The individual probability matrix for the transition of the demand in time 1 with a = {0} is shown in Table 14.5. The rows represent the inventory level for the current period and the columns for the future period.

For example, the condition is met when the transition probability from inventory 1 to 3 (0.7225) is lower than the one from inventory 2 to 3 (0.85).

Condition 3

States that the value function is superadditive in for all states and a = {0}. This condition, following Puterman's definition, can be expressed in Eq. (14.1):

Table 14.4 Example of the results for period 3 and inventory level 2

Period	Inventory	Demand	Shipment	Action cost
3	2	0	2	40.64
3	2	1	2	69.76
3	2	2	2	98.88
3	2	3	2	128

Table 14.5 Demand transition probability matrix

	0	1	2	3
0	0.0034	0.0574	0.3251	0.6141
1		0.0225	0.255	0.7225
2			0.15	0.85
3				1

$$u_{t+1}[(I_t, D_t), 1] + u_{t+1}[(I_t, D_t + 1), 0] \leq u_{t+1}[(I_t, D_t), 0] + u_{t+1}[(I_t, D_t + 1), 1] \quad (14.1)$$

Table 14.6 presents the example of inventory one in period two. The superadditive function is presented after the table and shows the compliance of the condition.

$$u_{t+1}[(1, 1), 1] + u_{t+1}[(1, 2), 0] \leq u_{t+1}[(1, 1), 0] + u_{t+1}[(1, 2), 1]$$

$$125.37 + 139.01 \leq 115.6 + 150.29$$

$$264.38 < 265.5$$

Condition 4

The condition states that the transition probability function is a superadditive function. This condition can be written as Eq. (14.2):

$$\begin{aligned} &q_{t+1}[(I_t, D_l)|\left(I_t, D_t^{+}\right), 1)] - q_{t+1}[(I_t, D_l)|\left(I_t, D_t^{+}\right), 0)] \\ &\leq q_{t+1}[(I_t, D_l)|\left(I_t, D_t^{-}\right), 1)] - q_{t+1}[(I_t, D_l)|\left(I_t, D_t^{-}\right), 0)] \end{aligned} \quad (14.2)$$

where $D_t^{+} > D_t^{-}$

Tables 14.7 and 14.8 show the transition probability of the demand from states 0–3, in each row, to states 0–3, in each column.

For a = {0}.

For a = {1}.

The following proves the superadditive property:

Table 14.6 Value function at time two and inventory 1

t	Inventory	Demand	Cost not sending	Cost sending
2	1	1	115.6	125.37
2	1	2	139.01	150.29

Table 14.7 Demand transition probability matrix for a = {0}

	0	1	2	3
0	0.0034	0.0574	0.3251	0.6141
1		0.0225	0.255	0.7225
2			0.15	0.85
3				1

Table 14.8 Demand transition probability matrix for a = {1}

	0	1	2	3
0	0	0	0	0
1	0.0087	0.1487	0.8426	0
2	0.0556	0.9444	0	0
3	1	0	0	0

$$\begin{aligned} &q_{t+1}[(I_t,3)|(I_t,2),1)] - q_{t+1}[(I_t,3)|(I_t,2),0)] \\ &\leq q_{t+1}[(I_t,3)|(I_t,1),1)] - q_{t+1}[(I_t,3)|(I_t,1),0)] \\ &0 - 0.85 \leq 0 - 0.7225 \\ &-0.85\& < -0.7225 \end{aligned}$$

Condition 5

The function of the final costs is non-decreasing in each inventory group through the demand levels. Therefore, it implies that the final cost is more significant when the accumulated demand in the last period is greater.

$$u_T(I_T, D_T) = r_T(I_T, D_T) \tag{14.3}$$

$$r_T(I_T, D_T) \leq r_T(I_T, D_T + i) \tag{14.4}$$

where $1 \leq i \leq n$

Table 14.9 shows the costs in period four and inventory level three.

$$\begin{aligned} &r_T(3,1) \leq r_T(3,2) \\ &\text{- } 10 < 10 \end{aligned}$$

Table 14.9 Cost table for final period and inventory level of 3

t	Inventory	Demand	Cost not sending
4	3	1	–10
4	3	2	10

14.4 Hurricane Katia Case Study

14.4.1 Overview of the Disaster

Several hydro-meteorological phenomena like tropical storms, hurricanes or floods, strike Mexican territory from the Atlantic and Pacific oceans or the Mexican Gulf. Moreover, even though there have been several initiatives to increase preparedness for these phenomena, their effects still leave important damage in the communities. This can be due to the geographical configuration of each place or the community's socioeconomic situation. Therefore, the impact can easily become more than what they can overcome by themselves.

This is the case of hurricane Katia in September of 2017; as presented in Fig. 14.3, it started as a tropical depression on September 5th and evolved quickly to a category 2 hurricane in the Saffir-Simpson scale on September 8th, impacting the shores of the state of Veracruz that same day (ERNtérate 2017). As a result, the emergency protocols were launched, i.e., opening shelters, evacuating people from high-risk areas, preventively closing highways, among others, were put in place to protect people's lives.

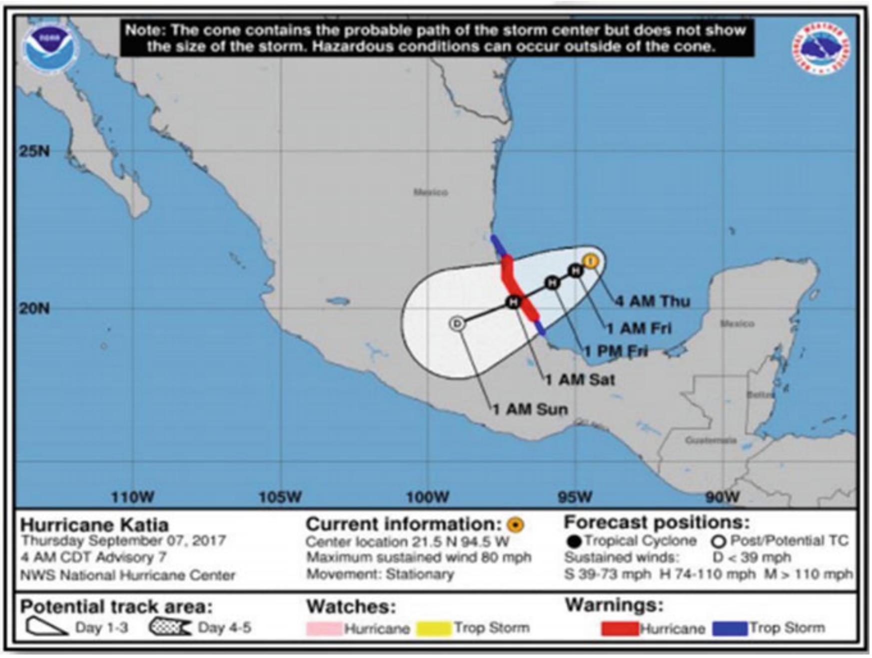

Fig. 14.3 Forecast of the trajectory and impact zone of Hurricane Katia. *Source* National Hurricane Center

The impact of Katia raised the sea level from 1.5 to 2.1 m and brought sustained winds of 150 km per hour and wind gusts of up to 205 km per hour. It landed on the night of September 8th and started to weaken quickly to category 1, and by September 9th, it became a tropical storm while it continued its trajectory inland. Additional to the winds, hurricane Katia also brought storms and a significant amount of rain. Figure 14.4 shows the areas that were more affected by these precipitations. The areas with the most intense red, which correspond to the area of Tecolutla, Veracruz, and the state of Puebla, registered up to 200 mm of accumulated rain that caused isolated landslides and intense flooding of all the affected area.

In Veracruz, 53 municipalities were affected, and 40 were declared a state of emergency. The damages Katia caused in Veracruz went from roofless houses, power cuts, landslides, fallen billboards and trees, affected highways to two dead people due to the heavy rains reported.

In one of the first assessments of the damages left by this disaster, Civil Protection Department reported the overflow of two rivers; one of them damaged around 235 houses and affected more than 900 people. However, only Xalapa 52 houses were completely flooded, and the families were hosted in the corresponding shelters (Baptista 2017).

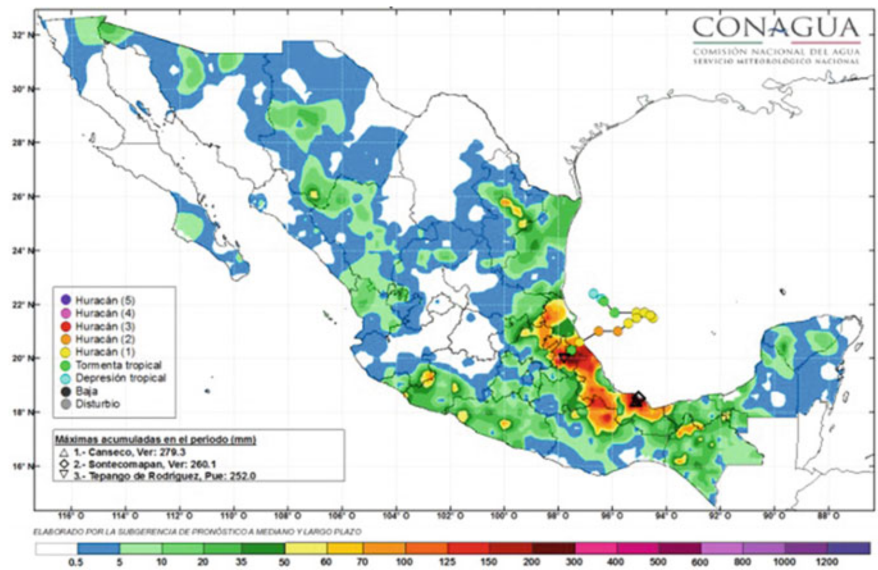

Fig. 14.4 Accumulated Precipitation caused by hurricane Katia. *Source* CONAGUA

Table 14.10 Parameters used for the Katia case study

Parameter	Value
Number of families in the affected area	52
Maximum number of kits that can be managed at the collection center at any given stage	30
Length of the decision-making time horizon	4
Probability a family requiring a kit in a period	0.9
Average number of donors that donate each period	10
Average amount of kits donated per donor	1
Penalty cost for each unit (kit) of unmet demand one period	200
Fixed shipping cost	5000
Variable shipping cost that depends on the number of kits sent	100
Cost for holding inventory at the collection center for one stage	200
Salvage value of the kits left in the Collection Center on the last period	10

14.4.2 Dataset

The data for this case study was collected from two main sources like official reports from the government and the experience in collection centers of different institutions like the Mexican Red Cross and the government of the State of Mexico. This way, the expertise of the decision-makers is considered and valued.

For this numerical instance, the 52 families hosted in the shelter are considered the total number of families requiring the food kits. Although a small-sized collection center is assigned to supply these families according to the demand, its total capacity was 30 kits. In addition, the time horizon is considered from September 5 to 9, the period the hurricane was considered a threat.

By experience, the decision-makers in the shelter know that people will rely entirely on the supplies they receive. Therefore, the probability of the families requesting food is high and was set to 0.9, while the donations rate is set to 10 donors daily, contributing with one kit per donor.

For this case study, the costs are considered in Mexican pesos. The fixed cost of shipping was $5,000, while the variable cost was $100 per kit. The holding cost for each kit is $200 due to the risk that implies having more stock and not satisfying the demand. The salvage value of the kits at the end of the period is set to $10. As for the cost of not satisfying the demand in one period is set to $200.

The complete list of parameters of the problem is presented in Table 14.10.

14.4.3 Results

The MATLAB program was executed with the parameters previously presented in a computer with an AMD Radeon processor and a RAM of 12 GB. It took 67 min to evaluate all possible states. The solution of this scenario resulted in 6,572 states along the four periods, grouped in 31 levels of inventory for each period.

A sample of the results provided are presented in Table 14.11 and 13.12, these tables illustrate a case when the behavior of the policy is present and one case that is not. For example, Table 14.11 presents the second period when the inventory level is 16. The non-decreasing policy is observed in the last column, where 0 represents the action not to send, and 1 is to make a shipment. Thus, the period and inventory are the same throughout the table, but the demand is increasing.

For this policy to be attractive for decision-makers, the goal is to define the threshold where the decision of sending a shipment will be valid from that point on. This makes it easier in terms of implementation. In this case this threshold is reached when the demand is 4 kits, and the shipment is made with all the inventory on hand.

On the other hand, Table 14.12 presents the case where the non-decreasing policy is not met. This case is also in the second period, but with an inventory level of 15. It also starts with the decision not to send, and when the demand becomes 4 it shows that the best is to start sending the value of the inventory on hand. However, when the demand reaches 30 kits, the action changes again to not sending. This behavior reflects that the non-decreasing part of the desired policy is not met.

Table 14.13 presents a summary of all inventory levels throughout the three periods when the decision is made (1 to 3). This provides a general perspective of the different state's behavior and to identify where the MONDP is met. As stated previously, not all the groups of inventory levels present the behavior of the policy. However, 64 out of 93 levels do; this represents almost 70% of the total number of inventory levels.

Inventory levels are highlighted in the table to identify two tendencies. The first one is that the central levels of inventory are the ones that present a bigger challenge in fitting into the MONDP, while the lower and the higher levels of inventory tend to fit in the policy. The second tendency is that through time, the number of non-fitting inventory levels decreases. For example, in time one there are 14 levels of inventory that do not show the MONDP behavior; meanwhile, in period 3 there are only 7.

Another important point to notice in the complete MATLAB output is that the shipment size is always chosen as the available inventory. This is because the expected value for the next period's demand is much higher than the current available inventory. For example, this may happen in many circumstances of disaster relief operations where the demand is much higher than the supply.

14.4.4 Sensitivity Analysis

Additional to the results, a brief sensitivity analysis was carried out to identify the impact each cost has on the behavior of the MONDP. For each cost, there was an increase and decrease of 50% of the original value. The impact of the policy is measured by the number of inventory levels that meet the policy's behavior. Table 14.14 consolidates the results of this analysis.

Table 14.11 Sample of an inventory level with non-decreasing behavior

Period	Inventory	Demand	Shipment	Cost not send	Cost send	Action
2	16	0	16	24,315.73	25,918.688	0
2	16	1	16	24,855.13	25,918.688	0
2	16	2	16	25,357.86	25,918.688	0
2	16	3	16	25,805.51	25,918.688	0
2	16	4	16	26,194.14	25,918.688	1
2	16	5	16	26,532.27	25,918.688	1
2	16	6	16	26,832.37	25,918.688	1
2	16	7	16	27,105.47	25,918.688	1
2	16	8	16	27,359.79	25,918.688	1
2	16	9	16	27,601.00	25,918.688	1
2	16	10	16	27,832.94	25,918.688	1
2	16	11	16	28,058.19	25,918.688	1
2	16	12	16	28,278.53	25,918.688	1
2	16	13	16	28,495.18	25,918.688	1
2	16	14	16	28,709.03	25,918.688	1
2	16	15	16	28,920.68	25,918.688	1
2	16	16	16	29,130.62	25,918.688	1
2	16	17	16	29,339.17	26,321.408	1
2	16	18	16	29,546.60	26,723.802	1
2	16	19	16	29,753.11	27,125.523	1
2	16	20	16	29,958.86	27,527.050	1
2	16	21	16	30,163.97	27,928.220	1
2	16	22	16	30,368.54	28,329.275	1
2	16	23	16	30,572.65	28,730.142	1
2	16	24	16	30,776.36	29,130.938	1
2	16	25	16	30,979.74	29,531.633	1
2	16	26	16	31,182.81	29,932.281	1
2	16	27	16	31,385.62	30,332.871	1
2	16	28	16	31,588.21	30,733.428	1
2	16	29	16	31,790.59	31,133.948	1
2	16	30	16	31,992.80	31,534.442	1
2	16	31	16	32,194.84	31,934.91	1
2	16	32	16	32,396.74	32,335.356	1
2	16	33	16	32,598.51	32,541.004	1
2	16	34	16	32,800.16	32,745.917	1
2	16	35	16	33,001.71	32,950.227	1

(continued)

Table 14.11 (continued)

Period	Inventory	Demand	Shipment	Cost not send	Cost send	Action
2	16	36	16	33,203.16	33,154.035	1
2	16	37	16	33,404.53	33,357.423	1
2	16	38	16	33,605.81	33,560.454	1
2	16	39	16	33,807.03	33,763.181	1
2	16	40	16	34,008.17	33,965.647	1
2	16	41	16	34,209.26	34,167.887	1
2	16	42	16	34,410.29	34,369.930	1
2	16	43	16	34,611.26	34,571.801	1
2	16	44	16	34,812.19	34,773.520	1
2	16	45	16	35,013.07	34,975.105	1
2	16	46	16	35,213.91	35,176.571	1
2	16	47	16	35,414.71	35,377.930	1
2	16	48	16	35,615.47	35,579.194	1
2	16	49	16	35,816.20	35,780.372	1
2	16	50	16	36,016.90	35,981.473	1
2	16	51	16	36,217.57	36,182.504	1
2	16	52	16	36,418.21	36,383.471	1

As shown in Table 14.14, the most improvement changes were decreasing the deprivation cost, decreasing the fixed shipping cost, and increasing the holding cost.

One of the main implications of reducing the deprivation cost is that the demand will be considered less urgent; therefore, fewer shipments are being sent. The latter is not desirable in the humanitarian context since helping the affected people is the primary goal.

On the other hand, reducing the fixed shipping cost and increasing the holding cost at the collection center would allow increasing the shipping frequency. Hence, the demand would be satisfied promptly. Reaching a fixed shipping cost that allows making more regular shipments is very desirable, and when the emergency reaches a certain level, donors are willing to step in. Nevertheless, it cannot be ignored that when we have an emergency, the difficulty of the vehicles to get to the affected area and their scarcity make the costs increase.

The changes that produced the most negative impact regarding the number of inventory levels that present the non-decreasing behavior are decreasing the holding cost, increasing the variable shipping cost, and increasing the deprivation cost. The increase of the deprivation cost would give more importance to the unsatisfied demand. In terms of humanitarian operations, it would be a positive change; nevertheless, the policy's compliance decreases considerably. The reduction of the holding cost and the increase of the variable shipping cost negatively affects the MONDP, but it also makes the shipments less frequent.

Table 14.12 Sample of an inventory level without non-decreasing behavior

Period	Inventory	Demand	Shipment	Cost not send	Cost send	Action
2	15	0	15	24,403.621	26,014.775	0
2	15	1	15	24,922.688	26,014.775	0
2	15	2	15	25,406.031	26,014.775	0
2	15	3	15	25,837.108	26,014.775	0
2	15	4	15	26,212.725	26,014.775	1
2	15	5	15	26,541.131	26,014.775	1
2	15	6	15	26,834.078	26,014.775	1
2	15	7	15	27,101.909	26,014.775	1
2	15	8	15	27,352.280	26,014.775	1
2	15	9	15	27,590.478	26,014.775	1
2	15	10	15	27,820.067	26,014.775	1
2	15	11	15	28,043.458	26,014.775	1
2	15	12	15	28,262.294	26,014.775	1
2	15	13	15	28,477.716	26,014.775	1
2	15	14	15	28,690.532	26,014.775	1
2	15	15	15	28,901.324	26,014.775	1
2	15	16	15	29,110.519	26,417.185	1
2	15	17	15	29,318.434	26,818.926	1
2	15	18	15	29,525.313	27,220.463	1
2	15	19	15	29,731.340	27,621.644	1
2	15	20	15	29,936.661	28,022.704	1
2	15	21	15	30,141.39	28,423.577	1
2	15	22	15	30,345.618	28,824.376	1
2	15	23	15	30,549.421	29,225.074	1
2	15	24	15	30,752.858	29,625.724	1
2	15	25	15	30,955.978	30,026.316	1
2	15	26	15	31,158.823	30,426.874	1
2	15	27	15	31,361.427	30,827.395	1
2	15	28	15	31,563.819	31,227.890	1
2	15	29	15	31,766.024	31,628.358	1
2	15	30	15	31,968.063	32,028.806	0
2	15	31	15	32,169.953	32,235.356	0
2	15	32	15	32,371.711	32,441.004	0
2	15	33	15	32,573.349	32,645.917	0
2	15	34	15	32,774.879	32,850.227	0
2	15	35	15	32,976.311	33,054.035	0

(continued)

Table 14.12 (continued)

Period	Inventory	Demand	Shipment	Cost not send	Cost send	Action
2	15	36	15	33,177.655	33,257.423	0
2	15	37	15	33,378.918	33,460.454	0
2	15	38	15	33,580.108	33,663.181	0
2	15	39	15	33,781.230	33,865.647	0
2	15	40	15	33,982.290	34,067.887	0
2	15	41	15	34,183.293	34,269.930	0
2	15	42	15	34,384.244	34,471.801	0
2	15	43	15	34,585.147	34,673.520	0
2	15	44	15	34,786.004	34,875.105	0
2	15	45	15	34,986.820	35,076.571	0
2	15	46	15	35,187.597	35,277.930	0
2	15	47	15	35,388.338	35,479.194	0
2	15	48	15	35,589.045	35,680.372	0
2	15	49	15	35,789.721	35,881.473	0
2	15	50	15	35,990.368	36,082.504	0
2	15	51	15	36,190.987	36,283.471	0
2	15	52	15	36,391.581	36,484.380	0

14.5 Conclusions

This chapter addressed the shipping decision faced in collection centers. In countries with an important percentage of in-kind donations, collection centers become a crucial point in the disaster relief supply chain. A Markov Decision Model was developed to represent the collection centers' operations, which is especially beneficial for the humanitarian organizations. It is also helpful to test this model in real instances to recognize its weaknesses and opportunities for improvement. However, the possible lack of reliable information during a crisis limits the application of this model.

In this chapter, two numerical instances were developed, so the existence of the MONDP was proved. The first one presents a small instance with a capacity of four kits and three families throughout four periods. For this instance, the families' probability of requesting aid kits decreased from one period to another. In this example, the MONDP was shown in all the periods and groups of inventory levels, indicating from what level of accumulated demand the optimal action will be to send. This example ompletes the validation of the five conditions and the adequate data that allows all the periods and inventory levels to present the policy.

The second numerical instance was based on the real case of Hurricane Katia in Mexico. The data were obtained from different sources. The instance was prepared with 52 families that were evacuated from the affected region and were living in

Table 14.13 Policy compliance of each inventory level throughout the three decision periods

Period	Inventory	Policy	Period	Inventory	Policy	Period	Inventory	Policy
3	0	Yes	2	0	Yes	1	0	Yes
3	1	Yes	2	1	Yes	1	1	Yes
3	2	Yes	2	2	Yes	1	2	Yes
3	3	Yes	2	3	Yes	1	3	Yes
3	4	Yes	2	4	Yes	1	4	Yes
3	5	Yes	2	5	Yes	1	5	Yes
3	6	Yes	2	6	Yes	1	6	Yes
3	7	Yes	2	7	Yes	1	7	Yes
3	8	Yes	2	8	No	1	8	Yes
3	9	Yes	2	9	No	1	9	Yes
3	10	Yes	2	10	No	1	10	No
3	11	no	2	11	No	1	11	No
3	12	No	2	12	No	1	12	No
3	13	No	2	13	No	1	13	No
3	14	No	2	14	No	1	14	No
3	15	No	2	15	no	1	15	No
3	16	No	2	16	Yes	1	16	No
3	17	No	2	17	Yes	1	17	No
3	18	Yes	2	18	Yes	1	18	No
3	19	Yes	2	19	Yes	1	19	No
3	20	Yes	2	20	Yes	1	20	No
3	21	Yes	2	21	Yes	1	21	No
3	22	Yes	2	22	yes	1	22	No
3	23	Yes	2	23	yes	1	23	No
3	24	Yes	2	24	yes	1	24	Yes
3	25	Yes	2	25	Yes	1	25	Yes
3	26	Yes	2	26	Yes	1	26	Yes
3	27	Yes	2	27	Yes	1	27	Yes
3	28	Yes	2	28	Yes	1	28	Yes
3	29	Yes	2	29	Yes	1	29	Yes
3	30	Yes	2	30	Yes	1	30	Yes

shelters, and a Collection Center with a capacity of 30 kits. The results, in this case, presented the MONDP in 68% of the inventory levels. The levels of inventory that present the policy were mostly the lowest or highest.

A small sensitivity analysis with the costs included in the MDP was performed, costs were increased and decreased from the original value to identify the ones with more effect on the compliance of the MONDP. The results show that the changes

Table 14.14 Sensitivity analysis of the impact of the values of costs

Varied Cost	New Cost	Impact in the policy
Original Values	–	64/93
Deprivation cost	100	73/93
Deprivation cost	300	60/93
Fixed Shipping cost	2500	79/93
Fixed Shipping cost	7500	62/93
Variable Shipping cost	50	66/93
Variable Shipping cost	200	59/93
Holding cost	100	48/93
Holding cost	300	78/93
Salvage Value of kits	5	66/93
Salvage Value of kits	15	65/93

with most improvement were decreasing the deprivation cost, the fixed shipping cost, and increasing the holding cost. In this case, the data did not present the values that allowed the policy to be shown in all of the inventory levels throughout the periods.

The results obtained with this work can motivate further research in inventory management for disaster relief situations, especially in-kind donations management. As presented, they represent a high percentage of the total supply. Therefore, incorporating material convergence presented with in-kind donations represents an important opportunity area for further research in this area.

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Chapter 15
Volunteers in Lockdowns: Decision Support Tool for Allocation of Volunteers During a Lockdown

Aleksandra Krstikj, Moisés Gerardo Contreras Ruiz Esparza, Jaime Mora-Vargas, and Laura Hervert Escobar

Abstract The challenge tackled in this study was to develop a practical decision support tool for coordination and spatial allocation of volunteers to aid people in isolation during lockdowns. The aim was to develop a tool that would allow for the sequential allocation of volunteers whose number is not foreknown to offer service to as many people as possible, prioritizing the most vulnerable. We established service proximity and the location of vulnerable and marginalized populations as crucial aspects of the modeling. Consequently, the tool was developed in three stages: (1) assessing residential proximity to services with a Voronoi diagram; (2) calculating the most conservative scenario for allocation of volunteers to attend all vulnerable populations daily based on routing; and (3) coordinating the sequential allocation of volunteers focused on equity of service provision. The tool enables decision-makers to estimate and localize the population in need, obtain the number and allocation of volunteers needed to attend the population, and make critical decisions during a lockdown based on the previous estimations. The tool could particularly be useful in settings with limited resources and/or incomplete information systems.

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15.1 Introduction

The rapid spread of the novel SARS-CoV-2 virus that was first detected in Wuhan, China, in December 2019 was declared the second pandemic of the twenty-first century by the World Health Organization on March 12, 2020 (WHO 2020). Despite warnings that rapid urbanization, environmental degradation, and global interconnectedness might contribute to the more frequent and global spread of new infectious diseases (Jones et al. 2008), the COVID-19 pandemic caused by the SARS-CoV-2 virus caught the world by surprise and exposed how unprepared we are for such a crisis. There is an urgent need for tools and protocols that can mitigate the impacts of pandemics since the urbanization trends that are causing them are likely to continue and intensify in the future.

Madhav et al. (2017) reported progress made by the international community toward pandemic preparedness after the SARS 2003 pandemic, evidenced in the more synchronized global response during the 2009 influenza pandemic. Nevertheless, they also reported significant gaps in detection, tracing, quarantine, and preparedness outside the health sector, particularly apparent in resource-limited settings. Poorly prepared countries can rely on foreign aid in times of localized outbreaks; however, in times of a full-scale global pandemic, they will need to rely on local resources (Madhav et al. 2017).

During the COVID-19 pandemic, some of the principal tools used by governments to slow down the propagation of the virus were complete or partial lockdowns and quarantines (WHO 2021; Parmet and Sinha 2020). These measures effectively put a major part of the population, especially vulnerable groups, in a difficult situation to obtain even the most basic products. For underdeveloped urban regions, a locally coordinated relief effort based on spontaneous volunteers to distribute food and supplies to people in isolation can mitigate the risks of exposure and alleviate the suffering of affected populations.

Nevertheless, the coordination of volunteers is one of the most challenging aspects of Disaster Operation Management (DOM) (Schonbock et al. 2016; Falasca and Zobel 2012). Volunteers cannot be predicted in numbers or skills. Besides, volunteers are not a paid workforce; thus, they cannot be held to do regular shifts either. Therefore, without adequate planning and coordination of their allocation, volunteers can become an obstacle to relief efforts (Oloruntoba 2005; Whittaker et al. 2015). Still, local volunteers usually know the area well and can contribute to the more effective supply distribution, saving the typically scarce resources (Ratliff 2007; Simo and Bies 2007; Holguín-Veras et al. 2013).

The challenge tackled in this study was to develop a practical method applicable in resource and information-scarce settings for coordination and spatial allocation of volunteers to aid people in isolation with obtaining supplies. The aim was to develop a spatial decision support tool that would allow for the sequential allocation of volunteers whose number is not foreknown to offer service to as many people as possible, prioritizing the most vulnerable. This task implied working with a rather large network of suppliers and serviced points, which in this case is formed by the locations of local shops that are operational during a health crisis and individual homes. The network would be connected by the volunteers who would perform the shopping and delivery of products.

15.2 Literature Review

The efficiency of disaster response efforts depends significantly on the ability of decision-makers to obtain and analyze relevant information and coordinate available resources. Decision support systems based on information technology can decrease the time needed to make critical decisions related to task assignment and resource allocation (Thompson et al. 2006). The experiences from the management of the COVID-19 crisis revealed that many cities lack information systems and decision support tools (Allam and Jones 2020; ARTICLE 19 2020). Nevertheless, such systems are crucial for effective preparedness and response to a health emergency (Braun et al. 2006), and can determine the success or failure of relief efforts (Kummitha, 2020). Recent studies have tackled decision support systems for the detection of critical Covid-19 phases and management of health personnel and materials (Braca et al. 2021; Krishna and Sirajuddin 2022). However, there is a lack of studies on non-for-profit tools for coordinating local volunteers to support vulnerable groups in isolation, even though volunteers have been recognized as an essential element that can support relief operations and supply distribution during lockdowns (FAO 2020).

The culture of spontaneous volunteering in times of crisis has been documented and studied as a social phenomenon (e.g., volunteers that were the first responders after the 85' earthquake in Mexico, see more in Quarentelli et al. 1988). However, the lack of methods or tools to efficiently coordinate volunteers often results in the omission of this task force from official relief operation planning (Oloruntoba 2005; Aguirre et al. 2016; Skar et al. 2016; Scanlon et al. 2014). Commercial Volunteer Management Systems (VMS) exist but have been found to deliver suboptimal results despite their complexity (Schonbock et al. 2016). Besides, the cost of commercial systems and the technical skills needed to operate them make these systems unfeasible for resource-scarce regions. Moreover, equity must be recognized as the alternative objective in not-for-profit settings while efficiency is still vital (Johnson and Smilowitz 2011; Sampson 2005).

Most of the Volunteer Labor Assignment (VLA) developed models focus on the unpredictability inherent to the coordination of the volunteer task force. Training and competence screening (Skar et al. 2016; Lassiter et al. 2015), volunteers' preferences for certain tasks (Falasca and Zobel 2012), and changing circumstances on the ground (Garcia et al. 2018) are some of the main aspects considered in the models. These works are important when the complexity of relief efforts demands various skills from the volunteers; however, in the context of a lockdown, volunteers are required to obtain supplies from local shops and deliver to people in isolation a local knowledge of the area is sufficient. A helpful characteristic that a tool for coordinating volunteers should replicate from previous models is the concept of retrofitting with from-the-ground information to adjust to quickly changing conditions in times of a pandemic.

Considering the uncertainty of volunteer numbers, previous models of arrivals and departures of volunteers in relief centers often utilize a queuing system. Mayorga et al. (2017) and Abualkhair et al. (2020) both developed models based on two parallel queues, one for donor and donations, and the other for beneficiaries at relief centers. However, while Mayorga et al. (2017) approach the demand at each queue as deterministic, Abualkhair et al. (2020) consider the uncertainty observed in the volunteers' behaviors at a Tuscaloosa relief center after the 2011 tornado and propose an agent-based simulation model. On the other hand, Zayas-Cabán et al. (2020) researched the problem using the Markov decision process in the context of volunteer reception center (VRC) for volunteer registration, generally founded by local authorities away from the affected areas. The studies undoubtedly contribute significantly to the coordination of operations related to relief centers; however, they do not offer a spatial tool for allocating volunteers in the context of a lockdown when people are stuck in their homes. In a lockdown, instead of a queueing system for a storage facility away from the affected area, decision-makers need a spatial tool that could orient the allocation of volunteers concerning operational shops and isolated people and take proximity, vulnerability and equity as determining factors for the management.

During a lockdown caused by a pandemic event, the vulnerable population can be classified as: older adults (>60 years old), people with pre-existing health conditions, people in quarantine (they already have or are suspected of having the disease), and low-income groups (people who depend on the informal economic sector and whose daily existence has been severely threatened by the socio-economic effects of the lockdown) (WHO 2020). These populations must be a priority in any non-for-profit tool to coordinating volunteers since the equity in public administration is crucial for social justice. Whereas equality assures that citizens are provided with equal prospects to fulfill their needs, equity makes sure that vulnerable groups receive more benefits to compensate for previous discrimination (Folger et al. 1995), also defined as ¨compensatory¨ equity. Equity, efficiency, and effectiveness are often referred to as the three pillars of planning in public management (Savas 1978; Flavin et al. 2012; Frederickson 2010).

Nevertheless, equity is not always successfully implemented in top-down non-for-profit or humanitarian operations since systemic discrimination is not easy to overcome (Waters 2014). Community-based operational research (CBOR) seems to offer better solutions in terms of integral and equitable management of logistic tasks (Johnson and Smilowitz 2011). Previous studies from this field focus on location-allocation, inventory, and routing for supply distribution or transportation. For instance, Yildiz et al. (2013), Wong and Meyer (1993), and Bartholdi et al. (1983) evaluated the effectiveness of meals-on-wheels by analyzing facility location and routing. In the context of CBOR, Bowerman et al. (1995) also tackled routing, who optimized school bus routes, considering efficiency and equity in a two-phase method merging student clustering and route generation. On the other hand, Chou et al. (2011) worked on a flexible model that allowed volunteers to be flexible in delivering unsold bread from bakeries to families, which improved efficiency. The studies can be particularly useful for areas where community networks have been well developed. Unfortunately, not all communities have the possibility of self-organization, and even less in a context of a lockdown when isolation seriously hinders social contact. In such conditions, a mixture between municipal management and spontaneous volunteering of local community members could present a more viable option.

15.3 Tool Development and Preliminary Results

The decision support tool was developed considering a residential urban area or a municipality under a partial or complete lockdown due to a health emergency, such as the COVID-19 pandemic context. The areas for which the tool was primarily intended are resource-scarce and information-limited settings that must rely on local resources in a context of a large pandemic since it is most likely that the international community would quickly become overwhelmed. The basic information required for the tool to operate is the addresses of operational shops during the pandemic period, the location and number, age, and marginalization (or another index that measures socio-economic disadvantage) of the local population. The tool functions in three phases: (1) digital mapping of operational services for which addresses are known; (2) assessment of most conservative scenario of volunteers, based on routing; and (3) coordination of the sequential allocation of volunteers, prioritizing vulnerable groups.

15.3.1 Digital Mapping of Services

During the COVID-19 pandemic, most of the lockdowns targeted non-essential activities. In most cases, the local corner shops and supermarkets, which are the primary everyday products' suppliers, remained open and, in some cases, even transitioned rapidly to home deliveries. Nevertheless, the conditions differed significantly case by case. Some shops closed altogether for an extended period of time. Thus, even though many local governments knew the locations of local shops before the pandemic, that information became unreliable during the pandemic. The last is why the first step for implementing the tool must be to verify operational services and their working hours. After such an inventory list with addresses of operational shops is confirmed, the digital mapping of services is necessary. If the digitalization of services before the pandemic has already been performed and exists as a geodata-base would be necessary only to select the operational shops in a new layer. If such digitalization does not exist, it is necessary to perform the digitalization.

For this purpose, we designed a code that relies on Google Geocoding API to automate reading an address from a data sheet and retrieving corresponding geolocation with latitude and longitude. The pseudocode for this process is given in Appendix 15.A.

The digitalization of operational services during a pandemic has another benefit, to offer a possibility for a web page design with a kml map where citizens can easily get information about the service available, operational hours, and home delivery options. This solution strengthens the information systems for citizens and allows them to avoid unnecessary contacts during the lockdown. With regular updates, the page can include new reopened services or exclude services that for some reason shut down, thus keeping people informed of the changing conditions. It is also an opportunity to share information about socio-economic support or public programs for vulnerable groups. Finally, such a web page can also help re-activate the economy after the pandemic by promoting local products to customers already getting used to the interface.

15.3.2 Assessing the Most Conservative Scenario of Allocation of Volunteers Based on Proximity to Service

The second step was to develop a method for assessing the most conservative scenario of allocation of volunteers. Every vulnerable citizen would receive the necessary help from a volunteer daily. To make that assessment, first, it was necessary to estimate the proximity of housing to operational service in a setting with limited information. The distance can be measured as a Euclidean straight line, Manhattan distance, or street network analysis. Several authors have argued that network analysis offers more accurate results considering the existing street routes and obstacles (Mora-Garcia et al. 2018; Comber et al. 2008). However, in the context of resource-scarce and information-poor settings, network analysis is not always the most viable solution. Besides, underdeveloped regions often have mapped roads that are restricted for use (e.g., affluent housing developments that function as gated communities accessible only to residents) or do not offer information about informal roads that are often used. Thus, the Euclidean distance is still the most dependable method in settings where the spatial data is incomplete or unreliable.

The main place-based methodological approaches to estimate proximity in previous literature are container, coverage, travel cost, gravity, and minimum distance (Sister et al. 2008; Talen 2003). A limitation observed in using these approaches is using a simplified representation of an administrative district with a central point that can lead to an aggregation error. Another limitation often mentioned when using administrative districts to calculate proximity is the boundary-supply error from housing near the administrative limit that might have other services available outside that limit that is not considered in the assessment. A radius approach can be an option to avoid the aggregation or boundary-supply error since it does not require administrative districts as a base for the calculations. Instead, the radius approach calculates a buffer zone around a specific service and identifies housing inside that buffer as having access to that service.

Nevertheless, most of the socio-demographic data necessary for the tool (i.e., population size, age, and marginalization) is usually available as aggregated data by census tracts. Thus, a districting problem is implied in the measurement of proximity to services.

Districting refers to the division of a geographical region into districts with the aim of planning. Several aspects need to be carefully considered when performing districting of an area. The balancing, contiguity, and compactness of a zone may affect the results (Novaes et al. 2009); therefore, the proximity assessment is more accurate if the urban zone is continuous and uniform. For this study, the challenge was to develop a districting method for a continuous urban zone where each district can house one operational service. All the housing in that district will be closest to that service than to any other. Moreover, the districts must be compact and convex and consider critical geographical features.

To evaluate the housing-services proximity at a municipal level, we proposed the use of a Voronoi diagram, which is a ¨fundamental structure in computational geometry that captures the notion of proximity in environments and provides a means of partitioning space into subregions to facilitate spatial data manipulation, modeling of spatial structures, pattern recognition, and locational optimization¨ (Okabe et al. 2000). In an ordinary Voronoi diagram, for a given set S of n points in the plane, we can associate each point s with a region consisting of all points in the plane closer to s than to any other point s' in *S* (Eq. 15.1):

$$\mathrm{Vor(s)} = \{\mathrm{p{:}\ distance(s,\ p)} \leq \mathrm{distance(s',\ p)},\ \forall \mathrm{s0} \epsilon S\} \tag{15.1}$$

where Vor(s) is the Voronoi region for a point *s.*

More formally, for a conventional line segment *pq* that connects two points *p, q* ϵ *S*, the bisector is a perpendicular straight line through the midpoint of segment *pq* that separates the halfplane *D (p, q)* = *{x* ∣ *d (p, x)* ≤ *d (q, x)}* closer to p from the half-plane *D (q, p)* closer to *q*. The Voronoi region *VR (p, S)* of a point *p* among a given set *S* of point sites is the intersection of n-1 half-planes *D (p, q)* where *q* ranges over all the other sites in *S*, as expressed by Eq. (15.2):

$$VRp, S = \bigcap Dp, \tag{15.2}$$

where $q \epsilon S$ and $q \neq p$. In a Voronoi region created around a node *p*, the Euclidean distances from all the points in that region to *p* are always shorter than the distance from those points to other nodes of the plane *S (q, r, …).*

Finally, the Voronoi diagram is the union of all Voronoi regions in a set (Eq. 15.3):

$$Vor(S) = \bigcup_{s \in S} Vor(s) \tag{15.3}$$

Ordinary Voronoi diagrams have been used in previous research of visual urban analytics to filter and cluster data on health center locations (Jia et al. 2014) and census tract districting (Abellanas and Palop 2008). Additionally, more advanced models based on non-ordinary Voronoi diagrams have also been developed to solve in a better way the obstacles and heterogenous space problems (Novaes et al. 2009; Feng and Murray 2018). The more complex non-ordinary Voronoi models offer more precise results but require advanced mathematical skills for implementation.

An example of a Voronoi diagram based on a set of shops for a certain urban region is presented in Fig. 15.1, left. To solve the problem of integrating data obtained in different districts for the proximity (Voronoi polygons) and the census data (census tracts), we proposed the overlay of a uniform orthogonal grid (red crosses in Fig. 15.1, right). The grid offers the possibility to disaggregate the demographic data in a census tract, which can then be used with the proximity measures. The grid points belonging to one Voronoi district share the characteristic of being closest to the same shop, thus being grouped for further assessments. The grid space can vary in different urban contexts depending on build density. However, to further develop the tool in this example, we used the spacing of 20 × 20 m as a relative distance between two houses in downtown areas.

Considering the grid points (homes) as destinations *g*, we calculated all the distances from the service origin point p to all homes as d1, d2, d3,… in each Voronoi district (distance_to_service). The distance between each g (a home) and its closest *p* point (a shop) can be defined by Eq. (15.4):

$$Dist(g, p) = \{d(g, p) | \forall g \in VR(p, S)\} \tag{15.4}$$

Secondly, we assessed the maximum capacity for the workload of one volunteer per day (volunteer_capacity). This variable is dependent on the proximity of the serviced house to the store (D), the time necessary to execute the full task (t) that will depend on the speed and distance D, and the total working hours per day (t'). Thus, a function f (D, t, t') was introduced in the equation to account for these relations.

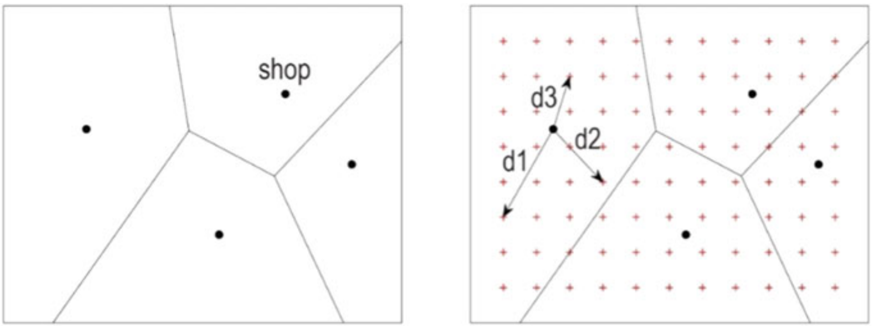

Fig. 15.1 Districting based on an ordinary Voronoi diagram (left); Assessment of distances from homes to a shop in each Voronoi district based on a uniform orthogonal grid (right)

For one census tract, the estimation of the function f (D, t, t') was performed as follows:

1. The vulnerable population was randomly distributed in the space occupied by the census tract (e.g., Random points inside the polygon in QGIS).
2. We calculated the shortest route from the shop (origin of the route) to each randomly distributed location (destination of the route) for each Voronoi polygon. We based the calculation on the real street network downloaded from Open Street Maps and the Dijkstra algorithm of pgRouting (http://pgrouting.org/). The Dijkstra algorithm supports the search for the shortest path from a starting to an ending vertex and can be used with both directed and undirected graphs (Mehlhorn and Sanders 2008). The open-source database used for the calculation was PostGIS. An average distance path was estimated for each Voronoi polygon (Fig. 15.2).
3. The procedure should be repeated as many times as necessary to obtain the statistically significant sample and determine the average distance path for each polygon. The average distance path was then divided with the transport speed to obtain the average time needed for a volunteer to perform one trip. Once the time for one trip is obtained, the time for one task t can be estimated as 2 × (one trip time) + time for shopping (approximation of 15 min can be used).

The method should be applied to all census tracts to optimize the estimation of volunteer capacity by considering real routes and the velocity of volunteers. The Voronoi diagram used on the municipal level is very useful for the first approximation

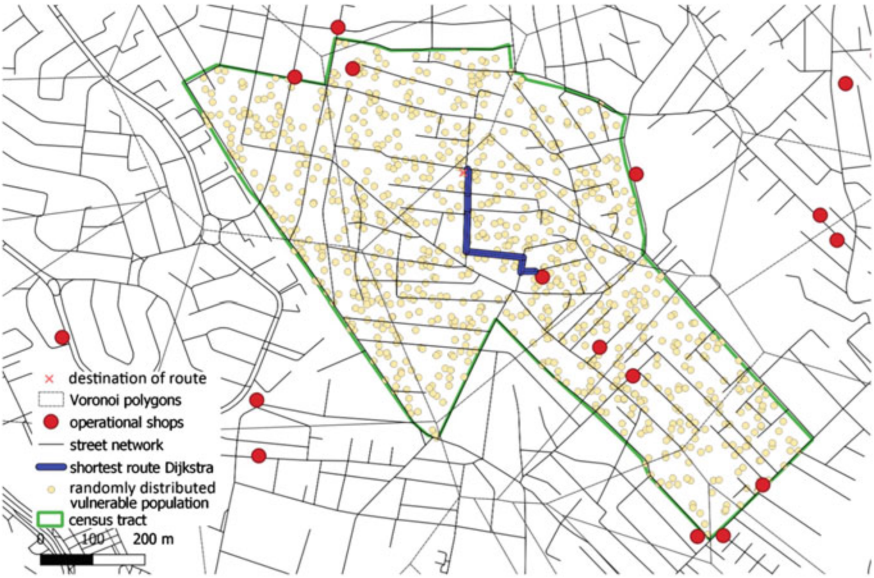

Fig. 15.2 Example of the shortest route estimated with Dijkstra algorithm of pgRouting in QGIS

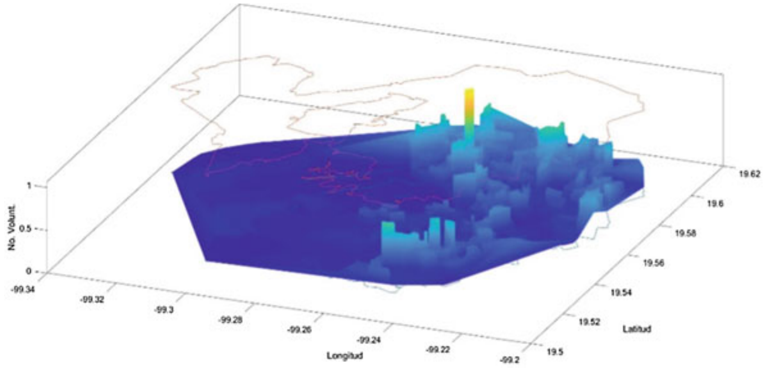

Fig. 15.3 Preliminary spatial diagram based on Eq. (15.7)

to the districting based on proximity to operational shops but does not consider obstacles and barriers. However, in this following step, the routing based on a real street network allows for the calculations of shortest real distances, thus optimizing each polygon's estimation. The velocity of the volunteer can also vary from walking speed in resource-limited settings to auto speed in more developed regions. The method presented above accounts for those differences and adjust the tool's conservative scenario estimation of allocation of volunteers based on the preset conditions.

Further, vulnerable citizens (e.g., older adults) that can be attended per day by one volunteer can be estimated, considering volunteer capacity and proximity to service by Eq. (15.5):

$$\mathrm{PA(g)} = \mathrm{f}\ (\mathrm{D, t, t'}) * \mathrm{Dist}\ (\mathrm{g, p}) \tag{15.5}$$

The number of vulnerable citizens, such as older adults (senior_citizens), in each census district or neighborhood was assessed based on existing census data. That number was further disaggregated based on the 20 × 20 m uniform grid that consists of points g (senior_citizens_20mgrid). Assigning the attribute *Pop(e)* to the population that occupies a specific district *e,* the population of each grid point g was estimated by Eq. (15.6):

$$\mathrm{Pop}\ (\mathrm{e, g}) = \mathrm{Pop(e)|N} \tag{15.6}$$

where N is the number of grid points g inside a district *e.*

Finally, we estimated the number of volunteers required in each grid point g for each district *e* (necessary_volun_20mgrid) by Eq. (15.7):

$$\mathrm{Nvol}\ (\mathrm{e, g}) = \mathrm{PA}\ (\mathrm{g}) * \mathrm{Pop}\ (\mathrm{e, g}). \tag{15.7}$$

Figure 15.3. presents a preliminary spatial diagram obtained for a case study in one municipality in the State of Mexico. The diagram shows the assessment of the number of volunteers needed for each grid point, based on a matrix of 20 × 20 m, using the available census data from 2010 for that municipality.

The most conservative scenario assessment is finalized by aggregation of the estimation of number of volunteers per district *e* (necessary_volun), presented in Eq. (15.8):

$$Nvol(e) = \sum_{i=1}^{N} Nolv(e, i) \tag{15.8}$$

The pseudo-code for the eight steps of the tool is presented in Appendix 15.B. It can also be accessed freely through Github on the following link:

https://github.com/AleksandraKrstikj/equitybasedDSS. The results can perform better when it is transferred into a digital map or geoprocessing application such as QGIS for further management.

15.3.3 Coordination of the Sequential Allocation of Volunteers, Prioritizing Vulnerable Groups

One of the challenges of working with volunteers is the unpredictability of their numbers. Moreover, the coordination of the allocation of available volunteers should prioritize vulnerable groups. Therefore, the problem was presented in defining a protocol for sequential allocation of volunteers that can consider changing conditions on the field in terms of available workforce and their allocation to most distressed neighborhoods. Based on the census data and the tool's assessment of the most conservative scenario for each neighborhood, we proposed an implementation of a distress index D*i* for neighborhoods that are marginalized and need many volunteers, as in Eq. (15.9):

$$\mathrm{D}i = i\mathrm{Vn}/\mathrm{Sc} + \mathrm{M}i \tag{15.9}$$

where M*i* is the marginalization or poverty index at the neighborhood level.

The distress index can define the priority intervention zones and help to coordinate the waves of volunteers. Based on the previous steps and calculations, a flow chart (Fig. 15.4.) was designed to support the decision-making process of sequential allocation prioritizing vulnerable groups. The flow chart is intended to serve as a base for the coordination that can be adapted as the effects of the lockdown unravel. The conservative scenario estimated beforehand not only allowed for an understanding of volunteers needed for all vulnerable groups daily, but also provided an estimate of the n-ratio of volunteer help needed per neighborhood or district. This is an important

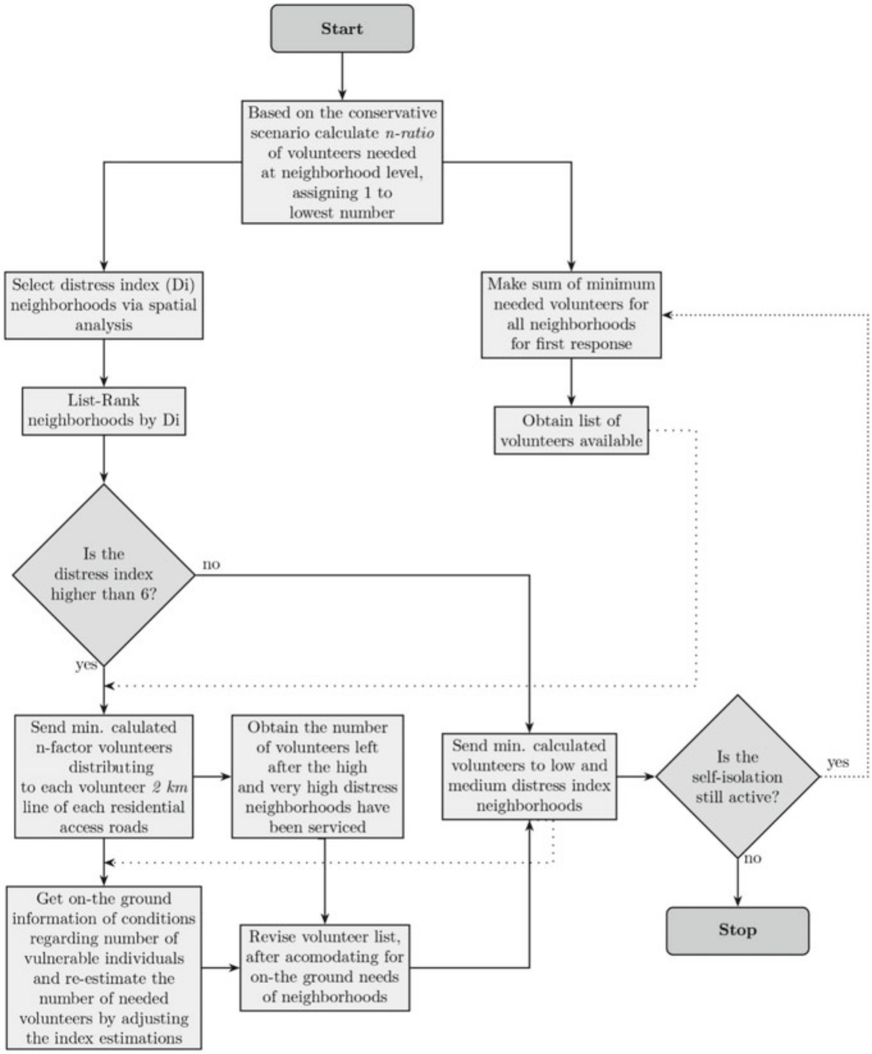

Fig. 15.4 Flow chart for the sequential distribution of volunteers, prioritizing distressed neighborhoods

information because it is very unlikely that the exact number of volunteers from the conservative scenario will be readily available once the lockdown is implemented. Nevertheless, if the n-ratio is known, the decision-maker can divide the available volunteer group and maintain the equity. The flow chart recommends the distribution of the first wave of volunteers to neighborhoods with a high distress index. In the next sequences, if there are more volunteers available, the rest of the neighborhoods can be serviced ensuring the equitable distribution of the help. The first waves of volunteers can also bring valuable from-the-ground information that can be integrated into the decision-making process to optimize the distribution of volunteers and account for changing conditions on the ground.

15.4 Discussion

Most of the existing decision support tools for the distribution of volunteers that exist today are either commercial or too complex (Schonbock et al. 2016) to be a viable option for resource-limited or information-scarce settings. Besides, the existing volunteer management systems rarely integrate the spatial aspect of allocating volunteers but mainly concentrate on coordination of arrivals, tasks, and skill training (Abualkhair et al. 2020; Falasca and Zobel 2012; Skar et al. 2016). While spatial models have been developed for logistics operations related to routing and distribution of supplies by volunteers to a small group of citizens (Yildiz et al. 2013; Chou et al. 2011), a practical tool for the spatial coordination of volunteers to aid a major part of the population in a specific lockdown context lacks. The scale of operations during a partial or complete lockdown needs a tool that can effectively and equitable distribute volunteer help to many people.

The mathematical tool proposed in this study supports the spatial allocation of volunteers during lockdowns. Special consideration was placed on prioritizing vulnerable groups in the modeling to support equity in relief operations. Thus, attention to vulnerable citizens was integrated upfront in estimating the most conservative scenario and the coordination protocol for the sequential allocation of available volunteers. Another important aspect of the tool is its practicality or ease of use. For example, the conservative scenario estimates the volunteer help needed for each vulnerable citizen in each district without motorized transport based on an ordinary Voronoi diagram that is easy to calculate.

Nevertheless, the tool can function even better with non-ordinary Voronoi diagrams that can improve the precision of the proximity assessment. Moreover, if the districts can afford motorized transport for volunteers, the variable of volunteer capacity can be adjusted, and the tool will calculate the new corresponding scenarios. On the other hand, the coordination protocol flow-chart was designed to incorporate from the ground information and retrofit the model to improve performance. The information can be gathered from the volunteers themselves by using GPS devices to gather spatial data and collect word of mouth information about vulnerable conditions of some citizens. Local shop owners usually know the community members and can be a source of valuable information that can be gathered by the volunteers and integrated into the system. Distributors of products that circulate districts through regular routes can also collect this information from shops clerks and pass it to the authorities.

Finally, the tool also supports other critical decisions that need to be made, such as the frequency of visits to houses performed by volunteers (e.g., daily, weekly) and priority zones in distress that house a large number of the vulnerable population. This data is crucial in situations when the number of volunteers is also scarce. Further studies should focus on integrating data such as optimization of travel, preference of journey routes by volunteers, health protocols, improving communication-based on pre-existing social networks, among others, to improve the tool's overall performance.

Some of the main limitations of implementing the tool in resource-scarce settings are the incomplete or inaccurate data or lack of time (or skills) to apply other complex tools (Clark-Ginsberg et al. 2020). Our tool is based on equity as a major consideration; however, to implement equity-based solutions, we first need to clearly define vulnerability in a specific socio-cultural context and who is disadvantaged in a particular crisis. The socio-cultural aspect of vulnerability during a pandemic is out of the scope of this study; nevertheless, we would like to caution the use of an indicator to measure vulnerability for the tool to be effective and equitable. For instance, the evaluation of marginalization of neighborhoods in Mexico was developed by the National Commission of Population (CONAPO), and it is an integral index based on living conditions, education, and income. Nevertheless, during a pandemic, other conditions such as age, family structure, and pre-existing health conditions need to be considered as well. A lockdown can be equally challenging for senior citizens without family networks regardless of economic status. In some underdeveloped regions, extended families are commonly found living close to each other due to scarce resources. Thus, lower-class seniors paradoxically can have more support in obtaining products in those regions during a pandemic and are more exposed to human contact. In a lockdown, older adults who require assistance are the poorest ones and the most isolated ones. The qualitative local-scale disaggregated data regarding the local population's living conditions and family networks (or practices) can be an invaluable input for the tool and should be used whenever possible.

The preliminary results of the tool's application in the allocation of volunteers show optimistic results. The tool was tested in a case study of a local municipality of the State of Mexico and provided a quick and practical analysis of the conservative scenario in minutes. It is practical performance on the ground remains to be seen. Nevertheless, the study's theoretical implication is to fill a gap in non-profit logistics research on volunteer distribution in the unique problem context posed by large-scale health contingencies. The tool is envisioned as an interface between science and politics in health crisis preparedness planning, where the main objectives are efficient and equitable resource management. The issue of governance, policy, and accountability is vital to improve disaster relief efforts and determine the social impact of solutions (Heinrich 2003). Community-based services usually generate low user fees and rely on support from nongovernmental organizations. Therefore, the design of preparedness and emergency response policies aimed at disaster relief operations must be an integral part of any effort to improve the efficiency of future planning. In this context, our model is just the starting point for involving urban planners, community groups, and local stakeholders in developing contingency strategies that advance the quality of life and social justice.

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Appendices

Appendix 15.A

```
[num,txt,raw]=xlsread('name_file.xlsx');
google_api_key='HereyouputtheGOOGLE_API_KEY';
ij=1;
for i=2: size(raw,1);
    street=raw{i,3};
    neighborhood=raw{i,4};
    municipality=raw{i,5};
    if ~isempty(street)&&~isempty(neighborhood)&&~isempty(municipality)
address=[street,',+',neighborhood,',+',municipality];
goolewebapi=['https://maps.googleapis.com/maps/api/geocode/json?address=',addres
s,',+CA&key=',google_api_key];
data = webread(googlewebapi);
        datagoogleT(ij)=data;
        ij=ij+1;
    end
end
save('datagoogleT.mat','datagoogleT')
```

Appendix 15.B

```
Volunteer_capacity = 8;
For each neighborhood do:
Senior_citizens = population for that neighborhood * percent of population over 60
Points_inside = find the grid points (x,y) located inside the neighborhood
For each points_inside
Senior_citizens_20mgrid = senior_citizens / number of Points_inside
Senior_citizens_attended_per_day = volunteer_capacity/distance_to_service
Necessary_volun_20mgrid = Senior_citizens_20mgrid /
Senior_citizens_attended_per_day
Necessary_volun = ∑ Necessary_volun_20mgrid
```

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Chapter 16
Facilities Location Under Risk Mitigation Concerns

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Abstract In this chapter, we explore the recent developments made to the literature in terms of facilities location while considering risks and the strategies to mitigate them. The bulk of this literature is focused on *disaster-relief* facilities location (DR-FL), but applications of the theory can also be found in other contexts. By disaster-relief facilities, we understand any temporal or permanent facility dedicated to providing assistance during a disaster event, or after this has been registered. Rather than attempting an exhaustive list, we focus on showcasing contributions with diverse methodologies, contexts, and objectives to provide the reader with an inkling to the existing literature on this topic. We will also point the reader to literature surveys where a more detailed discussion of the state of the art can be found. This chapter is organized in sections to highlight the different types of optimization problems modeled; solution methodologies employed, with their benefits and comparisons where possible; and real contexts where these models and methodologies have been applied. While we strived to provide as much variety as possible, our research revealed a preponderance of multi-objective optimization models, stochastic optimization, and response to natural disaster events as the focus of these contributions.

16.1 Introduction

The allocation of disaster-relief facilities is a complex and multi-dimensional problem that has been studied from many different angles. As many location problems, it is often modeled together with a distribution problem due to the strong ties between the two of them. According to Boonmee et al. (2017), the problem of allocating disaster-relief facilities "has become the preferred approach for dealing with emergency humanitarian logistical problems" and has become ever more relevant since the number of natural and man-made disasters has increased exponentially.

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While the main focus of the allocation problem is to choose the optimal placement of the facilities, the disaster-relief facilities problem often includes other relevant measures of humanitarian logistics. The scarcity of the resources, the uncertainty of the demand, the conditions of the network, and the rapid evolution of emergency situations differentiate the problem from other types of facilities location problems and provide justification for developing, or adapting, location models specifically for this context.

The rest of the chapter is organized in sections detailing basic models proposed for the disaster-relief facilities location problem (Sect. 16.2), extensions on the basic models and some approaches at solving the problem (Sect. 16.3), the contexts in which they have been applied and an example (Sect. 16.4), the chapter concludes with some final remarks in Sect. 16.5.

16.2 Models for Allocation of Disaster-Response Facilities

In this section we present some examples of developments made in allocating facilities that are subject to risk. We discuss briefly the main contributions of each work and provide some comments where appropriate. Later, we adapt a basic optimization model to solve a Deterministic Disaster-Relief Facilities Location Problem.

Loree and Aros-Vera (2018) developed a model to determine the location of distribution and inventory points in Post-Disaster Humanitarian Logistics. They seek to minimize placement, logistics, and opportunity costs (they define the term *deprivation cost* as that resulting from the lack of access to critical supplies). The model allows for demand nodes to be served from multiple locations. Loree and Aros-Vera consider the importance of the temporal component resulting in social costs in facility location.

Verma and Gaukler (2015) provide both deterministic and stochastic models that consider varying degrees of damages to service and demand locations. In these models, they consider a damage intensity measure related to the distance between the locations and the center of the disaster. The stochastic model extends directly considering this damage intensity measure as a random variable. Through these models, the authors reduce the expected cost of providing supplies when the damage caused by a disaster is considered.

Rizeei et al. (2019) study the location of emergency response centers using existing infrastructure. Their work seeks to assess the ideal time for providing service, considering the minimum impedance and maximum coverage location problems.

Chen et al. (2013) propose a hierarchical location model to place shelters considering the reality that requirements change over time during post-disaster evacuations. They found that the quality of the response depends not only on the placement strategy of shelters, but also on the trade-off between budget planning and evacuation efficiency.

Peng et al. (2011) study a strategic supply chain management problem to design reliable networks that perform as well as possible under normal conditions, while also performing relatively well when disruptions strike. They present a mixed-integer programming model whose objective is to minimize the nominal cost (the cost when no disruptions occur) while reducing the disruption risk using the p-robustness criterion (which bounds the cost in disruption scenarios).

Most of these works use as a basis a traditional location problem: P-median (Verma and Gaukler 2015; Chen et al. 2013) or Maximal demand covering (Rizzei et al., 2019), which have been adapted to reflect the nature of disaster relief problems. Furthermore, the mitigation of risk is often addressed by imposing a cost to avoid "risky" solutions.

16.2.1 A Deterministic Disaster-Relief Facilities Location Problem

This model (adapted from Verma and Gaukler 2015) seeks to minimize the average cost of covering the resulting demand from a disruption event. It considers different locations where disruptions are possible with a priori probabilities of occurrence. Furthermore, it considers the possibility of a diminished ability of the supply nodes as a result of the disruption event. Let:

- N: Set of nodes (demand and supply) in the network
- $I \subset N$: Set of demand nodes
- $J \subset N$: Set of potential supply nodes
- S: Set of possible disruptions
- D_i: Demand of node *i*
- k_j: Capacity of node *j*
- c_{sij}: Cost of supplying demand of node *i* from location *j* under disruption s
- m_{sn}: Damage at node *n* as a result of event *s*
- $x_j = \begin{cases} 1 \text{ If a facility is open at location } j \\ 0 \text{ Otherwise} \end{cases}$
- y_{sij}: Amount of service provided by facility j to demand point *i* under disruption *s*
- P: Denotes the upper limit on the number of facilities to be used

$$Min \sum_{s \in S} \sum_{i \in I} \sum_{j \in J} c_{sj} y_{sij} \tag{16.1}$$

Subject to

$$\sum_{j \in J} x_j \leq P \tag{16.2}$$

$$\sum_{i \in I} y_{sij} \leq \left(1 - m_{sj}\right) k_j x_j \ \forall s \in S,\ j \in J \tag{16.3}$$

$$\sum_{j \in J} y_{sij} \geq m_{si} D_i \ \forall s \in S, i \in I \quad (16.4)$$

$$x_j \in \{0, 1\} \ \forall j \in J \quad (16.5)$$

$$y_{sij} \in \{0, 1\} \ \forall s \in S, i \in I, j \in J \quad (16.6)$$

Equation (16.1) computes the total cost of sending supplies to demand nodes. This cost is mediated through the probabilities of occurrence for the different disruptions.

Constraints (16.2)–(16.4) adapt the classical location/demand covering constraints to the disaster relief context. Constraint (16.2) limits the number of facilities used given a budget P. Constraint (16.3) bounds the supplies provided by a facility with its capacity (k_j) and its available resources given the disruption occurred (m_{sj}). Constraint (16.4) requires that all demand generated by the event (m_{sj}) be covered. Finally, constraints (16.5) and (16.6) ensures the variables integrality.

For the objective of this model, the cost of covering the demand, c_{sij}, can be a function of the probability and distance of the disruption (as in Verma and Gaukler 2015), an opportunity, or deprivation, cost (as in Loree and Aros-Vera 2018), or a function of the severity of the event (as will be illustrated in Sect. 14.4).

16.3 Extensions on the Disaster-Relief Facilities Location Problem

In the previous section, we discussed the problem of allocating disaster-relief facilities in its more basic form, except for a couple of cases in which the same work referred to higher order models (such as Verma and Gaukler 2015). In the following section we will turn to extensions of the basic models mainly dealing with multi-objective or multi-stage optimization.

16.3.1 Multi-Objective

The works in this section focus exclusively on multi-objective optimization, we present a brief summary of the contributions before attempting to provide an overview of the models proposed.

Abounacer et al. (2014) consider a multi-objective problem for disaster response, to determine the number of required humanitarian aid distribution centers in a disaster region. The problem deals with the distribution of aid while attempting to minimize total transportation time from distribution to demand points; number of agents to open and operate the distribution centers; and the unmet demand within the affected area.

Najafi et al. (2013) propose a stochastic model to solve a problem with multiple objectives, modes, commodities, and periods to manage the logistics of both commodities and injured people in an earthquake response.

Geng et al. (2020) propose a model to find the optimal location for shelters considering the storage of relief materials pre-disaster. The model seeks to minimize distance to shelter and optimize distribution of refugees and inventory levels on site. The authors also consider service quality in terms of qualitative factors.

Doerner et al. (2009) present a model for multi-objective decision analysis with respect to the location of public facilities such as schools in areas near coasts, taking risks of inundation by tsunamis into account. The model seeks to optimize coverage, risk, and cost.

Huang et al. (2015) formulate a multi-objective optimization model that combines resource allocation with emergency distribution, and incorporates the frequent influx of information and decision updates in a rolling horizon approach.

16.3.1.1 Modeling Multiple Objectives

In what follows we will present some relevant objectives that have been addressed in the previous works. Where possible, we will adapt the notation to provide continuity between the sections. Let.

- t_{sij}: Time to reach demand node *i* from supply node *j* under disruption *s*
- l_{sj}: Loading time at location *j* in scenario *s*
- u_{si}: Unloading time at location *i* in scenario *s*
- Nsj: Required personnel at location *j* under scenario *s*
- ρ_{si}: Penalty at node *i* for failing to meet its demand under scenario *s*
- φ_{si}: Utility from covering demand at node *i* under scenario *s*
- $w_{sij} = \begin{cases} 1\text{If the path between } i \rightarrow j \text{ is traveled under scenario} s \\ 0 \text{ Otherwise} \end{cases}$
- z_s: Lowest *demand-covering rate* for any node under scenario *s*

$$\min \sum_{s \in S} \sum_{i \in I} \sum_{j \in J} (t_{sij} + l_{sj} + u_{si}) w_{sij} \tag{16.7}$$

$$\min \sum_{s \in S} \sum_{j \in J} N_{sj} x_j \tag{16.8}$$

$$\min \sum_{s \in S} \sum_{i \in I} \rho_{si} (m_{si} D_i - \sum_{j \in J} y_{sij}) \tag{16.9}$$

$$\max \sum_{s \in S} \sum_{i \in I} \varphi_{si} (\sum_{j \in J} y_{sij}) \tag{16.10}$$

$$\min \sum_{s \in S} z_s \tag{16.11}$$

Subject to

$$\sum_{j \in J} y_{sij} \geq z_s \ \forall i \in I, s \in S \tag{16.12}$$

$$w_{sij} \in \{0, 1\} \ \forall i \in I, j \in J, s \in S \tag{16.13}$$

$$z_s \geq 0 \ \forall s \in S \tag{16.14}$$

In the previous equations we have several examples of alternative objectives for the Disaster-Relief Facilities Location Problem. Equation (16.7) minimizes the total travel time between nodes in the network; Eq. (16.8) minimizes the personnel requirement over all scenarios; Eq. (16.9) minimizes penalties for unmet demand; Eq. (16.10) maximizes utility over demand covered; Eq. (16.11) seeks to minimize inequalities between affected areas. Constraint (16.12) ensures the demand covered from each node i is at least the minimum demand-covering rate for every scenario s. Finally, Eqs. (16.13) and (16.14) are the integrality constraints. Any subset of these equations can be used in a multi-objective problem.

16.3.2 Multi-stage

The models in this section refer to a sequential decision-making process, where the solution to the first part of the problem is used as input for the second part. The type of decisions varies depending on the objectives of the specific instances, but in general, the first stage deals with the selection of the sites, while the second stage handles decisions affecting the sites already selected. In this sense, we can see the stages taking place at different levels, the first stage is the strategic level, the second stage would be the tactical/operative level.

Oksuz and Satoglu (2020) develop a two-stage stochastic model to determine the location of temporary medical centers. Their model considers existing infrastructure, casualty types, and possible damages to the network. The authors find optimal locations for the facilities that minimize the setup cost and the expected transportation cost.

Zolfaghari and Peyghaleh (2015) develop a two-stage stochastic model to allocate reconstruction efforts after disasters hit. The model seeks to minimize mitigation, reconstruction, and especially large costs in highly disaster-prone areas.

16.3.2.1 Multi-objective Multi-Stage

Cavdur et al. (2016) propose a multi-objective, two-stage stochastic program for the allocation of temporary disaster relief facilities. The authors seek to minimize the distance traveled, the unmet demand, and the number of facilities placed.

Ghasemi et al. (2020) develop a stochastic multi-objective model logistic distribution and evacuation planning during an earthquake. This model considers both pre- and post-disaster decisions and solves these sequentially. The first phase deals with permanent relief centers and inventory of relief materials. The second phase determines optimal locations for temporary relief centers and distribution of relief materials.

16.3.3 Solution Methods

The models presented in this section are far more complicated to solve than those presented in Sect. 16.2. In this sense, a direct approach to solving the optimization model is not usually successful. In what follows we review the methods and techniques employed by the authors to solve their proposed models in a more efficient way.

Abounacer et al. (2014) propose an epsilon-constraint method to generate the Pareto front. The results require considerable computing time for relevant instances. The authors propose relaxing the stopping criterion by allowing an optimality gap, this method yields a good approximation of the Pareto front in relatively short computing times.

Najafi et al. (2013) develop a robust approach to obtain a plan that performs well under the uncertainty following an earthquake. One advantage of this model is that it linearizes their original stochastic proposition. Afterwards, they use a lexicographic approach to solving their multi-objective formulation.

Verma and Gaukler (2015) propose a decomposition to solve their stochastic model by creating, sampling, and solving scenarios to build a pool of potential solutions. Once a large enough pool has been obtained, they test the solutions in all the instances generated and evaluate the best performing.

Doerner et al. (2009) and Peng et al. (2011) use a metaheuristic based on genetic algorithms. While Doerner et al. use a non-dominated genetic algorithm to solve the multi-objective model, Peng et al. propose a hybrid with local improvement, and shortest augmenting path. Numerical tests show that the heuristic greatly outperforms CPLEX in terms of solution speed, while still delivering excellent solution quality. Furthermore, Peng et al. demonstrate the tradeoff between the nominal cost and system reliability, showing that substantial improvements in reliability are often possible with minimal increases in cost. The authors also show that their model produces solutions that are less conservative than those generated by common robustness measures.

16.4 Applications

Several applications of Disaster-Relief Facilities Location Problems can be found in the literature. A few examples dealing with the location of relief centers after earthquakes can be found in Oksuz and Satoglu (2020) in Istanbul, Turkey; Geng et al. (2020) in Sichuan, China; and Ghasemi et al. (2020) and Zolfaghari and Peyghaleh (2015) Tehran, Iran. As we mentioned before, while the majority of instances deal with earthquakes, there are studies addressing other type of disaster events, e.g. Rizeei et al. (2019) studies the allocation of shelters after flooding, and Doerner et al. (2009) deals with tsunami affected areas.

In this section we will propose a case based on information obtained from Mexico City. We believe the characteristics of the city warrant especial attention due to the frequency of events registered, its high population density, and the structure of the location it was built in.

16.4.1 The Area Under Study

Mexico City is divided in 16 Boroughs or administrative units each with its own characteristics as can be seen in Fig. 16.1. These Boroughs differ in size, demographics, and level of risk according to the type of soil they were built in. In this section we will attempt to provide clear picture of the information available. In Table 16.1 we present relevant demographic information for each of these Boroughs.

Figure 16.1 shows the largest Boroughs being Tlalpan and Milpa Alta, while the most populated ones are Iztapalapa and Gustavo A. Madero, finally, Tlahuac and Iztapalapa registered the most dwellings damaged by the September 19, 2017 earthquake.

Fig. 16.1 Mexico City's Boroughs

Due to the nature of the terrain where the city was built, it experiences a high risk derived from seismic events, which varies between medium, high, and extreme depending on the zone of interest. The Open System of Geographic Information (SIGCDMX) from the Digital Agency of Public Innovation (ADIP) maintains a wealth of databases pertaining to different aspects of the city, from locations of various service providers, city roads, public transportation, and also evaluations of risk from different sources. Figure 16.2 shows the estimation of risk for each of the 2454 zones in which Mexico City is studied in this database.

Table 16.1 Demographics of Mexico City's Boroughs (with data form SIGCDMX, 2021)

Borough	Population	Population at risk (housing)	Average inhabitants per dwelling	Damaged dwellings during the 2017 event
Alvaro Obregon	749,982	66,160	4.3	56
Azcapotzalco	400,161	17,836	3.4	6
Benito Juarez	417,416	87,574	1.7	150
Coyoacan	608,479	32,750	3.5	88
Cuajimalpa	199,224	9652	2.9	8
Cuauhtemoc	532,553	28,763	2.1	115
Gustavo A. Madero	1,164,477	73,602	4.5	58
Iztacalco	390,348	20,294	3.8	64
Iztapalapa	1,827,868	146,587	4.7	4095
Magdalena Contreras	243,886	6888	5.7	52
Miguel Hidalgo	364,439	22,282	1.9	18
Milpa Alta	137,927	7253	10.6	204
Tlahuac	361,593	33,180	4.8	1475
Tlalpan	677,104	19,446	4.0	107
Venustiano Carranza	427,263	30,733	3.5	69
Xochimilco	415,933	39,270	6.2	1036

Finally, we present in Fig. 16.3 a map illustrating the average construction or remodeling dates for the dwellings in Mexico City.

With respect to the existing shelter capabilities of the city, Table 16.2 shows a summary of the current available shelters as well as their capacities and estimation of risk. The location of the individual shelters can be seen in Fig. 16.4.

With this information we propose to solve the model presented in Sect. 16.2 in order to find the optimal location for shelters under different scenarios.

16.4.2 *The Scenarios Under Study*

The characteristics of Mexico City make the use of certain measures or considerations previously explored in the literature unadvisable. Note for example in Fig. 16.2 the distribution of the risk levels; when most of the earthquakes originate to the south or the east, this risk distribution would be incompatible with a distance-based measure. For this reason, we propose instead the use of parameters relative to the terrain itself,

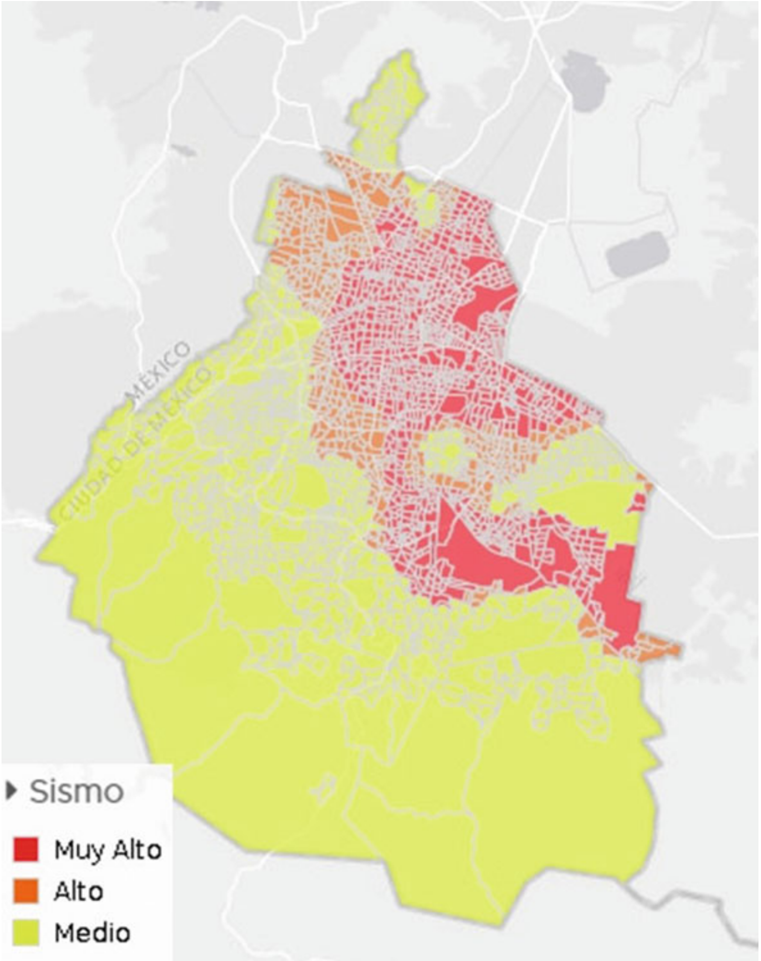

Fig. 16.2 Earthquake risk by severity (from SIGCDMX)

for example the maximum acceleration of terrain (a_0), the maximum acceleration of rocky terrain (a_0^r), or the maximum spectral acceleration (c).

These factors and the relationships between them provide the parameters under which a building is set to withstand the impacts of earthquakes and could be used in order to assess the risk of a building or area. We posit that the at-risk population of Mexico City has no access to dwelling that are up to standard and are thus likely to suffer damage during an earthquake and study different levels of impact as described in Fig. 16.5.

We propose two different probability profiles to assess the impact of an event on the probability that a building will suffer damage considering the maximum

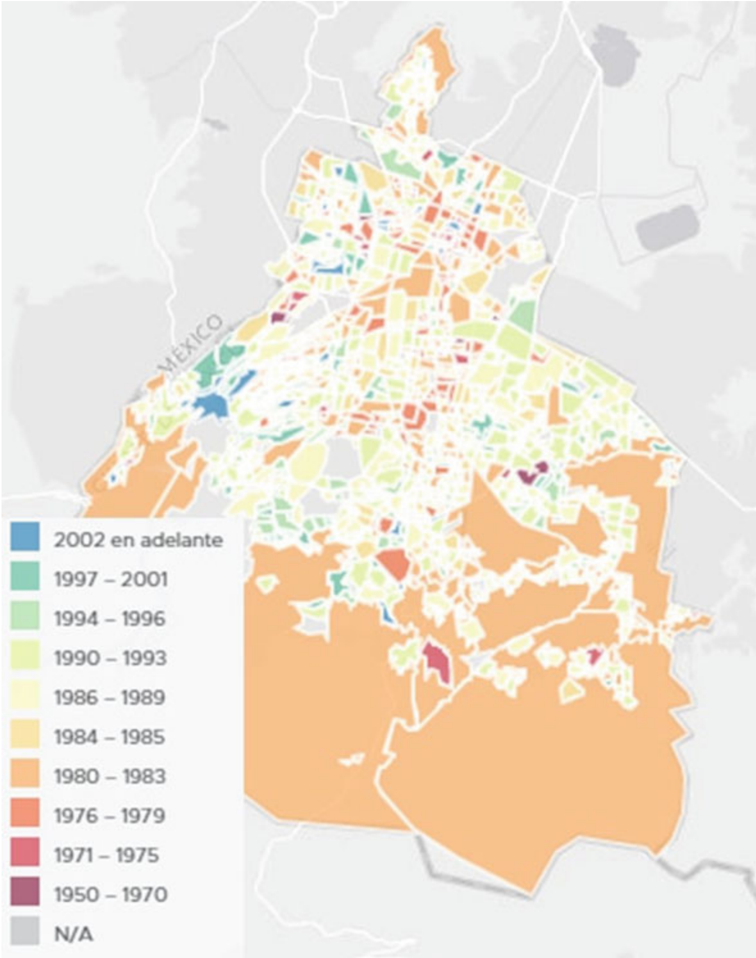

Fig. 16.3 Dwelling in Mexico City by year of construction/remodeling (from SIGCDMX)

spectral acceleration (c), as an approximation to the motion of the dwelling during the earthquake.

We use these functions in order to estimate demand/supply escalating factors according to the risk of each zone so that

$$m_{sn} = p_s(c_n) \cdot \delta$$

where m_{sn} is the scaling factor for the demand/supply of zone n, p_s is the probability function of the curve describing scenario s, and c_n is the maximal spectral acceleration of zone n. Finally, δ is the scaling factor according to the last big event estimated at 5.77%.

Table 16.2 Sheltering capabilities of Mexico City's Boroughs (with data form Portal de Datos Abiertos)

Borough	Number of shelters	Total capacity	Risk assessment
Alvaro Obregon	4	620	Medium
Azcapotzalco	1	500	High
Benito Juarez	1	35	Medium
Coyoacan	3	700	High
Cuajimalpa	1	900	Medium
Cuauhtemoc	7	1460	Extreme
Gustavo A. Madero	11	2260	High–Extreme
Iztacalco	5	1450	Extreme
Iztapalapa	3	650	Medium–High
Magdalena Contreras	6	1400	Medium
Miguel Hidalgo	5	1120	Medium–High
Milpa Alta	3	600	Medium–High
Tlahuac	5	570	Extreme
Tlalpan	4	2100	Medium
Venustiano Carranza	5	1500	Extreme
Xochimilco	3	685	Medium–High

Furthermore, we will be making the assumption that the shelters are built more adequately than the dwellings of at-risk population, so $m_{sj} = \alpha m_{si}$ for similar values of $c_j = c_i$, where $\alpha = \{0, 0.25, 0.33, 0.5\}$.

16.4.3 The Results

We present the results of our experiments where we solve both set-covering and p-median problems to explore the limits of the system. For the most extreme case (the concave pdf), the installed capacity of the relief centers is not enough to shelter the displaced population, so we assume an expansion of capacity is possible.

In this scenario we compare the impact that m_{sj} has on the minimum number of centers required to shelter all displaced population. The results can be seen in Fig. 16.6.

Furthermore, we take as base the case where $\alpha = 0.25$ and solve a P-median problem to minimize the total distance traveled by the displaced population. The results can be seen in Fig. 16.7.

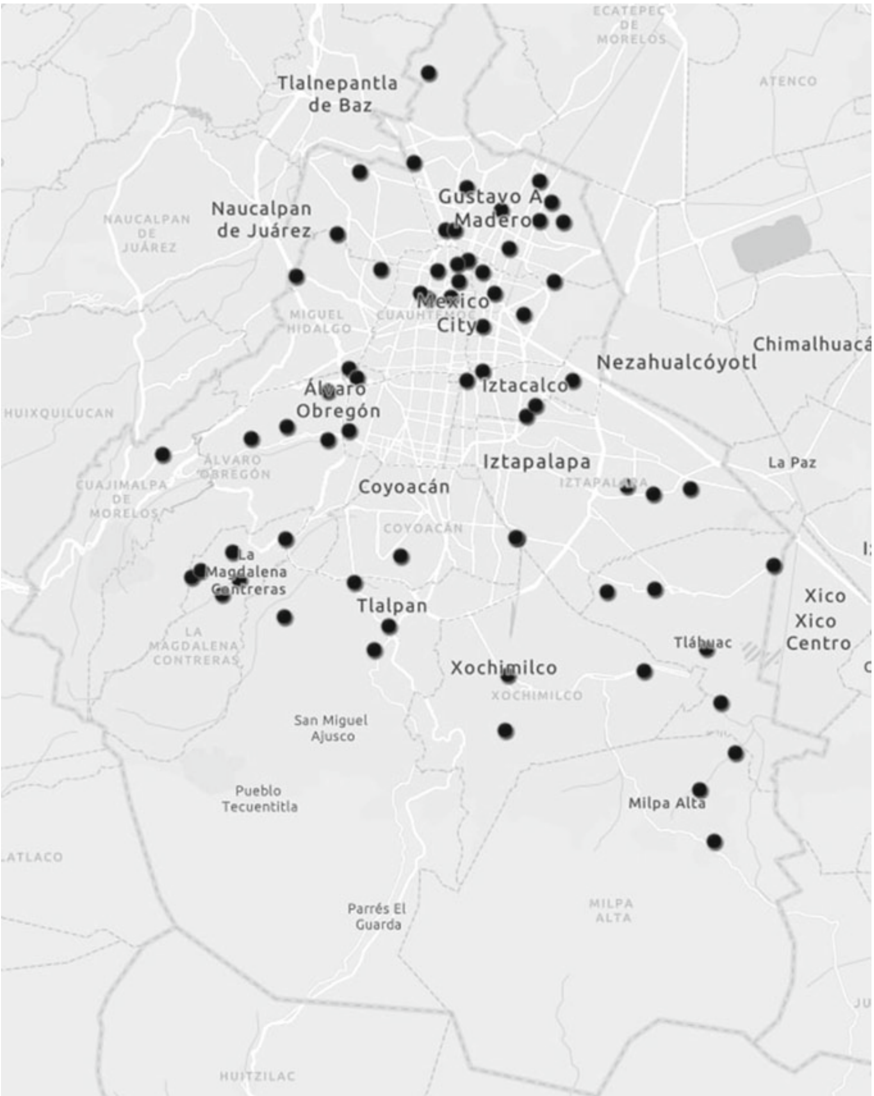

Fig. 16.4 Location of existing shelters in Mexico City (from Portal de Datos Abiertos)

Finally, we look at the less extreme event (for a convex pdf), our first observation is that in this case the installed capacity is enough to provide shelter to the at displaced population and focus on evaluating the impact of building the shelters adequately by comparing the different values of α. The results are shown in Fig. 16.8.

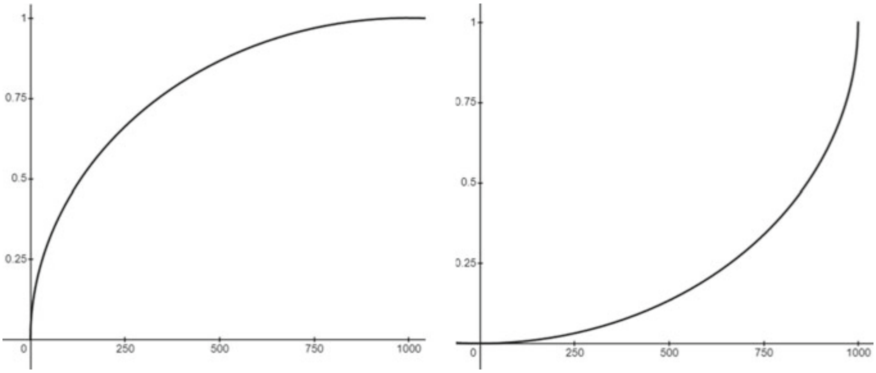

Fig. 16.5 Two possible pdfs for the probability of damage to a dwelling given a maximal spectral acceleration

16.5 Conclusion

In this chapter we attempted to provide the reader with various examples of facility location problems under risk. As could be intuited from the beginning, this problem is closely related to the general facilities location problem. Small adaptations to the optimization model are necessary to incorporate the risk considerations into the problem, such as introducing an element of uncertainty to the consideration of demands and capacities.

Another point worth noting is the prevalence of multi-objective/multi-stage models, which speak of an alternative way of dealing with the risk, by diversifying the measure of optimality or by delaying the decision making.

Furthermore, in the case where the risk comes from an earthquake, we propose the use of terrain-related measurements in order to implement the mitigation considerations, due to the fact that more common measures, such as distance, may be inadequate to represent a particular situation.

Finally, we present a case study based on Mexico City and propose that pre-selecting buildings that are up to standard would be beneficial to the risk mitigation concern, since they would be able to better withstand the impact of the disruption event. We show this for two different impact functions which would correspond to events of different nature.

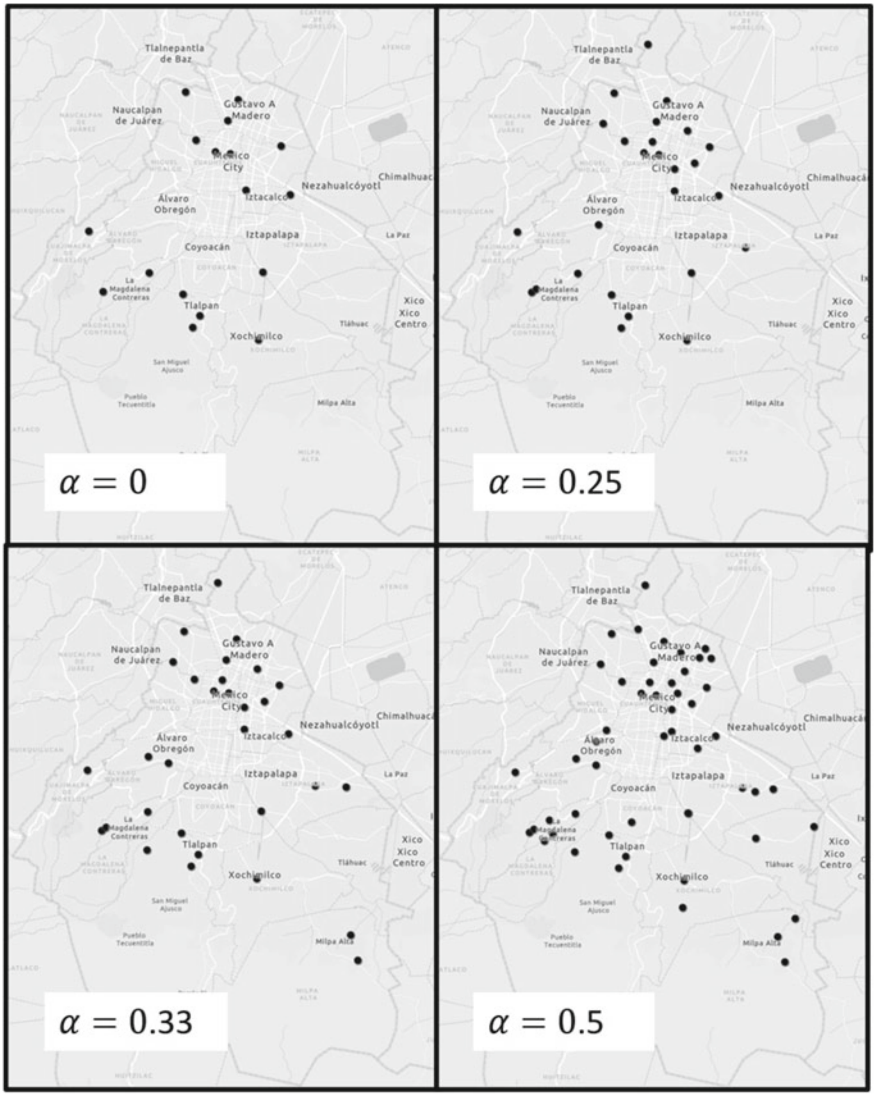

Fig. 16.6 Optimal shelter location by adequacy of building given a concave pdf

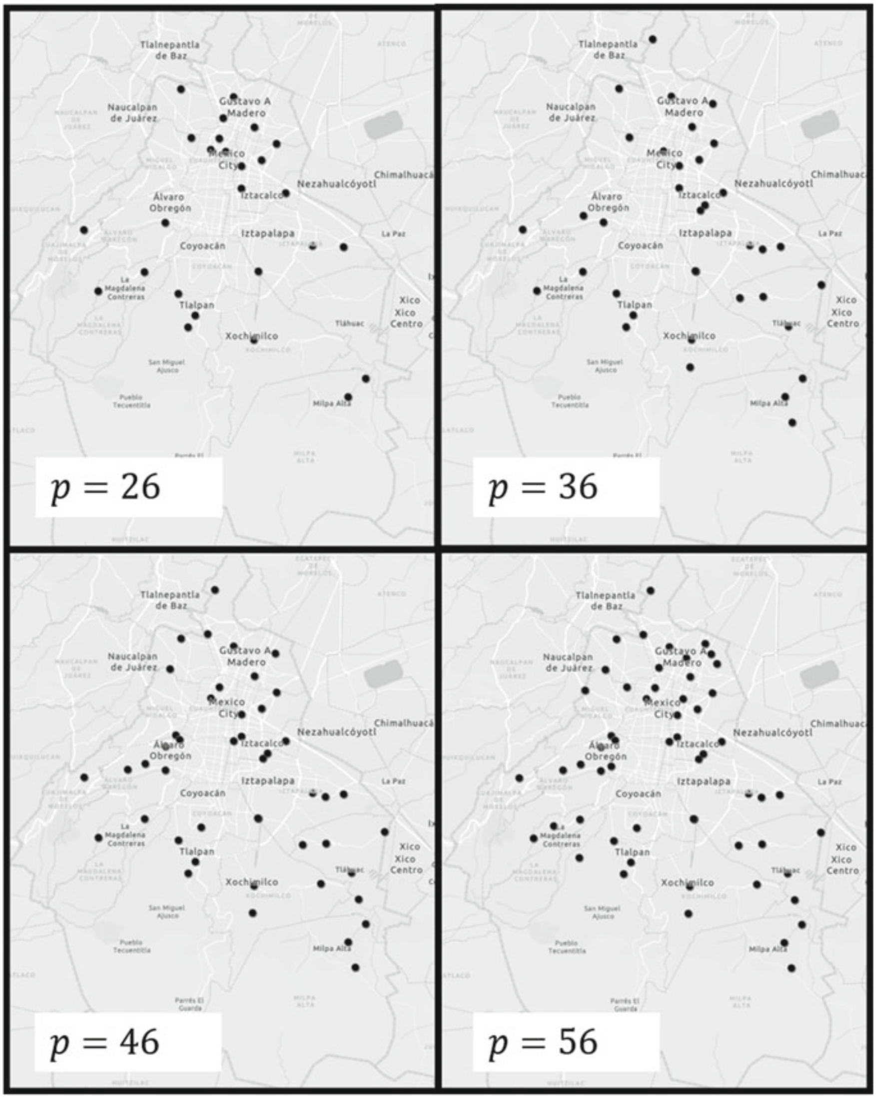

Fig. 16.7 Optimal shelter location by distance given a budget P

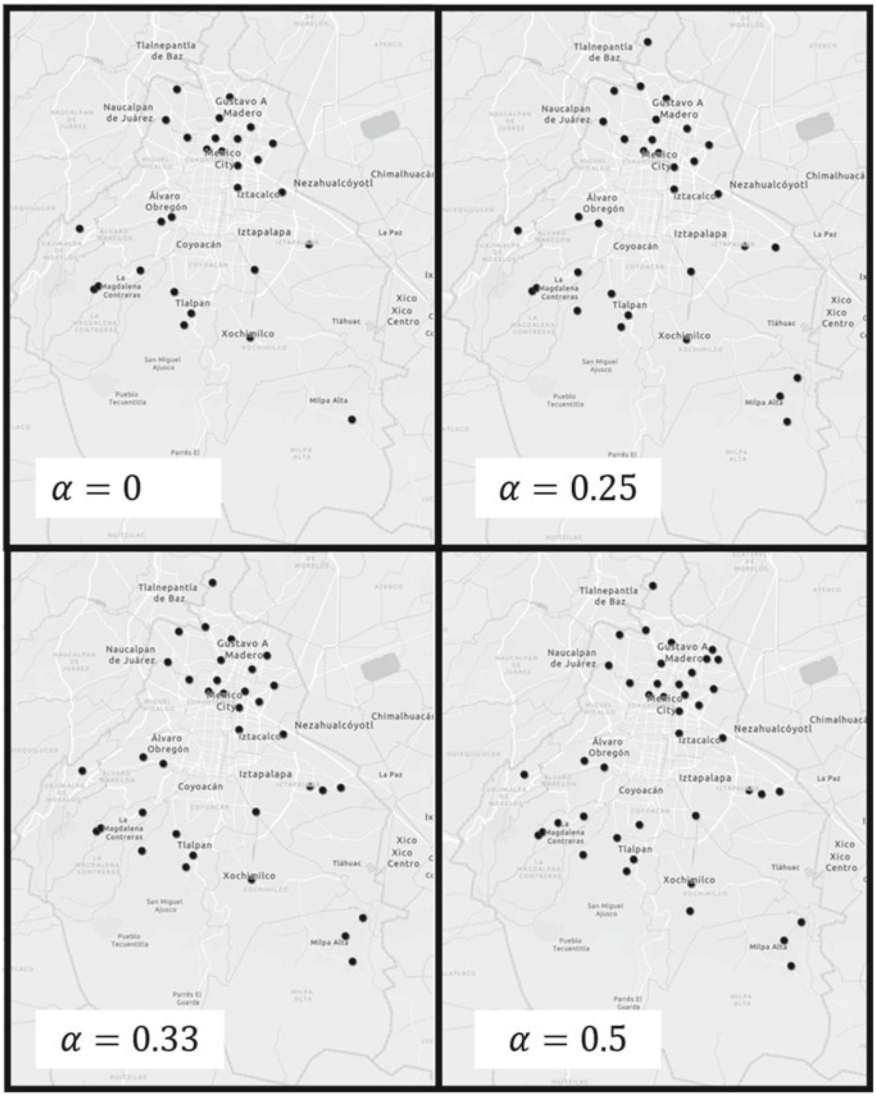

Fig. 16.8 Optimal shelter location by adequacy of building given a convex pdf

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Part III
Multi-criteria Approaches

Chapter 17
An Integrated FAHP-Based Methodology to Compute a Risk Vulnerability Index

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Abstract Humanitarian logistics activities have mainly focused on the response stage of the disaster management cycle. The concept of risk vulnerability enhances the scope of disaster management by highlighting the importance of improving the activities of the preparation stage. This work proposes a vulnerability index that comprises the dimensions of hazard, social and economic exposure, and preparedness. Three quantitative techniques are combined to identify key indicators comprising the index, determine the relative importance of the vulnerability dimensions, and categorize the states of Mexico according to their level of vulnerability toward hydrological disasters. The addition of both economic and social exposure in a vulnerability index acknowledges that the characteristics of the population influence their capacity to cope with disasters and uncovers the importance of adjusting strategies to local drawbacks and needs.

Keywords Vulnerability assessment · Social exposure · Hydrological events

17.1 Introduction

The number of hydrometeorological events (floods, heavy rains, typhoons, and hurricanes) worldwide has been increasing exponentially since 1900. Nowadays, the availability of information makes it possible to improve decision-making during the disaster management cycle by judging the expected consequences of a disaster and providing real-time information about the situation after the disaster occurrence

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(Díaz-Delgado and Gaytán-Iniestra 2014). The disaster management cycle comprises four stages: mitigation, preparedness, response, and reconstruction. Usually, humanitarian logistics-defined as the activities of planning, implementing, and controlling the flow and storage of goods, materials, and information effectively and efficiently to alleviate the impact of a disaster on people- are biased toward the response phase (Kopczak and Thomas 2005). Most of the literature on humanitarian logistics has focused on the problem of how to deliver aid to regions affected by disasters.

The limited local use of technology, human resource problems, and poor infrastructure are factors that, in addition to the uncertainty inherent to natural events (when they will occur and how much damage they will cause), contribute to the complexity of the humanitarian logistics activities (Mora-Ochomogo et al. 2016). However, some disasters such as floods can be predicted or simulated with an acceptable degree of accuracy in terms of timing, magnitude, and location. Consequently, the decisions and activities of the preparedness phase can be improved by providing the properly estimated vulnerability of communities to natural events (Díaz-Delgado and Gaytán-Iniestra 2014; Manopiniwes and Irohara 2016).

The preparedness phase comprises operations that can be implemented before (pre-disaster) the flood occurs and usually involve the pre-positioning of emergency response supplies, the location and estimated capacity of shelters, the identification and design of routes to facilitate evacuation, and the provision of information to inhabitants. However, evaluating the physical and social consequences of a disaster is also critical to mitigate its effects since the general objective of humanitarian logistics is to alleviate the suffering of vulnerable people and restoring self-sufficiency of the affected regions (Thevenaz and Resodihardjo 2010).

According to official records, disasters in Mexico represented an economic loss of 17,698 million MXN in 2015 (around 790,000 USD). Hydrometeorological events are natural events representing the highest hazard in Mexico; 96% of the reported disasters in the country correspond to this kind of event (CENAPRED 2020). The hydrometeorological events reported include storms and heavy rains (44%), floods (18%), and hurricanes (28%), the remaining 10% correspond to other events such as frost, hail, and draughts.

Traditional risk metrics used to evaluate the impact of disasters are based on their expected economic damage, computed as the direct tangible costs of the event. But risk assessment requires a more holistic view that allows evaluating risk management performance prevention measures and considers social and cultural dimensions (Carreño et al. 2005; Giupponi et al. 2013). For example, the Economic Union has developed a Regional Risk Assessment methodology that considers the social capacity to reduce risk and defines economic measures that go beyond direct tangible costs. Different types of hazards are considered. In the case of floods, the European Flood Directive has supported the development of flood risk maps that together with an economic valuation of potential damages are used to support humanitarian logistics decisions, such as where to locate humanitarian warehouses and facilities to promptly move supplies and people when the flood strikes (De Leeuw and Mok 2016). But the impact of disasters can be direct and indirect, which involves economic, environmental, social losses (e.g., deaths) or damages (e.g., reversible building damages).

Therefore, the definition of a valid and comprehensive risk measure is still an open issue in the humanitarian logistics literature.

However, the development of a valid risk measure is only one problem. Other problems include: (1) the lack of timely, reliable, and complete data about hazard events, their effects, and the response actions applied, particularly for developing countries; (2) the robustness and representativeness of the risk indicators, that among other factors, depend on the indicators selected, the weighting, and compensation of these indicators; and (3) the development of a risk index easily understood by public policymakers at national, sub-national and urban level (Carreño et al. 2005). This work aims to propose a vulnerability index that considers social exposure as a key element to assess the risk of the hydrological events that can affect the states of Mexico.

17.2 Literature Review

Depending on the perspective (social, economic, public administration, and environmental), the risk may be differently evaluated (Wisner et al. 2004). From an economic perspective, risk assessment is driven by direct tangible costs such as the cost of damaged infrastructure. While from an environmental perspective, the Panel on Climate Change focuses more on the assessment of vulnerability, considered an output of human and economic activities, and the combination of the adaptive capacity of the socio-ecological system and the local exposure to a specific hazard. These two perspectives have been gradually integrated because of the recognized relation between climate change and the increased frequency of extreme events. For example, De Ruiter et al. (2020) noted that countries and regions that suffer the consecutive impact of different types of disasters (natural and technological or man-made), pose additional challenges to long-term humanitarian logistics plans because the resilience of the affected region decreases after the occurrence of the first disaster.

Crichton (2002) describes risk as a multi-dimensional construct comprising three independent elements or dimensions: hazard, exposure, and vulnerability. Melching and Pilon (2006) view these dimensions as stages of a process of risk assessment. These stages are estimation of the hazard (location, frequency, and severity), estimation of the exposure (number of people, buildings, industries, and resources under threat), estimation of the vulnerability of the risk elements (expressed as a percentage of losses), and evaluation of the risk as to the combination of hazard, exposure, and vulnerability.

Several studies have proposed frameworks to evaluate risk. For example, Davidson (1997) proposed a Disaster Risk Reduction Model, where vulnerability is a central element. In this model, the risk is calculated as the multiplicative aggregation of hazard, exposure, vulnerability, and the community's adjustment capacity. Hazard is defined as the probability or severity of an event, exposure is determined in terms of the demographic and economic structure of a region, vulnerability encompasses physical, social, economic, and environmental aspects, while capacity refers to the management policies and resources that can mitigate the effect of the disaster. The Regions of Risk Model proposed by Hewitt (1997) considers vulnerability as the result of hazard, the community's susceptibility, and the community's adjustment capacity to a dangerous environment. Thus, the model acknowledges disasters occur when a hazard interacts with exposure and vulnerability.

Other risk assessment models are the Pressure and Release (PAR) model and the Access to Resources (ATR) model developed by Blaikie et al. (2004) and Wisner et al. (2004), respectively. The PAR model details how to recognize a potential disaster based on the identification of root causes, macro-forces, environmental fragility, and lack of policies and resources to face the hazard. Vulnerability is regarded as a consequence of different factors. The most relevant are a) economic, demographic, dynamic pressures (social, economic, and political activities in the area), deficiencies in the preparedness toward disasters, general unsafe conditions for living, and sociopolitical context that determines the population's access to resources.

The ATR model is designed to understand how people make decisions based on their accessibility to resources. By analyzing the people's access profile, the model looks to track the causes of the disaster, the extent of its impact, the pre- and post-disaster coping mechanisms, and the future recovery scenarios.

Although the PAR and ATP models are primarily qualitative, Argawal (2018) applied them to enhance the understanding of the reasons for the damages caused by Hurricane Katrina that hit New Orleans in 2005. The study included risk perceptions and public strategies as critical determinants for disaster preparedness and the creation of resiliency for vulnerable groups. The identification and evaluation of the vulnerability of different population segments and the gathering of documentary information demonstrated to be outstanding components of the decisions made by affected households. The lack of transportation, limited access to information, low education, capital availability, and unemployment resulted in the greatest levels of impoverishment, disability, and fatalities among disadvantaged segments. Based on the relevance of social vulnerability, Argawal (2018) proposed to compute risk as to the product of hazard (likelihood of a disaster) by vulnerability by the community perception of the impact of disasters. Thus, the PAR framework applied to a specific disaster feeds into the ATR model to better understand the consequences of providing better living conditions to communities, facilitate their access to resources, and improve risk awareness.

Other models that consider vulnerability as a key determinant of community risk and the basis of resilience are the Hazards-of-Place (HOP) model and its extended version, the Resilience of Place (DROP) model (Cutter et al. 2009). The DROP model considers vulnerability a mixture of social vulnerability and a biophysical condition (potential exposure) in a specific area (Dewan 2013). The United Nations International Strategy for Disaster Reduction (UNISDR 2009a, b) developed a framework for disaster risk reduction, where vulnerability is evaluated considering four categories: physical, social, economic, and environmental.

The Risk Management Index (RMI) proposed by Carreño et al. (2005) focuses on measuring the performance and effectiveness of institutional actions to reduce the vulnerability and losses in a region and recover from disasters. The RMI provides a quantitative measure of risk management based on the computation of the distance between the current conditions and qualitative benchmarks. The RMI is particularly oriented to the revision of public policies, which include the identification of risk (risk perceptions and an objective assessment), risk reduction (prevention and mitigation), disaster management (response and recovery), governance, and financial protection. Each of the RMI components includes six indicators because using a larger number of indicators could be redundant and unnecessary. Carreño et al. (2005) applied the fuzzy analytical hierarchy process (AHP) to determine the relative weights of importance of the four components of the RMI.

Several studies in humanitarian logistics literature have applied quantitative methods to evaluate the different dimensions of risk. Regarding the hazard component, research has mainly focused on forecasting the incidence and magnitude of disasters. For example, Madsen and Jakobsen (2004) developed a forecasting model to determine the intensity of storms caused by cyclones based on air pressure and wind speed. The model results were evaluated using simulations. Koutsoyiannis et al. (2007) and Papalexiou et al. (2011) used a stochastic approach to determine the uncertainty in future hydroclimatic predictions by comparing probabilistic scenarios to represent all rainfall events under similar conditions. Wang and Ling (2011) developed a quantitative model based on Geographical Information Systems (GIS) to assess how typhoons may cause heavy rains and floods, while Pedrozo-Acuña et al. (2014) formulated a simulation model to measure the risk of extreme floods in Mexico. GIS maps have been successfully used to represent the intensity/hazard (depth, persistence, and velocity) of flooding. Topographical data are digitized in grid cells, and hydraulic models are used to simulate flood flows compared against previous floods to validate results (Demir and Kisi 2016).

Concerning the exposure dimension of risk, Dutta et al. (2003) proposed a mathematical model to estimate the economic losses of floods; the model was tested using simulations. Lee et al. (2017) estimated the cost of the damage caused by natural events in Korea through regression analysis. Paul and Sharif (2018) used historical information from 1960 to 2016 to evaluate the damage of hydrometeorological disasters in Texas, USA, through statistical forecasting methods. GIS mapping has also been used to estimate the risk exposure (Gain and Hoque 2013). For example, Jonkman et al. (2008) used GIS mapping to estimate the economic loss of floods in the Netherlands. The loss of lives and the possibility to evacuate the population during these events were also considered.

Quantitative methods, among them Multi-Criteria Analysis (MCA), have also been applied to assess vulnerability (Ball et al. 2012). Li et al. (2013) estimated the flood relative vulnerability at the county (city) level in Dongting Lake, China, using disaster system science as theoretical background and the technical support of GIS and Remote Sensing (RS). The flood relative vulnerability was calculated based on flood damage data, physical and socioeconomic statistical data of 23 districts across several periods. The flood assessment of spatiotemporal vulnerability allows the evaluation of the efficiency of regional disaster systems and the identification of appropriate actions to reduce vulnerability (Koks et al. 2015). In Mexico, Krishnamurthy et al. (2011) built a vulnerability index at the household level for the case of hurricanes. The methodology applied includes GIS mapping and statistical analysis of survey and secondary data. Poor infrastructure and scarce community' capabilities to cope with unsafe housing were identified as critical vulnerability sources.

To improve risk assessment, and particularly the evaluation of vulnerability, Giupponi et al. (2013) outline the KULTURisk framework, which considers the direct and indirect social costs of disasters and individuals' social capabilities and disadvantages. Four dimensions integrate the framework; they are hazard, vulnerability, exposure, and risk, where the outcome of the first three determines the last one. Social indicators such as percent of single-parent households, percent of disabled residents, percent of the isolated population, and unemployment rate are suggested as specific indicators to evaluate the exposure or potential harm of people, assets, and economic activities. In addition to the direct tangible indicators, intangible costs related to psychological distress and damage to cultural heritage are considered. Therefore, risk assessment includes an objective valuation of economic loss but also individual perceptions and social representation. Unfortunately, information about the indirect costs of risk requires data collection from individuals who have previously suffered the effects of a disaster to estimate their risk perceptions, coping, and adapting behaviors.

To summarizing, disaster risk has been assessed as the potential economic, social, and environmental consequences of a natural event. However, as Carreño et al. (2005) noticed, risk indexes have been biased toward economic loss. A multidisciplinary perspective for risk assessment requires considering the geophysical, environmental risk (hazard) and its financial damage and the capacity of inhabitants to respond to hazards. Particularly, the social fragility and the poor resilience of a region increase its intrinsic susceptibility and reduce its response capability, thus enhancing the probability of loss (Koks et al. 2015). Thus, once the hazard (probability, intensity, and length) is predicted (GIS and meteorological forecasting models are the most suitable approaches), assessing vulnerability is the next step (Cardona et al. 2008).

Although several quantitative and qualitative approaches have been used to assess risk, qualitative and semi-quantitative methods are the most widely used to evaluate flood vulnerability because of their simplicity to use and applicability despite data scarcity. One of the most popular semi-quantitative methods is AHP, a multi-criteria methodology that has been widely used in several areas, including humanitarian logistics (Sandeep et al. 2014). Carreño et al. (2005) and Wang and Ling (2011) used AHP to take advantage of the knowledge and experience of decision-makers to compute vulnerability indexes of flood hazards. The relative importance (weights) of the vulnerability indicators is computed by asking experts to make pairwise comparisons between indicators. Once indicators are weighted and aggregated, a ranking of alternatives that can be areas, cities, counties, states, or countries is generated. This allows identifying the most vulnerable entities that will need more resources to deal with disasters and extra efforts to improve their resilience.

We selected AHP as the multiple-criteria approach for building a vulnerability index. AHP expresses a complex problem into a hierarchical structure to weight the importance of several criteria and compute a ranking of alternatives. In this study, the vulnerability dimensions are multi-dimensional variables measured through several indicators proposed in the disaster management literature. Selecting the most appropriate indicators is a complex process that may have undesired consequences such as redundancy and unnecessary indicators. The use of a reduced number of key indicators simplifies assessing vulnerability while reducing the effort and use of data resources (Koks et al. 2015). Confirmatory Factor Analysis (CFA), a latent multivariate statistical method, was applied to identify and select the critical social and economic indicators to be used in the computation of the vulnerability index (Brown 2015). The integration of CFA, FAHP and a clustering technique (k-means) provides a systematic approach that decision-makers can use to identify which regions are most vulnerable to floods and require reinforcement of the preparedness operations of humanitarian logistics.

17.3 Methodology

The first stage of the methodology was identifying the indicators associated with the three vulnerability dimensions: hazard, exposure, and preparedness. Because vulnerability is a complex concept without a standardized definition, we conceptualize the term as the characteristics of a community (state) that reduce the capabilities of its inhabitants to deal with hazards and increases the threat to the regional economy and infrastructure. Based on this definition, we proposed exposure comprises two subdimensions, social and economic. The preparedness dimension was incorporated to consider if the community has the public infrastructure required to provide aid in case of a disaster. Although these resources are mainly public, they are considered part of the community's assets.

The process of selecting and assigning indicators to each of the vulnerability dimensions was completed based on a systematic review of the literature. The following studies were the main references used: Cardona (2005), Cardona et al. (2008), Carreño et al. (2005), Fekete (2009), Giupponi et al. (2013), Koks et al. (2015). We verified if the recommended indicator is available in official Mexican sources and, if it was the case, it was included. Also, indicators that describe the social and economic conditions that increase a community's vulnerability in case of hydrometeorological disasters and are mentioned in several studies comprised the set of selected indicators.

Table 17.1 lists the indicators, including a brief description of each one, its measurement units, and the data source where the indicator is located. Most of the indicators are reported in the National Network of Metadata of the Institute of Statistics and Geography (INEGI 2020), an open platform to access the information catalogs with the population and economic information of the country. Specific links used to retrieve the indicators are reported in Appendix 17.A. Historical data (2000–2015) about the frequency and the economic damages caused by hydrological events in Mexico were obtained from the CENAPRED (Centro Nacional de Prevención de Desastres) databases (CENAPRED 2020).

Table 17.1 Description of vulnerability indicators

Vulnerability Dimension	Indicator	Description	Data source
Hazard			
	Cost of deaths	Cost of human losses (MXN) = average remaining productive life of 100 individuals x average median income x number of deaths caused by events	Sugiyantoa and Santib (2017) CENAPRED
	Economic loss	Impact of damages and material losses (millions of MXN)	CENAPRED
	Frequency	Average number of hydrometeorological events per year during 2000–2015	CENAPRED
Exposure			
Social exposure			
	Vulnerable population	Population over 65 years old and less than 5 years	INEGI
	% Women	Percentage (%) of women	INEGI
	Households with more than seven people	Number of homes inhabited by more than 7 people	INEGI
	Median Income	Median nominal (MXN) income of the employed population aged 15–29 years old	INEGI
	Illiteracy	Percentage (%) of illiterates of the total population aged over 15 years old	INEGI
	Population with basic education	Percentage (%) of the total population who has completed High School	INEGI
	Population with low income	Percentage (%) of the employed population over 15 years old with a wage below 2.5 USD	INEGI

(continued)

Table 17.1 (continued)

Vulnerability Dimension	Indicator	Description	Data source
	Gini index	Statistical measure (0–1 or equivalently 0–100%) of the distribution of income across income percentiles in the population representing the inequality of a nation or in this case per state	INEGI
	People living in poverty	Percentage (%) of the population living in poverty	INEGI
Economic			
	Primary activities	Annual average variation rate of the contribution of the primary sector to the state Gross Domestic Product	INEGI (quarterly indicator of state economic activity)
	Manufacturing activities	Annual average variation rate of the contribution of the manufacturing sector (secondary activities) to the state gross domestic product	INEGI (quarterly indicator of state economic activity)
	Tertiary activities	Annual Average Variation Rate of the contribution of the tertiary sector to the state Gross Domestic Product	INEGI (quarterly indicator of state economic activity)
	Area	The area affected by hydrometeorological events per state (m^2)	CENAPRED
	FDI	Foreign Direct Investment (millions of USA)	INEGI
	Inhabited Houses	The number of inhabited houses per state	INEGI
	Economic Units	Number of business (economic units) in all economic sectors: commerce, services, tourism and industry by state	INEGI
Preparedness			
	Number of beds	Number of hospital beds per 10,000 habitants	INEGI

(continued)

Table 17.1 (continued)

Vulnerability Dimension	Indicator	Description	Data source
	Unemployment rate	Unemployment rate (%) per state	INEGI
	Telephone lines	Number of fixed telephone lines	INEGI
	Length of the road network	Length (km) of the road network per state	INEGI
	Number of Medical Doctors	Number of medical doctors (MD) in public health institutions per 10,000 habitants	INEGI
	Number of shelters	Number of shelters in case of contingency	CIVIL PROTECTION
	Houses without basic services	Percentage of houses (%) without basic services (water, electricity, drainage)	INEGI
	Insecurity perception	Percentage (%) of the population over 18 years old with insecurity perceptions (crime)	INEGI
	Police trust	Percentage (%) of the population over 18 years old who trust the police	INEGI

Note The specific links used to retrieve the indicators are reported in Appendix 17.A

The second stage of the methodology was to assign the indicators to the three proposed vulnerability dimensions. A hierarchy describing the components of these dimensions and the indicators that unveil each one was built. Figure 17.1 depicts the hierarchy. The three criteria at the first level of the hierarchy are complex criteria that cannot be directly observed and measured. Therefore, we conceptualize them as latent variables (criteria in the context of AHP), which can be inferred from a set of indicators (Brown 2015; Fekete 2009).

The third stage of the methodology was the application of CFA to validate the structure of the proposed index and eliminate redundant and non-critical indicators. The depuration strategy was based on the size of the factor loadings. Indicators with standardized factor loadings below 0.5 indicate that the observed indicator explains a small amount of the latent variable variance (0.52 = 25%). Therefore, indicators with low factor loadings were judged non-critical or highly correlated with other indicators (redundancy). The larger the factor loading, the larger the indicator's contribution in explaining the variance of the latent criterion.

The factors identified can be used for the computation of the composite vulnerability index by using the factor scores as the "value" of the latent criterion (Fekete

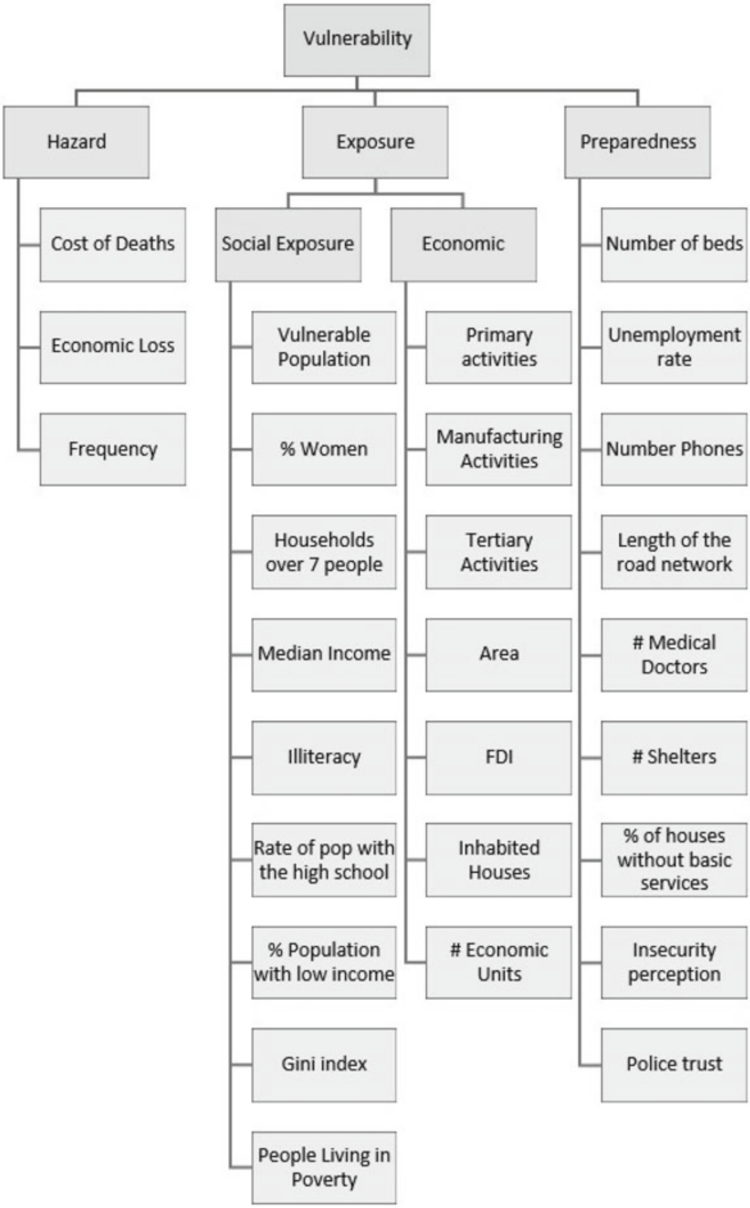

Fig. 17.1 AHP-based hierarchy for vulnerability risk assessment

2009). This is advantageous for using CFA because we do not need to ask DMs (decision-makers) to make pairwise comparisons between indicators, which could be cumbersome and time-consuming. The variance-based structural equation modeling method of partial least squares (PLS) was used to perform the CFA. PLS is a non-parametric method appropriate for working with small samples that relies on bootstrapping to perform statistical tests (Hair et al. 2017). All computations were performed using SMARTPLS3 software.

The fourth stage of the methodology was the application of Fuzzy AHP (FAHP) to compute the vulnerability indexes of each state of Mexico. FAHP is properly suited to handle uncertainty when judging how important is one criterion with respect to others in those situations when criteria are vague and imprecise (Demirel et al. 2008). The application of FAHP requires performing the following steps:

1. Integration of a group of decision-makers that would build or validate the hierarchy and assess the relative importance of one criterion over another. The DMs should be experts who know how the regional conditions are related to the extent of the damage caused by previous hydrological events. In this work, six experts with different viewpoints -three researchers whose area of expertise is humanitarian logistics and three managers or private organizations who have participated in humanitarian logistics projects- integrated the DM group.

   The evaluation and planning of risk mitigation require DMs who are policymakers or disaster managers of official governmental organizations. In the case of Mexico, these authorities are the National Center of Disaster Prevention (CENAPRED) and the Civil Protection System.
2. Construction of individual pairwise comparison matrices where decision-makers compare criterion *i* (e.g., exposure) against criterions *j* (e.g., preparedness) and then express the relative importance of one criterion over the other on a linguistic scale from one to nine. The pairwise linguistic comparisons of the DMs are transformed into triangular fuzzy numbers (TFN) according to the assignment scheme suggested by Balli and Korukoğlu (2009).

   Deffuzing of the fuzzy pairwise comparison matrices is required before the aggregation of the experts' evaluations. We used the synthetic extent value method (EAM) to obtain synthetic extent values corresponding to the relative weights or priorities assigned to the criteria by each DM (Chang 1992).
3. Determination of the dimension weightage is the computation of a group vector of the relative degrees of importance per criterion. This is a critical step because each expert could assign different degrees of importance to each criterion based on his/her background, preferences, and influences. There is no uniform aggregation methodology to weight individual criterion, which in this case corresponds to the three vulnerability dimensions.

Based on the results reported by Castañeda et al. (2020), we applied the weighted geometric mean method combined with the data envelopment analysis method (WGMM-DEA) to aggregate the individual weights to compute a composite index of vulnerability for the 32 states of Mexico. Additionally, we built three additional scenarios by proposing different sets of weights for the three vulnerability dimensions. The proposed weighting schemes were the following:

- Scenario 1. Equal weights for all dimensions (1/3, 1/3, 1/3).
- Scenario 2. The largest importance (weight) is assigned to the exposure dimension, followed by the hazard dimension, and finally, the preparedness dimension (1/3, 1/2, 1/6).
- Scenario 3. The largest importance (weight) is assigned to the exposure dimension and equal weights for the other two dimensions (1/4, 1/2, 1/4).

Because the exposure dimension has two second-order criteria (see Fig. 17.1), the assigned weight was equally distributed between its two components. All FAHP computations were performed in Excel.

In the final stage of the methodology, the unsupervised clustering machine learning algorithm of *k*-means was used to segment the 32 states into clusters with similar degrees of vulnerability. This clustering method has been extensively used in several areas with satisfactory empirical results. The rationale of the algorithm is to find a partition of the alternatives (states), such that the variability between the cluster's centroids is maximized while the variability within the cluster is minimized. Thus, the algorithm identifies the small number of clusters (k) that results in well-separated but homogeneous groups. The algorithm is sensitive to the number of clusters defined. Therefore, a hierarchical clustering algorithm was first applied to identify an initial number of clusters. The clustering computations were performed with the use of the programming language Python 3.8.

17.4 Results

Nineteen out of the original twenty-eight indicators selected to integrate the vulnerability index had standardized factor loadings above 0.5. These indicators were judged critical to assess vulnerability. When using CFA, researchers need to examine the average variance extracted (AVE), which measures the amount of variance captured by a latent variable (criterion) in relation to the amount of variance due to measurement error. According to the Fornell and Larcker criterion, an AVE value larger than 0.50 indicates a sufficient degree of convergent validity, meaning that the latent variable (criterion) explains more than half of its indicators' variances (Fornell and Larcker 1981; Hair et al. 2016).

The latent criterion also must share more variance with their assigned indicators than with indicators of other latent criteria to support discriminant validity. This assures indicators were properly assigned to a specific vulnerability dimension, for example to social versus economic exposure. To support discriminant validity, the squared correlation between the three latent criteria at the first level of the hierarchy in Fig. 17.1, and the squared correlation between the two sub-criteria at the second

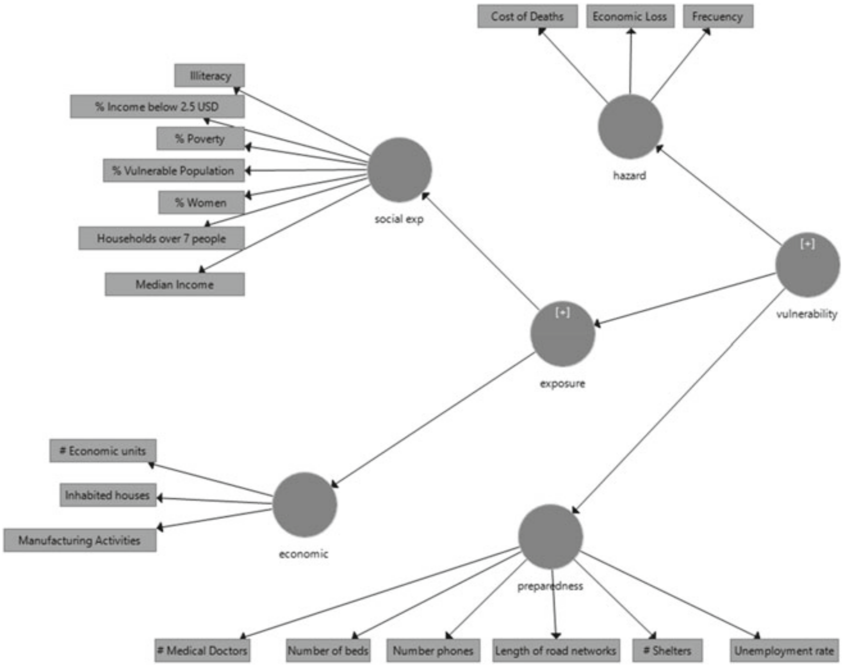

Fig. 17.2 The final structure of the vulnerability index

level, should be lower than the square root of AVE. This was the case, thus supporting the validity of the vulnerability index proposed.

The final structure of the index is described in Fig. 17.2. The numbers reported are the standardized path coefficients which vary from 0 to plus or minus 1. Paths closest to absolute 1 being the most important components of vulnerability, these coefficients are equivalent to the beta weights in regression analysis. By using full bootstrapping with 5000 samples, confidence intervals and tests of significance can be performed. The values between parentheses are the corresponding P-values. All coefficients are highly significant, thus providing evidence of the multi-dimensional structure of the vulnerability construct and the relevance of considering the social dimension.

Then, the group weight vectors were used to compute a composite vulnerability index as Eq. (17.1):

$$\text{Vulnerability of the state} = w_1(\text{hazard}) + w_2(\text{exposure}) - w_3(\text{preparedness}) \tag{17.1}$$

The group weight vector computed by aggregating the individual pairwise comparison matrices stated by the six DMs equals (0.5925, 0.2431, 0.1644). The judgments of the participant DMs, particularly the three humanitarian logistics

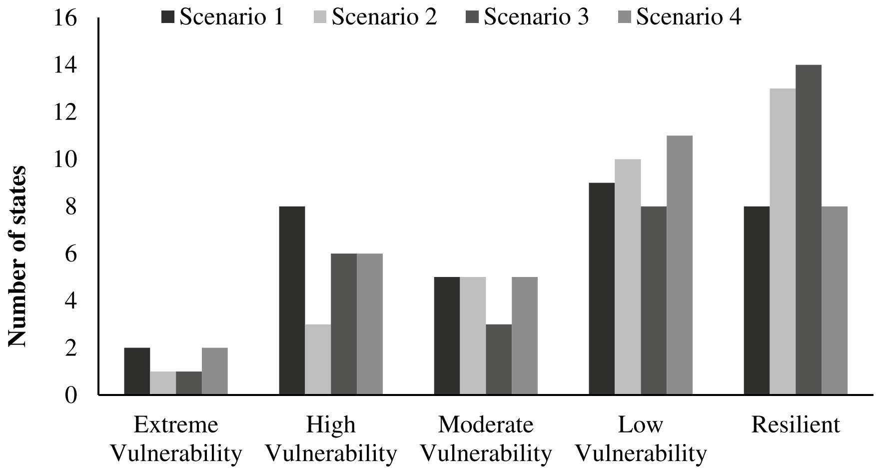

Fig. 17.3 Comparison among scenarios

researchers, are biased toward the hazard dimension, which has been the usual criterion to assess vulnerability as indicated in the literature review section.

Figure 17.3 graphically compares the segmentation results for the four weighing schemes, namely the obtained by asking the group of DMs to evaluate the relative importance of criteria (scenario 4) and the three scenarios that assigned a larger weight to the exposure dimension. In all cases, five clusters resulted in being an appropriate solution, and they were named accordingly with their aggregated scores in each vulnerability criterion or dimension. The size of the vulnerability segments is highly dependent on the weighing scheme. Only one or two states are rated as extremely vulnerable under all scenarios. If the hazard is considered extremely important (scenarios 3 and 4), these states are Guanajuato and Veracruz, but if the largest weight is assigned to exposure, then the extremely vulnerable cluster only includes the State of Mexico. A larger number of states is categorized as lowly vulnerable under scenario 4, which integrates the opinions of actual DMs. This happens because about 60% of the vulnerability contribution score comes from the historical records of economic loss and deaths.

The largest number of states in the resilient segment is obtained under scenario 3, where the exposure dimension has the largest weight and the other two vulnerability dimensions (hazard and preparedness) have the same relative importance. This scenario balances the importance assigned to all vulnerability components, including the two exposure sub-dimensions. Also, under this scenario, the states that scored low in preparedness were acknowledged as highly vulnerable to natural events. Thus, increased prevention actions and better infrastructure that enable a quick response are required to reduce states' vulnerability with low preparedness.

The cluster results obtained using the group vector computed by integrating the DMs opinions are shown in Fig. 17.4. Guanajuato and Veracruz are in the extreme vulnerability segment because they have the largest score in the three indicators

Fig. 17.4 Clustering of Mexican states according to their vulnerability judged by six experts

comprising the hazard dimension: frequency of hydrological disasters (Veracruz) and the most serious recorded economic damage and cost of deaths (both states).

Chiapas, Guerrero, and Tabasco are categorized as moderate vulnerable states from the DMs perspective despite their high social exposure. This assignation is rectified under scenarios 2 and 3, where the largest overall weight (1/2) is assigned to exposure. Something important to emphasize is that the State of Mexico was consistently rated as extremely or highly vulnerable either because of its largest record on economic losses or its high social and economic exposure.

The graph in Fig. 17.5 compares the states accordingly to their overall vulnerability indexes under the four different scenarios. From the graph, noteworthy cases can be identified. For example, the state of Baja California Sur (BCS) is classified as resilient under the perspective of the six DMs because the state's high hazard rate is overly compensated by its low population density and relatively low level of manufacturing activities and inhabited houses. Meanwhile, Queretaro (QUE) is judged moderately vulnerable because of the high economic losses reported for relatively infrequent hydrological events. The composite vulnerability of QUE increases if the weight assigned to the hazard decreases and the weight of exposure increases (scenarios 2 and 3) according to the population and economic growth of the state. A similar situation is observed in the case of Mexico City (CDMEX).

The states that are consistently classified as resilient are Aguascalientes (AGS), Campeche (CAM), Morelos (MOR), and Yucatan (YUC). Meanwhile, the states judged as extreme or highly vulnerable under all scenarios are Guanajuato (GUA), Veracruz (VER), and the State of Mexico (MEX). The more equivalent scenarios

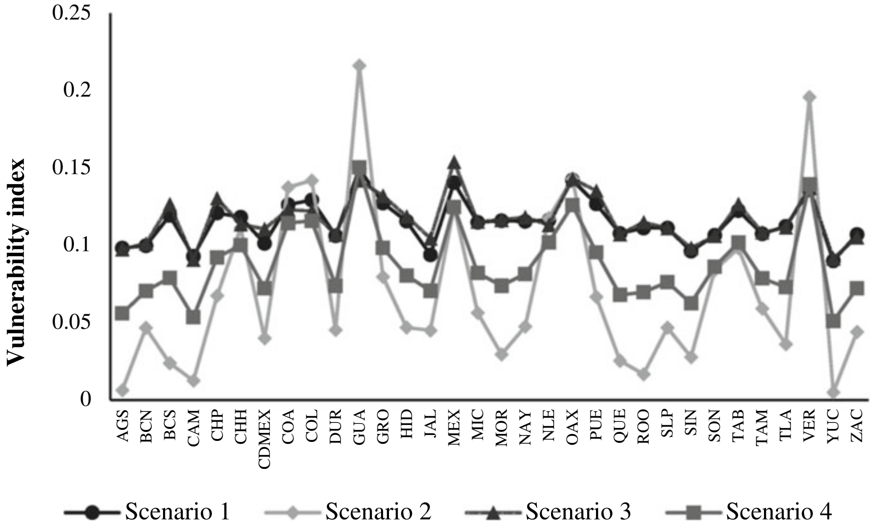

Fig. 17.5 Vulnerability index under different scenarios

are scenario 1 (equal weights to all vulnerability dimensions) and scenario 3 (the largest weight to exposure and equal weights to the other two dimensions). If a larger weight is assigned to a hazard, the clustering results change significantly because the vulnerability related to social exposure and preparedness is minimized.

All states located near the coast have a higher frequency of hydrometeorological events. However, government authorities at all levels (municipal, state, and federal) and Non-Governmental Organizations (NGO's) have been increasing the number of preventive campaigns and enhanced the instruction of the population concerning how to respond in the case of disaster. For example, Sinaloa (SIN) has been consistently reduced their hazard scores and increased their preparedness indicators. Thus, this and other states such as Jalisco (JAL) and Tabasco (TAB) are categorized as fairly vulnerable or even resilient (Sinaloa) under all scenarios.

17.5 Conclusions

Usually, vulnerability indexes have only considered the extent and intensity of disasters. However, to better assess how vulnerable is a region, hazard data must be combined with information concerning the social vulnerability of households and the financial and social resources at hand in case of a disaster. Inhabitants of regions with limited resources may have more potential problems to be privately prepared to face disasters. Given the increasing threat that hydrometeorological events in Mexico represent to the economic activities and the properties and wellbeing of inhabitants, a multidisciplinary approach to vulnerability is commended. The identification of the states of Mexico with the largest exposed population and more socially vulnerable households is relevant to revise and reinforce the risk mitigation plans focusing on the specific vulnerabilities of a region. Additionally, taking into account the social characteristic of a community is relevant to improving the population's abilities to cope with natural hazards.

This study proposes a vulnerability index that considers three main dimensions, hazard, exposure, and preparedness. The exposure dimension considers social and economic vulnerability. The integration of three well-known quantitative methodologies –confirmatory factor analysis, fuzzy AHP, and the clustering method of *k*-means allows the identification of a reduced number of key indicators associated with each of these dimensions. This allows the computation of the suggested composite vulnerability index, which is the basis to categorize the states of Mexico.

Depending on the weighting scheme, states are differently classified. However, the most vulnerable states, either because of their large scores in the hazard or exposure dimensions as well as the least vulnerable states, are consistently identified. Other states, with a large exposed population, are acknowledged as highly vulnerable only if a larger weight is assigned to the exposure (social and economic) dimension. The results of this study show the shortcomings of assessing vulnerability based mainly of hazard information (frequency and associated economic loss). Due to this limited view, states such as Chiapas, Oaxaca, and Guerrero were judged by experts in humanitarian logistics as moderately vulnerable when in the case of a disaster, the expectations are more individuals would be affected and the recuperation of these states will take longer.

Extensions to this study are derived from its limitations. First, only secondary indicators available in open sources were considered. The integration of primary data concerning the degree of preparedness and coping responses of households living in vulnerable areas would result in a more comprehensive index. The use of GIS information to better evaluate the hazard dimension of vulnerability is another venue of research. Including more precise information about the preparedness plans of state governments is also relevant to improve the content validity of the preparedness dimension. Finally, the evaluation of vulnerability at the municipal, city, and regional levels is another topic of research that will contribute to the efficiency of the preparedness and recuperation stages of the disaster management cycle.

Appendix

Appendix 17.A. Links to Databases Containing the Selected Indicators

CENAPRED. Datos abiertos, Secretaria de Gobernación. https://www.gob.mx/cenapred, last accessed 2020/08/01.

INEGI. Indicadores por entidad federativa. https://www.inegi.org.mx/app/estatal/#grafica, last accessed 2020/08/01.

INEGI. Indicadores económicos de coyuntura. https://www.inegi.org.mx/sistemas/bie/, last accessed 2020/08/01.

INEGI. Indicadores de población. https://www.inegi.org.mx/app/tabulados/default.html?nc=602, last accessed 2020/08/01.

INEGI. Indicador trimestral de actividad económica estatal. https://www.inegi.org.mx/temas/itaee/default.html#Herramientas, last accessed 2020/08/01.

INEGI. Red de carreteras por región y entidad federativa (Kilómetros) de Presidencia creado el 2017-11-16 17:45. https://datos.gob.mx/busca/dataset/mexico-prospero-estadisticas-por-entidad-federativa/resource/39222646-6f07-4323-81d3-c1d5ddd798bc, last accessed 2020/08/01.

Protección Civil. Número total de refugios temporales en el país. Disponible en: http://www.proteccioncivil.gob.mx/work/models/ProteccionCivil/Almacen/DCEM/totalesrt.pdf, last accessed 2020/08/01.

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Chapter 18
A Multi-criteria Decision-Making Framework for the Design of the Relief Distribution Routes

Fabiola Regis-Hernández, Angel Ruiz, and Jaime Mora-Vargas

Abstract In the aftermath of a natural disaster, humanitarian aid must be delivered as fast as possible to the affected population to alleviate human suffering and minimize deaths. To this end, humanitarian logistics managers must design an adequate supply chain and organize complex logistic activities. Considerable research efforts have been devoted to elaborating optimization models to help experts make these decisions quickly and effectively. However, available research shows significant drawbacks concerning the integration of qualitative and quantitative models. We, therefore, propose a multi-criteria methodology for designing a relief distribution network that, using the Analytical Hierarchy Process, structures the stakeholders' preferences concerning humanitarian logistics' performance goals, including economic, social, and reliability goals. These indicators are integrated into a quantitative model that aims to maximize the performance of the relief distribution network. A sensitivity analysis is conducted to demonstrate that the proposed methodology helps to find solutions that achieve very good performance with respect to all the considered objectives.

18.1 Introduction

The occurrence and severity of natural and human-made disasters and their impact on the affected populations have continuously increased in the last decade, stressing the importance of humanitarian logistics. The goal of humanitarian logistics is to ensure

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a fast and efficient response to the affected population to minimize the damages in the aftermath of a disaster. Thus, decision-makers must (1) balance adequately a large ensemble of discording goals, such as the control of logistic costs and the maximization of the network coverage, while (2) dealing with several sources of uncertainty, including, among others, the damages to the transportation infrastructures or the demand itself (Hoyos et al. 2015). On the one hand, the presence of several stakeholders with their preferences and goals makes the humanitarian decision-making process a very complex multiple decision-maker, multi-criteria decision-making (MCDM) problem. On the other hand, humanitarian logistics decisions are characterized by a high level of uncertainty. Indeed, in the specific case of natural disasters, infrastructures are usually affected by physical damages, downed trees, or debris accumulation, which makes it difficult, or in some cases impossible, to distribute relief to the affected populations (Horner and Widener 2011). For instance, Vitoriano et al. (2011) claim that the state of the routes in the aftermath of a disaster impacts the reliability of logistic decisions; the researchers refer to reliability as the probability of successfully performing the planned activities. Therefore, increasing the reliability of the humanitarian aid distribution network becomes an important objective in the supply chain design process along with other well-known relief distribution goals, such as minimizing the number of deaths and injured people and mitigating the suffering of the affected population.

In this context, this chapter presents a multi-criteria decision support framework to ensure that all the stakeholders' goals and objectives, including the one related to the reliability of the distribution process, are adequately considered in the design of the distribution process. A systematic literature review (SLR) was performed to identify the goals proposed in previous scientific works. Then, a multi-criteria framework is proposed to integrate the selected goals and objectives into quantitative optimization models. The application of the proposed framework is illustrated through an academic example introduced in Naji-Azimi et al. (2012), and that uses the so-called "satellite distribution centers" to deliver relief to people in need. The problem seeks to decide which satellite distribution centers to open and how to supply them so that logistic cost is minimized and people in need do not have to travel more than a specified distance to reach a satellite distribution center. Finally, a sensitivity analysis is conducted to support a discussion regarding the possible trade-offs between the multiple goals pursued by the decision-makers.

The chapter is organized as follows. Section 18.2 presents a systematic review of previous multi-criteria contributions related to the relief distribution problem. Section 18.3 explains the multi-criteria framework. In Sect. 18.4, a case study is introduced. Section 18.5 presents the numerical experiments. Finally, the conclusions and future research works are performed to finish the chapter in Sect. 18.6.

18.2 Literature Review

In the last decade, several quantitative and qualitative approaches have been proposed to tackle the challenges of the relief distribution problem in the aftermath of a natural or human-made disaster. However, the discordant nature of the pursued goals and the lack of consistency of stakeholders' priorities have considerably diminished the ability of those approaches and their solutions to be used in practice. This section provides a systematic review (SLR) of the main contributions of multi-criteria decision-making approaches applied to humanitarian aid distribution. An SLR seems particularly suitable for the purpose of this research. Indeed, since we intend to inspire by the goals reported in the literature to form a relevant multi-criteria objective for a further optimization formulation, a replicable and non-biased methodology is required.

We first present the research methodology, and then we analyze the results of our research concerning the nature of the considered objectives. We refer the reader interested in more general aspects of humanitarian aid distribution such as descriptions, or problem classifications, to previous literature reviews (Altay and Green 2006; Anaya-Arenas et al. 2014; Galindo and Batta 2013; Hoyos et al. 2015).

18.2.1 Systematic Review

This subsection describes the research methodology briefly. The systematic review encompassed the following three steps.

Identification research. This stage aims to set the goals and motivations of the literature review. In our case, we intend to identify the criteria proposed in previously published papers and quantify their relative importance. To this end, we searched the literature for contributions in which multi-criteria and multi-objective decision-making approaches were applied to the network design and relief distribution problems in humanitarian logistics related to the aftermath of a disaster. Moreover, we aim to compare the trend that contributions related to single-objective and multi-objective approaches present.

Material collection. To conduct such broad research, we submitted a query containing the keywords "multi-criteria", "multi-objective", "disaster", "humanitarian", "relief", "response", and "distribution" to the ISI Web of Knowledge © and Scopus © databases.

Inclusion aspects. The literature review considered analytical and empirical academic publications, such as peer-reviewed papers, conference proceedings with full papers, books, and dissertations. The search was limited to the contributions within the Operational Research, Transportation, and Industrial Engineering categories. Also, because contributions to the field included more than one objective or criteria, started to appear in the late 1990s (Altay and Green 2006), the search was limited to contributions published since 1995. Additionally, to reflect our interest in the response stage, the selected contributions were focused on this stage and limited to the network design, transportation, and relief distribution problems. Furthermore, given a large number of papers in the response stage context, we limited our search to papers that considered natural, sudden-onset disasters only (Van Wassenhove 2006).

Exclusion aspects. Manuals and governmental or military reports were excluded from this research. Articles solely related to the pre-positioning or warehousing problems and articles that were not written in English were also excluded from the research.

This search produced a total of 1,063 documents found in the mentioned databases. In order to refine the results, duplicates were eliminated, and a second filter was applied to ensure that the remaining documents met the inclusion criteria previously presented. As the articles were reviewed, other papers cited by them appeared to be pertinent to the search and thus were included. A total of 71 papers that met the inclusion and exclusion criteria were included in the study. These 71 papers constituted the knowledge base for the forthcoming analysis.

18.2.2 Analysis of the Managers' Criteria

Efforts devoted to the development of modeling approaches to support relief transportation in the aftermath of a disaster are overgrowing, mostly in response to the need for models that incorporate goals for better representing real settings (Anaya-Arenas et al. 2014; Galindo and Batta 2013; Luis et al. 2012). Indeed, determining the appropriate objective or set of objectives remains one of the main challenges in humanitarian relief distribution. As shown in Tables 18.1, 18.2, 18.3 and 18.4, although the minimization of the overall costs is one of the most popular goals, this is not the case for all organizations and contexts. In particular, the level of service (minimization of the unmet demand) and the maximization of equity have been included in recent contributions as the main goals of non-profit organizations that provide humanitarian relief.

Several efficiency-oriented performance criteria that aim to minimize overall costs (Ferrer et al. 2016; Gralla et al. 2014; Ortuño et al. 2011; Ransikarbum and Mason 2016; Vitoriano et al. 2009; Wang et al. 2014) or minimize the number of required vehicles (Najafi et al. 2013) have been proposed. Efficacy is also one of the most common goals pursued by decision-makers dealing with the distribution of humanitarian aid. Efficacy has been approached by several objectives, such as transportation time minimization (Ferrer et al. 2016; Gralla et al. 2014; Liberatore et al. 2014; Rekik et al. 2013), traveled time minimization (Ortuño et al. 2011; Wang et al. 2014), and maximization of the satisfied demand (Gralla et al. 2014; Liberatore et al. 2014; Najafi et al. 2013; Ransikarbum and Mason 2016).

Recently the equity, which refers to the ability to satisfy comparably the need of all the populations (Huang et al. 2012, 2013), along with the notion of fairness (Anaya-Arenas et al. 2013, 2018; Ferrer et al. 2016; Gralla et al. 2014; Ransikarbum and Mason 2016), which refers to guaranteeing equity of the amount of relief received

Table 18.1 Single-objective models proposed to tackle relief distribution problems

References	MC	MTD	MPC	MLA	MESD	MV	MUD	MRT	MTT	MTR
Haghani and Oh (1996)	*									
Viswanath and Peeta (2003)	*									
Barbarosolu and Arda (2004)	*									
Özdamar et al. (2004)							*			
De Angelis et al. (2007)							*			
Horner and Downs (2007)	*									
Jia et al. (2007)							*			
Sheu (2007)								*		
Yi and Özdamar (2007)							*			
Hsueh et al. (2008)									*	
Haghani et al. (2009)							*			
Horner and Downs (2010)	*									
Ben-Tal et al. (2011)	*									
Görmez et al. (2011)		*								
Gu (2011)								*		
Berkoune et al. (2012)									*	
Naji-Azimi et al. (2012)		*								
Noyan (2012)										*
Özdamar and Demir (2012)									*	
Anaya-Arenas et al. (2018)					*					
Rodríguez-Espíndola et al. (2018)	*									
Zanganeh et al. (2019)								*		
Gao (2019)									*	

MC: Min. Costs; **MTD**: Min. Travel Distance; **MPC**: Min. Path Complexity; **MLA**: Min. Latest Arrival; **MESD**: Max. Equity of Satisfied Demand; **MV**: Min. Vehicles; **MUD**: Min. Unmet Demand; **MRT**: Min. Response Time; **MTT**: Min. Traveled Time; **MTR**: Min. Travel Reliability

Table 18.2 Multi-objective models proposed to tackle relief distribution problems

References	MC	MTD	MPC	MLA	MESD	MV	MUD	MRT	MTT	MTR
Haghani (1997)	*							*		
Barbarosoglu et al. (2002)	*							*		
Tzeng et al. (2007)	*						*	*		
Yi and Kumar (2007)							*	*		
Balcik and Beamon (2008)	*						*			
Campbell et al. (2008)	*			*						
Zografos and Androutsopoulos (2008)	*									*
Lin et al. (2009)							*	*	*	
Vitoriano et al. (2009)	*									*
Yuan and Wang (2009)			*						*	
Zhu and Ji (2009)	*						*			
Adıvar and Mert (2010)	*									*
Chern et al. (2010)								*		*
Mete and Zabinsky (2010)	*						*		*	
Nolz et al. (2010)	*	*		*			*			
Rawls and Turnquist (2010)	*						*			
Tatham et al. (2010)	*							*		
Campbell and Jones (2011)	*							*		
Horner and Widener (2011)	*						*			
Lin et al. (2011)	*				*		*			*

MC: Min. Costs; **MTD**: Min. Travel Distance; **MPC**: Min. Path Complexity; **MLA**: Min. Latest Arrival; **MESD**: Max. Equity of Satisfied Demand; **MV**: Min. Vehicles; **MUD**: Min. Unmet Demand; **MRT**: Min. Response Time; **MTT**: Min. Traveled Time; **MTR**: Min. Travel Reliability

by people in need, have been identified as key goals for managers dealing with relief distribution. Finally, the risk (Hong et al. 2015; Liberatore et al. 2014; Ortuño et al. 2011; Vitoriano et al. 2009) and the reliability (Ferrer et al. 2016; Liberatore et al. 2014; Vitoriano et al. 2009; Wang et al. 2014) have also been indicated as major concerns in humanitarian logistics.

This literature review confirms that identifying and considering objectives and goals closer to practical needs is one of the main researchers' concerns. To this end, stakeholders' preferences (quantitative and qualitative) must be translated and integrated into homogeneous models to produce balanced solutions. Moreover, an

Table 18.3 Multi-objective models proposed to tackle relief distribution problems (cont.)

References	MC	MTD	MPC	MLA	MESD	MV	MUD	MRT	MTT	MTR
Ortuño et al. (2011)	*								*	*
Vitoriano et al. (2011)	*				*		*		*	*
Zhan and Liu (2011)							*		*	
Cantera (2012)					*		*	*	*	
Huang et al. (2012)					*			*	*	
Tricoire et al. (2012)	*						*			
Rottkemper et al. (2012)	*						*			
Wohlgemuth et al. (2012)						*			*	
Anaya-Arenas et al. (2013)	*				*		*			
Clark and Culkin (2013)	*					*	*			*
Bozorgi-Amiri et al. (2013)	*						*		*	
Najafi et al. (2013)						*	*			
Rekik et al. (2013)							*		*	
Zhang et al. (2013)		*							*	
Abounacer et al. (2014)	*						*		*	
Barzinpour and Esmaeili (2014)	*						*			
Battini et al. (2014)	*					*	*		*	
Gralla et al. (2014)	*				*		*		*	
Liberatore et al. (2014)				*			*			*
Rath and Gutjahr (2014)	*						*			

MC: Min. Costs; **MTD**: Min. Travel Distance; **MPC**: Min. Path Complexity; **MLA**: Min. Latest Arrival; **MESD**: Max. Equity of Satisfied Demand; **MV**: Min. Vehicles; **MUD**: Min. Unmet Demand; **MRT**: Min. Response Time; **MTT**: Min. Traveled Time; **MTR**: Min. Travel Reliability

increasing trend of multi-objective approaches can be noticed (see Fig. 18.1), leading in most cases to consider conflicting multiple objectives simultaneously in relief distribution. Thus, adapted multi-objective approaches that can address various objectives and preferences of stakeholders must be designed to support managers' decisions to balance managers' multiple goals and specific preferences.

Table 18.4 Multi-objective models proposed to tackle relief distribution problems (cont.)

References	MC	MTD	MPC	MLA	MESD	MV	MUD	MRT	MTT	MTR
Rennemo et al. (2014)	*							*		
Wang et al. (2014)	*								*	*
Edrissi et al. (2015)		*					*	*		
Hong et al. (2015)	*						*			
Ferrer et al. (2016)	*				*				*	*
Ransikarbum and Mason (2016)	*				*		*			
Mishra et al. (2017)							*		*	
Sahebjamnia et al. (2017)	*						*	*		
Gao and Lee (2018)	*								*	
Mishra et al. (2018)							*		*	
Sanci and Daskin (2019)	*						*			

MC: Min. Costs; **MTD**: Min. Travel Distance; **MPC**: Min. Path Complexity; **MLA**: Min. Latest Arrival; **MESD**: Max. Equity of Satisfied Demand; **MV**: Min. Vehicles; **MUD**: Min. Unmet Demand; **MRT**: Min. Response Time; **MTT**: Min. Traveled Time; **MTR**: Min. Travel Reliability

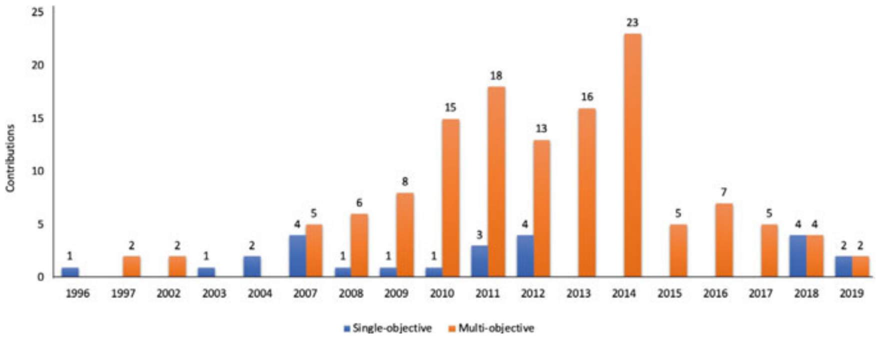

Fig. 18.1 Literature review

18.3 A Multi-criteria Framework to Support Decision-Making in the Context of Relief Distribution

This section presents a multi-criteria methodology for translating multiple and heterogeneous expectations and stakeholders' preferences concerning humanitarian supply chain performance into quantitative values to further integrate into an optimization model. The proposed framework (see Fig. 18.2) contains three main phases: (1) criteria identification, (2) multi-criteria evaluation, and (3) optimization and sensitivity analysis. Although the combination of MCDM and optimization methods have

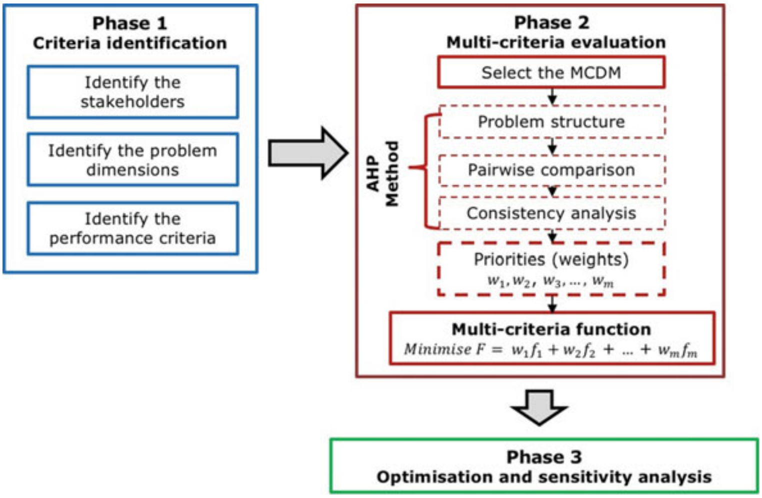

Fig. 18.2 Proposed framework

been applied before, our approach offers an effective and efficient way to address various relief distribution problems, specifically those related to logistics activities.

Various approaches and methods have been proposed in the literature to achieve several goals at the same time. Two strategies and a third one that results from the combination of them are possible. The first strategy is to use MCDM approaches to identify and evaluate stakeholders' preferences and goals. By doing so, it is possible to produce a set of weights that represent the relative importance of the considered criteria, and that will be used to elaborate a coherent multi-objective function to be optimized (Akhtar et al. 2012; Gralla et al. 2014). In the second strategy, it is assumed that these weights are not known in advance. Therefore, solutions are produced for several combinations of values, and stakeholders analyze the proposed solutions and decide which one to implement. Although this second strategy does not require an MCDM phase, the number of combinations to explore may become very large, and there is no guarantee that stakeholders will agree on the solution to implement (Liberatore et al. 2014; Najafi et al. 2013; Ortuño et al. 2011; Ransikarbum and Mason 2016; Rekik et al. 2013; Vitoriano et al. 2009). Finally, a combined strategy is also possible. Indeed, an MCDM phase may provide a first approximation of reasonable weights for the multi-objective function. Later, a sensitivity analysis of these values allows decision-makers to explore a reduced set of potential solutions (Ferrer et al. 2016).

18.3.1 Phase 1. Identification of Goals, Criteria, and Performance Indicators

The first phase aims to identify the stakeholders' goals and preferences. Indeed, all the actors in a humanitarian situation would undoubtedly agree that their goal is to mitigate the needs of the affected people. However, each stakeholder will be more or less sensitive to the different aspects, including efficacy, efficiency, and level of service, and therefore will promote different lines of action. Consequently, a structured process encompassing generic and specific data collection must select applicable and satisfactory criteria. Generic data collection aims at identifying potential and consistent criteria. To this end, international standards and reports from government agencies, non-governmental organizations, and scientific literature are revealed as the most valuable sources.

On the other hand, specific data collection aims to reach stakeholders' agreement on the goals and criteria to be pursued. The literature proposes various techniques to select the main criteria in a consensual or agreed manner. Among them, the Delphi survey, the Nominal Group technique, consensus conferences, and the TRIAGE technique (Gervais and Pépin 2002; Lamontagne et al. 2010) have been successfully used in different contexts to help a team of experts or stakeholders resolve differing views or opinions. Finally, during a structured discussion process, the experts select a given number of criteria to be used in Phase 2.

18.3.2 Phase 2. Multi-criteria Evaluation

The purpose of Phase 2 is to assess and quantify the relative importance of the selected criteria. For this purpose, the Analytic Hierarchy Process (AHP), a well-known MCDM method, was proposed because of its flexibility and ability to handle experts' imprecise judgment to prioritize the stakeholders' preferences. This method assesses the relative importance of the criteria and alternatives and translates subjective judgments into relative weights of importance (Saaty 1980). Recently, fuzzy logic has been used to accept semantic evaluations to handle the associated uncertainties in mapping the decision maker's qualitative and quantitative judgments, leading to a new MCDM methodology referred to as Fuzzy-AHP (Abbasgholizadeh Rahimi et al. 2016). Nonetheless, since our research will not rely on experts' opinions but on quantitative analysis of the literature, the AHP methodology will be applied.

The AHP decomposes the problem hierarchical. The overall decision objective is at the top, and the criteria, sub-criteria, and decision alternatives are at each descending level of the hierarchy (Dolan et al. 1989; Partovi et al. 1990). Decision-makers compare each factor with all the other factors (at the same level of the hierarchy) using a pairwise comparison matrix to determine each factor's weight or relative importance. The AHP contains three main steps, as shown in Fig. 18.2. The first step refers to structuring the problem. In this step, a hierarchy is designed based on the characteristics of the problem so that the first level represents the goal to be achieved, the second level represents the performance criteria, and the third level presents the alternatives of the problem. The second step consists of the pairwise comparison, in which experts compare the relative importance of each pair of considered criteria according to their preferences. A consistency analysis is performed in the third and last step, and the relative weights are generated.

18.3.3 Phase 3. Formulation of the Multi-criteria Objective Function and Model

The third phase of the multi-criteria framework aims to formulate a model (for example, a mathematical model or a simulation model) representing the situation under study. All the problem constraints, including limitations on the available resources, will be considered, and a set of decision variables is proposed. The goal of the formulation is to identify the values for the decision variables that maximize (or minimize) one or several objectives or utility functions that should quantify the stakeholder's wishes. So, a crucial part of this process is to ensure a strong consistency between what stakeholders expect from the distribution network and how the proposed decision variables influence the network to achieve the expected results. In other words, coherency analysis aims at validating how alternative decisions impact the performance of the supply chain under study.

18.4 Case Study

The case study considered here is inspired by the so-called Satellite Distribution Centres (SDC) problem proposed in Naji-Azimi et al. (2012), which has been extended to encompass aspects related to the risk and, in particular, the uncertainty regarding the state of the infrastructures. Naji-Azimi et al. (2012) proposed a two-echelon aid distribution network with a single depot, a set of demand points representing groups of the affected population, and an ensemble of potential locations in which SDCs can be deployed. SDCs are light and mobile installations to deliver or distribute humanitarian aid. Since the affected people must walk to reach these SDCs, they need to be located so that the distance between any demand point and its closet SDC will be lower than a given limit. On the other hand, it is assumed that a limited number of people are available to operate the SDCs, thus, to limit their number and to restore the logistics infrastructure, the cost and the repairing efforts (time) of such activities are dependent on the actual damage suffered by the routes and facilities. Finally, it is also assumed that facilities and routes are unavailable at the time that repair or maintenance operations are carried out on the SDCs. The following paragraphs illustrate how the proposed framework applies to the academic case study.

18.4.1 Phase 1. Identification of Goals, Criteria, and Performance Indicators

As explained in the previous section, generic and specific data collection must adequately identify and select performance measures that may suit stakeholders' goals and objectives. In the present case, we only used generic data to identify potential goals and objectives because we did not have access to real stakeholders in a real situation. We analyzed our systematic literature review results to identify the most common objectives in the related literature. Based on the analysis, we concluded that cost minimization (28.26%), unmet demand (27.17%), travel time (15.22%), and response time (13.04%) are the most pursued goals. On the other hand, it is worth mentioning that risk minimization or equity criteria are not yet among the most favored performance criteria in humanitarian logistics supply chains (5.43% and 4.35%, respectively). However, the number of works considering these two criteria is increasing rapidly in recent years.

According to the performance criteria to be evaluated, we classified the objective functions into three groups: economic, social, and reliability. Finally, to measure the performance criteria, performance indicators or "proxies" were proposed. Because the economic performance criterion is based on all the costs involved, we decided to have one economic indicator (C1_I1). In contrast, due to their heterogeneous nature, the social criterion is represented by two performance indicators, where coverage and equity cannot be unified in one term (C2_I1 = coverage and C2_I2 = equity). Similar to the social impact, two performance indicators were proposed (C3_I1 = reactiveness and C3_I2 = risk). The performance criteria and their performance indicators are described in Table 18.5, where the relationship between the performance criteria and the performance indicators is presented and a short description of each performance indicator.

18.4.2 Multi-criteria Evaluation

This step seeks to translate stakeholders' qualitative preferences into quantitative weights used in a mathematical optimization model. To illustrate this phase and consider that we did not have access to stakeholders involved in real situations, we required five researchers from the Université Laval (Québec, Canada) with expertise in the design of humanitarian logistics networks. From here and after, we will refer to these five academics as stakeholders one to five (Sk1,..., Sk5). We proposed the set of objectives selected in Phase 1 to all the stakeholders, and we required each of

Table 18.5 Performance criteria and performance indicators relationship

Criterion	Indicators	Description
Economy	Costs	It refers to all the costs incurred for the relief distribution
Society	Coverage	The need to reach major population groups facing life-threatening risk wherever they are
	Equity	Refers to which all recipients receive comparable service. In this case, it will be evaluated as a satisfying percentage for each demand point
Reliability	Reactiveness	It is usually represented by the time it takes to achieve its purpose. It measures the quick and adequate response
	Risk	It is a deterministic value obtained from prior disasters. It concerns the infrastructure damage and the risk it represents for reliable aid delivery

them to compare the importance of each objective with respect to the others. To this end, and based on the AHP, we structured the problem as shown in Fig. 18.3.

Also, we adapted the linguistic scale in Saaty (1980) so that, for every two criteria, the expert selects the word in the scale that he considers better qualifies their relationship. Table 18.6 illustrates the scale associates with each word with a numerical value between 1 and 9.

Using the linguistic comparisons produced by each expert, a pairwise matrix containing RI_{ij}, the relative importance of objective *i* over *j* of each objective, can be obtained. For example, Sk1 believes that objective C3_I2 is very strongly more important than C2_I2. Therefore, the cell (C3_I2, C2_I2) in his pairwise matrix takes the value 7, and, inversely, the cell (C2_I2, C3_I2) takes the value 1/7. Table 18.7 reports the pairwise matrix produced by Sk1.

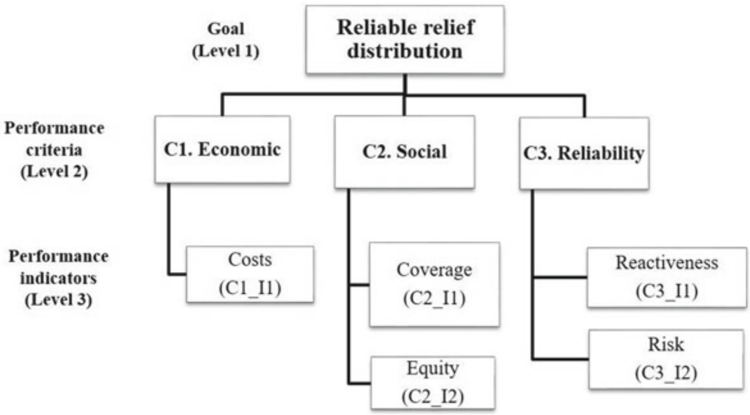

Fig. 18.3 Proposed hierarchy for a reliable aid distribution

Table 18.6 Linguistic scale to perform a pairwise comparison between criteria

Indicator "x" is …than indicator "y"	Numerical value
Equally important	1
Moderately more important	3
Strongly more important	5
Very strongly more important	7
Extremely more important	9

Table 18.7 Linguistic scale to perform pairwise comparison between criteria

Indicator	C1_I1	C2_I1	C2_I2	C3_I1	C3_I2
C1_I1	1	9	5	5	7
C2_I1	1/9	1	1/7	1/9	1
C2_I2	1/5	7	1	1	1/7
C3_I1	1/5	9	1	1	7
C3_I2	1/7	1	7	1/7	1

Once the pairwise matrix for each stakeholder is developed, the eigenvalue for each performance indicator is obtained to produce a set of weights that represents. According to Saaty (1980), the relative importance that each stakeholder gives to each indicator. Finally, the preferences of all the stakeholders must be integrated into a single set of weights. However, because in most real cases, not all the stakeholders have the same experience, expertise, or credibility, they receive a specific numerical value that indicates the weight or importance of their opinions on the group decision. Since we aim to show the application of the methodology, we assume a different responsibility of the stakeholders across, in our academic case, we assign arbitrary weights 0.05; 0.15; 0.2; 0.25; 0.35 to stakeholders one to five, respectively (see Table 18.8). Therefore, according to the stakeholders' opinions considered in this example, distribution risk is the most important criterion, with a weight of 47%;

Table 18.8 Group-Multi-criteria analysis

	Stakeholder and his/her assigned weight					
Criterion	Sk1 w1 = 0.05	Sk2 w2 = 0.15	Sk3 w3 = 0.20	Sk4 w4 = 0.25	Sk5 w5 = 0.35	Final (%)
Costs	0.037	0.756	0.722	0.647	0.137	3
Coverage	0.033	0.162	0.203	0.089	0.314	20
Equity	0.193	0.062	0.035	0.127	0.376	11
Reactiveness	0.181	0.017	0.031	0.132	0.171	19
Risk	0.553	0.002	0.007	0.002	0.001	47
Sum	1.000	1.000	1.000	1.000	1.000	100

coverage (demand satisfaction) is the second most important, with a weight of 20%; and reactiveness, which is related to the time until the vehicle delivers the supplies at each point, is the third one, with a weight of 19%. Finally, equity in the relief delivery and costs are the less important criteria for the consulted stakeholders, as they receive relative weights of 11% and 3%, respectively. Table 18.8 summarizes the results produced by the multi-criteria analysis.

18.4.3 Phase 3. Formulation of the Multi-criteria Objective Function and Model

Once the performance indicators have been evaluated according to the stakeholders' preferences, they can be formulated as a multi-objective function, whose general form is given by the following Eq. (18.1):

$$\min \alpha_1 \mathrm{E}_1 + \alpha_2 \mathrm{S}_1 + \alpha_3 \mathrm{S}_2 + \alpha_4 \mathrm{R}_1 + \alpha_5 \mathrm{R}_2 \tag{18.1}$$

where coefficients α_i correspond to the weights set in Phase 2 for the Economic performance (C1_I1), Unmet Demand (C2_I1), Inequity (C2_I2), Reactiveness (C3_I1), and Risk (C3_I2), respectively. To formulate a single objective function to be minimized and keep it consistent, the coverage was reformulated as "unmet demand" and equity as "inequity". The model aims at deciding the SDCs to be opened, the quantities of aid to be delivered at each SDC, the routes to be repaired, and the routes to be performed by each vehicle. The input information used to solve the problem includes the demand of the affected population, travel costs between any two SDCs, travel time from an SDC to any demand point, the capacity of the vehicles, available repairing nodes teams, required costs, and periods to repair an arc, and the percentage of damage among the arcs. The decisions are restrained by constraints that consider the vehicles' capacity and the restoration teams, the demand, and finally, constraints related to the routing. The sets, parameters, and decision variables to formulate the model are summarized in Table 18.9.

The model aims to minimize the overall costs, uncovered demand, inequity, reactiveness, and cumulative risk. The five objective functions are grouped according to the performance criteria that were presented in Fig. 18.3 and are given in Table 18.10.

The first objective function (*OF1*) aims to minimize the overall costs incurred for the relief distribution (i.e., travel cost, cost of opening SDCs, and cost of arcs' restoring activities). The second and third objective functions are related to the social criteria and aim to minimize unmet demand (*OF2*) and inequity (*OF3*). Finally, objective functions (*OF4*) and (*OF5*) are related to reliability and seek to minimize, respectively, the reactiveness (*OF4*) and the risk (*OF5*).

The model is subject to the following sets of constraints.

Table 18.9 Sets, parameters, and decision variables of the mathematical model

SETS	
N	SDC possible locations
M	Demand points
V	Nodes of the network given by {0,…, n + m}
A	Set of arcs (i, j)
K	Vehicles
S	Type of supply
Parameters	
w_s	Volume of supply s
Q_k	Volume capacity of vehicle k
γ_{js}	Number of items type s required by the affected population j
Δ_{ij}	Damage in arc (i, j) given in percentage (0,1)
δ_{ij}	Distance between node i and node j
tc_{ijk}	Travel cost from node i to node j in vehicle k
rc_{ij}	Cost of restoring the arc (i, j)
oc_i	Cost of open a SDC_i
A_{ij}	Binary matrix, where *1* if $dist_{ij}$ τ; 0 otherwise
τ	Maximum distance between a SDC_i and a demand point j
$BigM$	A big number
G	Available teams to repair damaged arcs
Decision variables	
x_{ijk}	1 if vehicle k uses arc (i, j); 0 otherwise
z_{ij}	1 if SDC_i supplies demand point j: 0 otherwise
y_{ij}	1 if arc (i, j) is repaired; 0 otherwise
o_i	1 if SDC_i is opened; 0 otherwise
D_{ijsk}	Number of items s delivered to demand point j by vehicle k coming from point i
w_{ik}	Free variable used for the sub tour elimination constraints

$$\sum_{\substack{i=0\\i\neq j}}^{N} x_{ijk} = \sum_{\substack{i=0\\i\neq j}}^{N} x_{jik} \qquad \forall\ j \in N,\ k \in K \tag{18.2}$$

$$\sum_{j=1}^{N} x_{0jk} = 1 \qquad \forall k \in K \tag{18.3}$$

$$\sum_{j=1}^{N} x_{j0k} = 1 \qquad \forall k \in K \tag{18.4}$$

Table 18.10 Objective functions

Criterion	Ind	Value	
Economic	E1	$\min \sum_{\substack{i=0 \\ i \neq j}}^{N} \sum_{\substack{j=0 \\ i \neq j}}^{N} (tc_{ijk} x_{ijk}) + \sum_{\substack{i=1 \\ i \neq j}}^{N} \sum_{\substack{j=1 \\ i \neq j}}^{N} (rc_{ij} y_{ij}) + \sum_{\substack{i=0 \\ i \neq j}}^{N} (oc_i o_i)$	*(OF1)*
Social	S1	$\min m - \sum_{i=0}^{N} \sum_{j=n+1}^{M} z_{ij}$	*(OF2)*
	S2	$\min 100 * \sum_{j=n}^{N+M} \sum_{s=1}^{S} \left(\frac{\gamma_{js} - \sum_{\substack{i=0 \\ i \neq j}}^{N} \sum_{k=1}^{K} D_{ijsk}}{\gamma_{js}} \right)$	*(OF3)*
Reliability	R1	$\min \sum_{\substack{i=1 \\ i \neq j}}^{N} \sum_{\substack{j=1 \\ i \neq j}}^{N} \sum_{k=1}^{K} (\delta_{ij} x_{ijk})$	*(OF4)*
	R2	$\min \sum_{\substack{i=1 \\ i \neq j}}^{N} \sum_{\substack{j=1 \\ i \neq j}}^{N} (\Delta_{ij}(1 - y_{ij})) + \sum_{\substack{i=1 \\ i \neq j}}^{N} \sum_{\substack{j=1 \\ i \neq j}}^{N} \sum_{k=1}^{K} (\Delta_{ij} x_{ijk})$	*(OF5)*

$$\sum_{\substack{i=0 \\ i \neq j}}^{N} \sum_{k=1}^{K} D_{ijsk} \geq \sum_{i=0}^{N} \gamma_{js} z_{ij} \qquad \forall j \in N, s \in S \tag{18.5}$$

$$\sum_{\substack{i=0 \\ i \neq j}}^{N} \sum_{s=1}^{S} w_s D_{ijsk} \leq Q_k \sum_{\substack{i=0 \\ i \neq j}}^{N} x_{jik} \qquad \forall j \in N, k \in K \tag{18.6}$$

$$\sum_{\substack{i=0 \\ i \neq j}}^{N} \sum_{\substack{j=1 \\ i \neq j}}^{N} \sum_{s=1}^{S} w_s D_{ijsk} \leq Q_k \qquad \forall k \in K \tag{18.7}$$

$$\sum_{s=1}^{S} D_{ijsk} \leq BigMx_{ijk} \qquad \forall i, j \in N^{'}, k \in K \tag{18.8}$$

$$\sum_{k=1}^{K} x_{jik} \geq M\Delta_{ij} \qquad \forall i, j \in N, i \neq j \tag{18.9}$$

$$\sum_{\substack{i=0 \\ i \neq j}}^{N} \sum_{\substack{j=1 \\ i \neq j}}^{N} y_{ij} \leq G \tag{18.10}$$

$$\sum_{k=1}^{K} x_{ijk} \leq 1 - y_{ij} \qquad \forall i, j \in N, i \neq j \tag{18.11}$$

$$\sum_{k=1}^{K} x_{ijk} \leq 1 - y_{ji} \qquad \forall i, j \in N, i \neq j \tag{18.12}$$

$$y_{ij} - y_{ji} = 0 \qquad \forall i, j \in N, i \neq j \tag{18.13}$$

$$A_{ij} o_{ij} \geq z_{ij} \qquad \forall i, j \in N, i \neq j \tag{18.14}$$

$$u_{ik} - u_{jk} + |N| x_{ijk} \leq |N| - 1 \forall i, j \in N, i \neq j, k \in K \tag{18.15}$$

$$x_{ijk} \in \{0, 1\} \qquad \forall i, j \in N, k \in K \tag{18.16}$$

$$z_{ij} \in \{0, 1\} \qquad \forall i, j \in N \tag{18.17}$$

$$y_{ij} \in \{0, 1\} \qquad \forall i, j \in N \tag{18.18}$$

$$o_i \in \{0, 1\} \qquad \forall i \in N \tag{18.19}$$

$$D_{ijsk} \geq 0 \qquad \forall i, j \in N, k \in K, s \in S \tag{18.20}$$

$$u_{ik} \in R \qquad \forall i \in N, k \in K \tag{18.21}$$

Constraints (18.2) guarantee the flow of vehicles through the arcs by stating that if a vehicle arrives at a node $j \in N$, then it must depart from the same node. Constraints (18.3) and (18.4) ensure that any route starts and ends at the depot. Constraints (18.5) determine the number of satisfied demand points. Constraints (18.6)–(18.8) ensure together that the vehicle capacity is not exceeded. Constraints (18.9) ensures that each route includes only not damaged arcs. Constraints (18.10) warrant that no more than the available repairing teams are used. Moreover, Eqs. (18.11) and (18.12) restrict the available arcs to those that are not being repaired, and Eqs. (18.13) guarantee the symmetry of the arcs, meaning that if arc (*i, j*) is been repaired, it is unavailable, as well as the arc (*j, i*). Constraints (18.14) establish that a vehicle cannot use the arc (*i, j*) if the distance among those points is greater than τ, and constraints (18.15) ensure that routes do not have sub-tours. Finally, Eqs. (18.16)–(18.21) define the integrity of the variables.

18.5 Numerical Experiments

This section illustrates how the multi-criteria framework presented in this chapter can support decision-makers handling aid distribution situations where more than one criterion needs to be considered simultaneously and in a balanced way. To this end, an academic example is provided.

The instance: Based on the instances proposed by Naji-Azimi et al. (2012), a single-period relief distribution problem, having $|M| = 21$ demand points, $|N| = 9$ possible SDCs locations, one depot, and a heterogeneous fleet of $|K| = 5$ vehicles is considered. The capacity of the vehicles are 50, 75, 100, 150, and 150 volume units, respectively. SDCs opening cost oc_i is set to $12,000 for all $i \in N$. For each demand point and each potential SDC location, the coordinates (*i, j*) were randomly generated from a uniform distribution [0,100] distance units. Euclidian distances were computed to obtain the parameter δ_{ij} and tc_{ijk}. The damage percentage Δ_{ij} between each pair of nodes *i* and *j*, $i, j \in N$, are given in Table 18.11, and, as it can be observed, they are asymmetric. It was assumed that five repairing teams ($|G| = 5$) were available. Four types of supplies ($|S| = 4$) with volumes of 1 ft^3, 2 ft^3, 3 ft^3, and 4 ft^3, respectively, were considered. Finally, the demand was also generated under a uniform distribution within [0, 5] units for each demand point and type of required product.

Experiments were conducted on a desktop computer with Intel® Core ™ i7 CPU, 3.40 GHz with 4 GB of RAM, and the software IBM ILOG CPLEX Optimization Studio 12.6.1was used to solve the formulation.

Experiments and results: The formulation presented was solved six times, with each time aiming to optimize one of the objective functions *OF1* – *OF5* in addition to the multi-objective Eq. (18.1) with weights $\alpha_i = \{0.03, 0.20, 0.11, 0.19, 0.47\}$ set in Phase 2, and that will refer to as *O6*. To solve the multi-objective version, we relied on the weighted goal programming technique (Charnes et al. 1968). The method requires to compute for each objective OF1 to *OF5* the corresponding optimal value,

Table 18.11 Arcs' damage percentages

i	*j*								
	1	2	3	4	5	6	7	8	9
1	–	0.5	0.8	0.0	0.0	0.7	0.0	0.7	0.0
2	0.5	–	0.5	0.8	0.0	0.0	0.7	0.0	0.0
3	0.8	0.5	–	0.8	0.0	0.0	0.0	0.2	0.3
4	0.0	0.8	0.0	–	0.0	0.1	0.0	0.0	0.0
5	0.0	0.0	0.0	0.0	–	0.0	0.0	0.1	0.0
6	0.7	0.0	0.0	0.1	0.0	–	0.6	0.0	0.0
7	0.0	0.7	0.0	0.0	0.0	0.6	–	0.9	0.0
8	0.7	0.0	0.2	0.0	0.1	0.0	0.9	–	0.2
9	0.0	0.0	0.3	0.0	0.0	0.0	0.0	0.3	–

referred to as “target”, without considering the others. Then, in order to harmonize the scales and units of these heterogeneous results, a set of constraints that compute the normalized deviation of each criterion i, δC_i defined as: $\delta C_i = (O_i - O_i^*)/(\hat{O}_i - O_i^*)$ where (O_i and O_i^* are the current and the target values of objective i, respectively, and $\hat{O}_i$ is an upper bound or maximum deviation allowed for criterion i. Another set to guarantee that $\delta C_i \geq 0 \forall i \in I$ was also added to the formulation.

Table 18.12 presents the numerical results, in which each column reports the values achieved by the solution produced by *O1–O6* concerning each criterion. For instance, let us consider the first line, which corresponds to how the formulation was solved to minimize *O1* (Costs). The cost of this solution was 62.10, which is the best possible performance. This solution produced values of 22 concerning Unmet Demand, 0.45 for Inequity, and 599.34 and 7.15 for Reactiveness and Risk criteria, respectively, which are clearly poorer than the best potential values for each criterion (obtained by objectives *O2–O5*, respectively). Therefore, results in Table 18.12 show that optimizing with respect to a single objective produces, as expected, lower performance of the others.

However, Table 18.12 also shows that when the stakeholders’ preferences are considered altogether by the model (i.e., *O6*), the values for each performance criteria do not have big gaps with respect to their potential best. More precisely, *O6* achieves the best possible solution for three criteria (Unmet Demand, Inequity, and Risk), and values of only 2.09% and 2.76% over the optimal Cost and Reactiveness, respectively. In other words, a relative increase in Cost and Reactiveness of less than 3% allow a solution for which optimal values are achieved concerning the other criteria. Figure 18.4 shows the relative performance of each solution with respect to the others and for all five criteria.

Finally, a sensitivity analysis was performed using the index proposed by Hoffman and Gardner (1983). This sensitivity index (SI) aims at comparing the minimum and maximum values obtained for each criterion under different parameters. The index is computed using the equation $SI_i = (O_i^m - O_i^*)/O_i^m$, where O_i^m is the worst value achieved by any objective function to criterion i. Numerical results of the sensitivity

Table 18.12 Single and multi-criteria results

	Value				
Objective	I	Unmet demand	Inequity	Reactiveness	Risk
O1	**220,755**	22.00	0.45	599.53	7.15
O2	211.00	**1.00**	1.00	788.68	8.95
O3	62.90	22.00	**0.03**	557.56	7.15
O4	62.30	22.00	0.47	**444.41**	7.15
O5	64.25	22.00	0.64	557.56	**5.05**
O6	63.40	1.00	0.03	456.68	**5.05**
%	2.09	0.00	0.00	2.76	0.00

O1: Costs; **O2**: Unmet demand; **O3**: Inequity; **O4**: Reactiveness; **O5**: Risk; **O6**: Multi-criteria

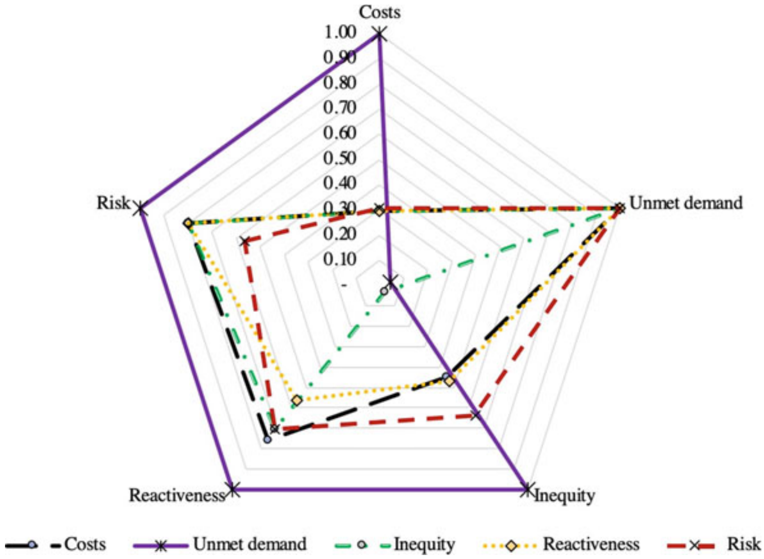

Fig. 18.4 Relative performance of each solution in comparison with the other criteria

analysis are reported in Table 18.13, where it is shown that the criteria Inequity and Unmet Demand are highly sensitive concerning the other criteria Inequity and Unmet Demand are highly sensitive with respect to the other criteria. Also, the criterion related to the Economic performance (Costs) seems to be highly sensitive when compared to Reactiveness and Risk criteria.

The results obtained from the numerical experiments show that the proposed approach can be successfully applied to develop a multi-criteria tool where several stakeholders with different preferences, which is the case in most humanitarian interventions, can be involved in the decision-making process. Moreover, the results also show that, when compared to the solutions produced to a single criterion, the deviations of the multi-criteria solution are relatively small, suggesting that considering several criteria at the time leads to well-balanced solutions.

Table 18.13 Sensitivity index per criterion

Criterion	Max	Min	SI
Costs	211.00	62.10	0.71
Unmet demand	22.00	1.00	0.96
Inequity	1.00	0.038	0.96
Reactiveness	788.68	444.41	0.44
Risk	8.95	5.05	0.44

18.6 Conclusions and Future Research

Relief distribution decisions are challenging due to the number of stakeholders with diverse goals and the urgency of the decisions to be made. This chapter proposes a multi-criteria framework to support humanitarian logistics managers in their decision-making processes. Throughout the proposed decision support tool, decision-makers are guided in the decisional process, thus ensuring the balanced integration of the stakeholders' preferences (humanitarian, governmental, donors, and beneficiaries). The proposed methodology allows for the translation, from quantitative to quantitative, of different stakeholders' preferences for integrating into a multi-criteria optimization model. Although limited to an academic case study, the applicability of this methodology was demonstrated. Performance indicators, such as costs, coverage, equity, reactiveness, and risk, were considered to formulate an objective function. Furthermore, a sensitivity analysis showed that the results produced by the multi-criteria approach are very robust.

However, this study presents various limitations. Firstly, it assumes that all the required information, including the needs of the affected people or the real situation of routes and infrastructures, is available and accurate. Indeed, the integration of technologies for gathering information about the consequences of a disaster in an accurate and timely manner, mostly the situation of routes and infrastructures as well as the real needs of the population, is a promising topic of future research. Secondly, we had to rely on university experts to identify and evaluate decision-makers' preferences and goals and validate how the model's solutions satisfy their needs. Additional research is required to obtain information from different organizations involved in the humanitarian supply chain to identify their real drivers and goals and other constraints not considered by our model, but which impact their day-to-day operations.

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