A Method for Analyzing the Risk Components of Climate Change Hazards at the Local Level: The Case of Chetumal, Quintana Roo

Adriana Lucia Trejo-Albuerne[1]

Abstract

Due to the possible negative externalities associated with the effects of climate change, it is necessary to have methodologies to understand the risks at the local scale and to propose alternative solutions so that decision-makers can optimize resources and efforts in specific mitigation works according to the specific hazards. This methodological proposal has resulted in a local scale risk index for the border city of Chetumal, Quintana Roo in Mexico, which, through spatial and cartographic analysis, has determined the importance and priority of each hazard in 5 territorial risk units. The results are per block, which is the finest resolution in Mexico that can be obtained from official data.

Keywords: Risk, Hazards, Climate Change, Geographical Information System, Index.

[1] Universidad Nacional Autónoma de México, Instituto de Geografía. Ciudad Universitaria, México. email: cartografia.riesgos@geografia.unam.mx

Introduction

The significant rise in global temperature, which has already reached 1.1°C, is rapidly reshaping the global risk landscape and increasing the frequency and severity of natural hazards. This trend is shown by the doubling of extreme weather events over the last two decades. An effective response to this climate crisis depends crucially on short-term mitigation and adaptation measures, together with risk reduction strategies. Planning that does not adequately address these risks may create new hazards and induce maladaptive responses. Risk reduction and adaptation to Climate Change (CC) are therefore inextricably linked and require a deep understanding of climate information to achieve effective results (UNDRR & WMO 2023).

This research[2] analyzes the risks of the territory of the city of Chetumal, the political capital of the state of Quintana Roo in Mexico, from a holistic paradigm: Systems Theory (Cardona 2001). This approach allows us to explore the elements that interact in the social construction of risk and, with this understanding, to define a replicable method at other scales and in different spaces for the elaboration of Territorial Risk Units (TRU). This method, as a tool and means of spatial analysis, serves decision-makers as a reference to be considered in plans for territorial planning, environmental management, and disaster risk management. In these plans, risk should be one of the central axes for seeking integrated local development in all its areas, especially in the face of the already palpable effects of Climate Change (Lavell 2010).

The territorial unit is thus understood as the integration of biotic, abiotic, and anthropic elements that interact through a series of relationships, in this case, expressed and applied to the concept of risk. This condition provides one of the qualities of the system, characterized by being dynamic and with flows of matter and energy. Within this approach, the present research conducts an integrated and synthetic analysis of the components of risk to set up a method that allows the construction of the TRU in a defined urban area: the city of Chetumal.

The interest in defining Chetumal as a study area lies in the consideration that Chetumal is a relatively new city, founded in 1898 by Othón P. Blanco, where the spatial processes that have taken place have responded not only to specific economic and socio-cultural conditions but also to the adaptation of a unique geographical environment. It is a city that shares a border with Belize and has the possibility of organizing and reorganizing its space based on scientific and multidisciplinary knowledge that allows it to exploit all its potential and minimize its weaknesses (González 2019).

The city of Chetumal is in the state of Quintana Roo, in the municipality of Othón Pompeyo Blanco, in the southeast of the Mexican Republic; the entity is in the physiographic province called the Yucatán Peninsula, with the extreme geographic coordinates north 21° 35', south 17° 49' north latitude; east 86° 42', west 89° 25' west longitude. It is bordered on the north by the state of Yucatán and the Gulf of Mexico; on the east by the Caribbean Sea; on the south by the Hondo River, Belize, and Guatemala; and on the west by Campeche and Yucatán (Figure 1). The state's extension

[2] The research presented in this paper is based on the doctoral thesis entitled "Development Planning from Territorial Risk Units. Chetumal", which is available at the following link: https://www.researchgate.net/publication/351885660_Development_Planning_from_Territorial_Risk_Units_Chetumal. This topic was also discussed at the VIII Belize-Mexico Binational Seminar "Building Transnational Networks to Strengthen Economic, Social, and Ecological Resilience to Climate Change", held from October 25th to 27th at the University of Belize.

is 50,843 km², including the islands of Cozumel, Isla Mujeres, Holbox, Isla Blanca, and Contoy, among the most important. The state stands for 2.55% of the national territory (INEGI 2010).

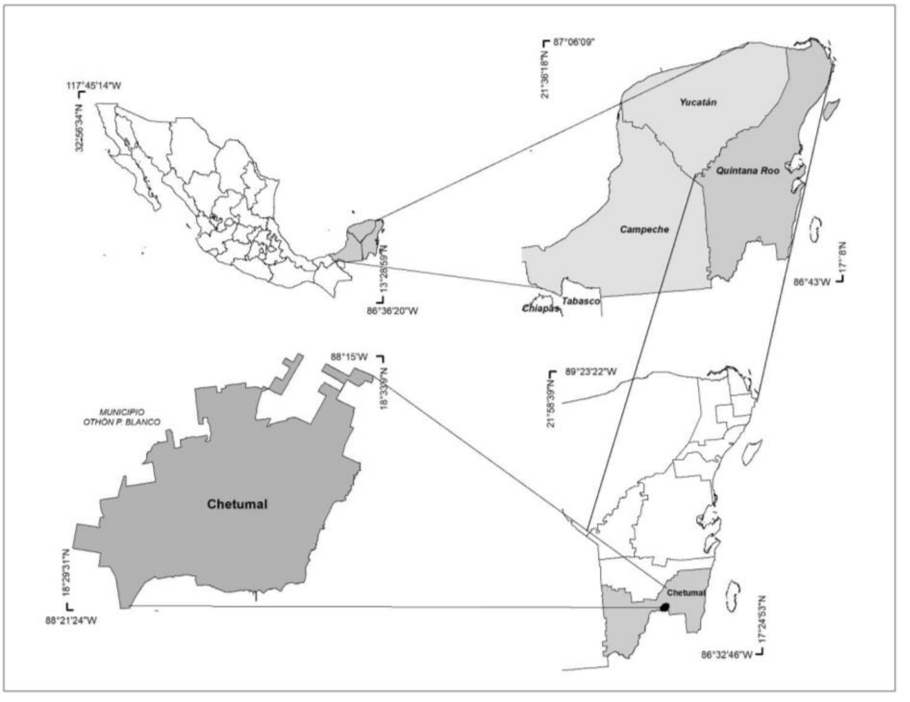


Figure 1. Location of Chetumal in Quintana Roo, Mexico.

Throughout its history, its urban growth has brought it close to natural and anthropogenic hazards, which have manifested themselves in emergencies and major disasters such as Hurricane Janet in 1955 (Castillo, 2009; 2019; Romero, 2014). The city of Chetumal has thus grown without proper planning considering the risks and hazards, leaving its population and infrastructure more exposed to them. Therefore, it is essential to address the issue of territorial organization and urban planning to avoid the future increase in the negative externalities of potential disasters and to consider adaptation to CC and its long-term effects.

The social construction of risk means transforming contingencies into something accessible, assessable, measurable, and manageable: into probabilities (Kruger 2013; Trejo & Campos 2019). This can be represented by different formulas, but for this research and approach to the study of risk, the principles of the following expression are taken up again, which is the basis for the analysis and implementation of the TRU: Risk = Hazard + Vulnerability + Exposure.

Conceptual confirmation of the terms used throughout the research, both in its theoretical part and in the development of the model and the practical part, will be as follows:

Risk, from the point of view of the General Theory of Systems, is defined as the probability of damage or probable losses to an influenceable agent because of the interaction between its vulnerability and the presence of a disturbing agent. Hazards are the probability of occurrence of a potentially damaging phenomenon of a certain intensity, during a certain period, and in a certain place, according to the method developed by CENAPRED (2016).

Vulnerability is the result of the set of social and economic characteristics of the population that limit society's capacity for development, together with its capacity to prevent and respond to a phenomenon and the local perception of risk by the population (CENAPRED 2014). Other elements considered by the United Nations Office for Disaster Risk Reduction (UNDRR) for the same concept are the characteristics and circumstances of a community, system, or asset that make it vulnerable to the harmful effects of a hazard (UNISDR 2009).

Another element to consider is exposure, which is usually expressed both geographically and in monetary terms as the damage or loss to lives, property, infrastructure, and existing systems that are likely to be damaged or harmed by an emergency or disaster (CENAPRED 2016). A hazard is a phenomenon that can be of natural origin, such as climatological, hydrological, geological, or maritime, among others. Hazards can also be of anthropogenic origin, resulting from human activities such as the development and management of corrosive substances, deforestation, land-use change, pollution, etc., which can cause damage, death, injury, or other health effects, as well as property damage, loss of livelihoods and services, social and economic disruption, or environmental damage (UNISDR, 2009).

According to the International Strategy for Disaster Reduction (ISDR), a disaster is a serious disruption in the functioning of a community or society that results in many deaths, as well as material, economic, and environmental losses and impacts that exceed the ability of the affected community or society to cope with its resources (FAO 2009; UNISDR 2009).

According to UNDRR, new approaches must be based on integrated risk management, as reflected in its new Strategic Framework 2022-2025 (UNDRR 2012). This framework gives high priority to climate emergency management, integrating it into the climate agenda and naming it as a key outcome. The UNDRR's flagship initiative, Comprehensive Climate Risk and Disaster Management (CRM) aims to adapt policies to climate change and improve coherence between disaster risk reduction and climate adaptation to improve planning and decision-making at different scales (UNDRR & WMO 2023).

In this sense, it is proposed that the usefulness of this project and its results, in addition to providing a methodological process that integrates the risks in territorial units, allows the prioritization of the risks that need to be addressed and invested in the first instance block by block, thus facilitating the spatial understanding of the territory analyzed to apply political, economic, and social actions to intervene in the territorial development of the city, promoting sustainability.

Methods and Results

To analyze the risk components in Chetumal, the spatial expression of hazards, vulnerability, and exposure was examined. Initially, hazards with the highest incidence and probability of affecting the city were selected through participant observation in the study area, as well as a bibliographic and cartographic review of documents such as the State and Municipal Risk Atlases, and the electronic portal of the National Risk Atlas (SEDESOL & CIG-UQROO 2011; CENAPRED 2019).

As a result, a territorial risk methodological proposal was generated, considering physical and social aspects of vulnerability, exposure, and seven representative hazards of the region: karstification, subsidence, earthquakes, pluvial flooding, storm surge flooding, chemical hazards from spills, and chemical hazards from leaks and transportation.

The results were disaggregated into local units composed of blocks, prioritizing attention to each hazard according to its probability of occurrence at the local scale. This approach is termed Territorial Risk Units (TRU).

Phase I. Basic Mapping

Initially, the study delineated the geographical scope and defined the operational scale using administrative boundaries provided by the National Institute of Statistics and Geography (INEGI) at the municipal level. Urban areas were identified using the 2019 National Geostatistical Framework (MGEN-19) for Chetumal City. This aided in the identification and geographical referencing of economic establishments, residences, and agricultural and forestry units, which are essential for various projects including risk reduction, poverty alleviation, public policies, and infrastructure development.

According to INEGI (2010), urban areas are delineated as geographic units composed of blocks bounded by streets, avenues, or other features, primarily serving residential, industrial, service, or commercial purposes.

Further spatial disaggregation was undertaken considering the levels of information provided by INEGI's Geostatistical cartography, which includes the minimum observation units of the 2010 Population and Housing Census: localities and urban blocks. Consequently, the analysis method was applied at the block level to manage a local scale, functional for generating operational census and survey data. This ensured effective information management and utilization at the most granular level within MGEN-19.

Figure 2. Established cartographic parameters for the basic cartography of Chetumal.

Phase II. Vulnerability and Exposure to Risk

To obtain the social vulnerability used in the model, it was necessary to develop it in three parts and assign them a percentage. When added together, these percentages result in qualitative values that determine the areas of social vulnerability:

a. Social and economic characteristics (50%),
b. Response capacity (25%), and
c. Local perception (25%) (CENAPRED 2016).

For this purpose, 18 indicators were analyzed using information obtained from the 2010 INEGI census, a survey of response capacity, and the application of local perception questionnaires in Chetumal.

Regarding structural vulnerability, five types were classified:

a. Residential houses,
b. Buildings for housing, offices, and schools,
c. Special constructions such as theaters, auditoriums, churches, and industrial warehouses,
d. Extensive systems or those with multiple supports such as bridges, and
e. Surface or buried pipelines (Ibid. 2019).

In the GIS, the geometries and attributes of the social vulnerability shapefiles were combined with those of the structural vulnerability, resulting in the Integrated Vulnerability (Figure 3).

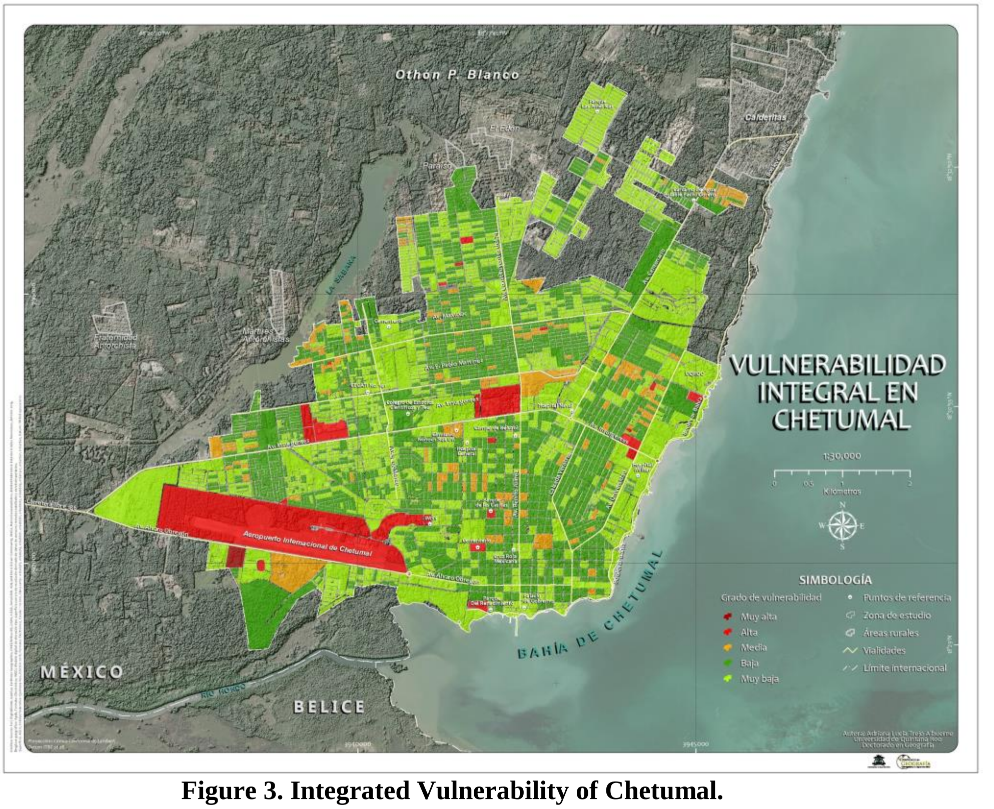


Figure 3. Integrated Vulnerability of Chetumal.

Exposure remains unchanged for risk calculations; it is used for all hazards as there are no specific elements other than the Urban Development Plan (UDP) (PDU 2018), from which it can be inferred that areas with higher socioeconomic status, showed by factors such as property value and property tax, will incur greater costs. Since the exact costs are unknown, exposure is assessed qualitatively, noting that residential areas with higher property values are more exposed than lower-cost housing. Additionally, the UDP provides population density data for each area. Each of these aspects is assigned a category of higher or lower exposure, enabling the identification of areas where losses are likely to be greater and where more people are likely to be affected in case of a disaster.

The cartographic process involved digitizing blocks within the MGEN-19, based on the economic attributes of zones previously delineated in the UDP, along with population density data. Ultimately, the final spatial representation reflects the standardized exposure for the city of Chetumal (Figure 4).

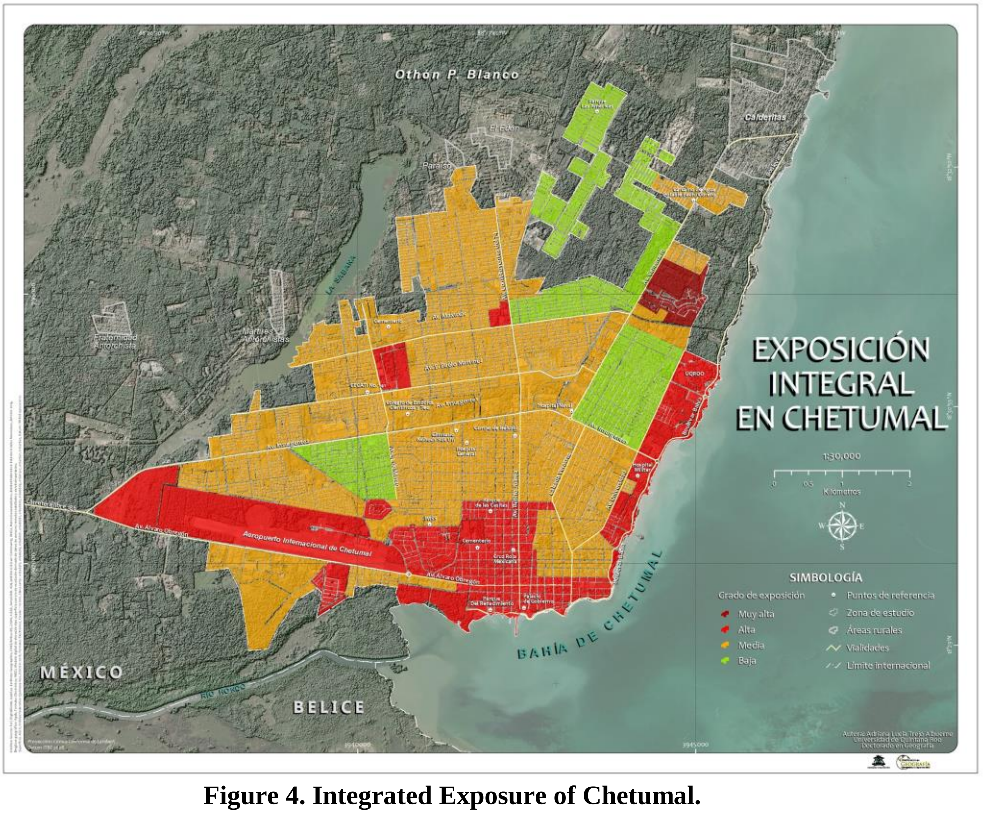


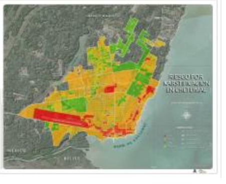
Figure 4. Integrated Exposure of Chetumal.

Phase III. Hazards

The hazards were selected based on data availability, scale, and currency for mapping, using a cartographic overlay of hazard, integrated vulnerability, and integrated exposure with standardized data. The cartographic sequence began with a spatial analysis of the specific hazard, followed by correlating the hazard with the vulnerability found in the earlier phase. Subsequently, this result was further correlated with integrated exposure, resulting in the final synthesis of spatial correlations for each specific hazard (Figure 5).

For this stage, the following specific hazards in Chetumal were analyzed (CENAPRED 2019):

1. Karstification and **2.** Land Subsidence: These phenomena are associated with the geological and soil nature upon which the city has been built. Coupled with rainfall patterns, proximity to the water table, and coastline, they result in karstification, a phenomenon referring to the dissolution of limestone rock due to chemical reactions with fresh or rainwater, resulting in cavities. This threat can affect urban structural integrity as sudden and abrupt collapses may occur, forming cavities of varying diameters.
3. Earthquakes: This phenomenon occurs due to the sudden rupture of the Earth's rigid outer layer, called the Earth's crust.
4. Pluvial Flooding: Pluvial flooding results from various causes or their combination. The accumulation of water in undesired areas has natural origins such as thawing, rainfall, waves, or the growth and overflow of water bodies, as well as natural drainage from soils and subsoils, and proximity to water tables and coastlines, among others.
5. Tidal Storm Surge: Storm surge is an increase in the average sea level in a coastal area. It is the result of the ocean's surface being pushed by winds generated by storms or tropical cyclones, often combined with heavy waves.
6. Spills: Spills are generated by the violent action of different substances resulting from their molecular or nuclear interaction.
7. Leakage and Transportation Spills: These materials are hazardous due to their composition for humans, the environment, and infrastructure during their production, storage, transportation, distribution, use, and disposal. In this sense, the danger from chemical transportation is posed by the infrastructure used for this purpose, such as pipelines for chemical transportation.

Spatial analysis of the hazard	Correlation between hazard and integrated vulnerability	Successive correlation of the previous result with the integrated exposure	Synthesis of correlations
Karstification 	Integrated Vulnerability 	Integrated Exposure 	Karstification Risk 
Subsidence 	Integrated Vulnerability 	Integrated Exposure 	Subsidence Risk 

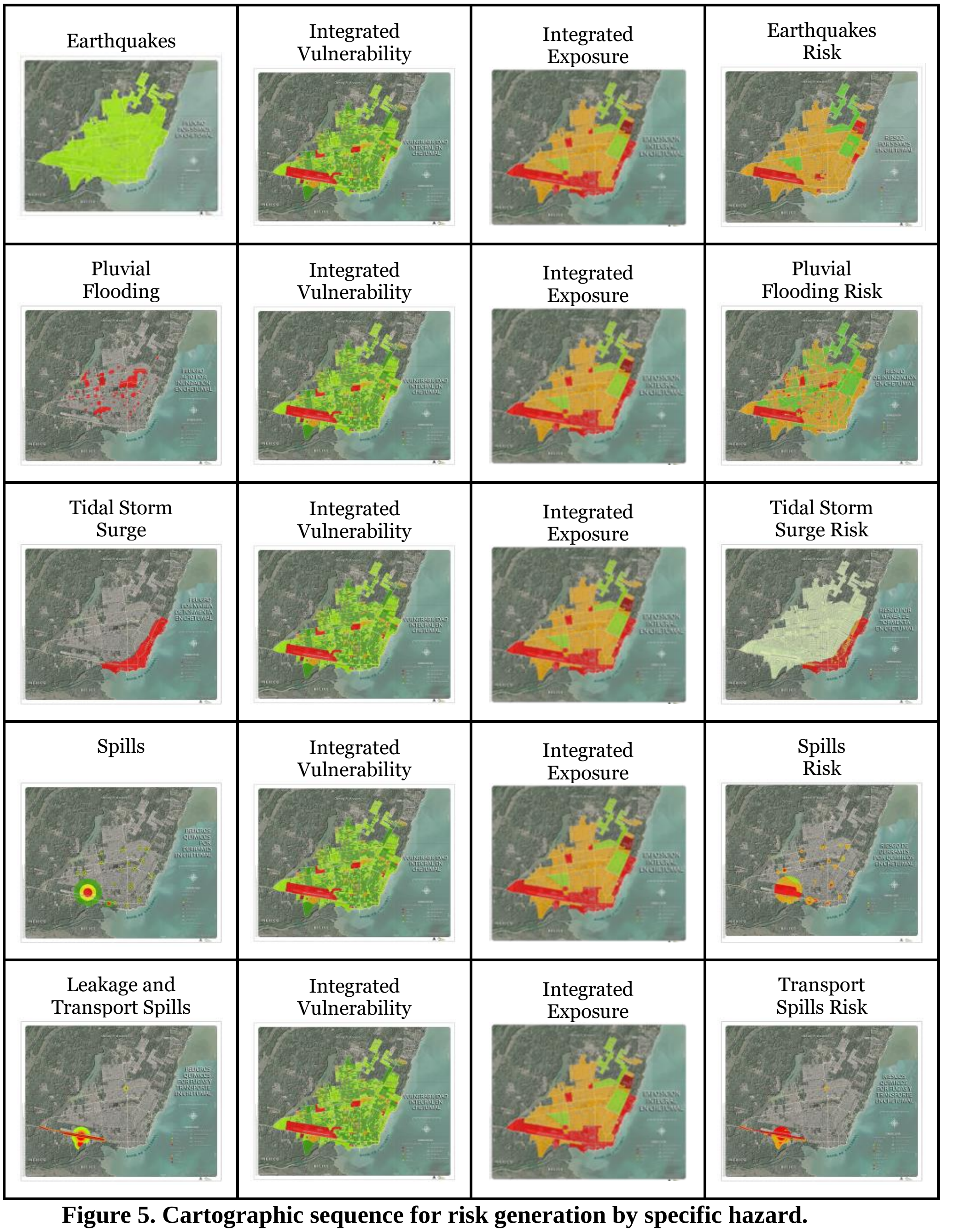


Figure 5. Cartographic sequence for risk generation by specific hazard.

Phase IV. Risk Index

In this phase, the cartographic criteria were unified with the homologated risk index, obtained from the average of the risks by specific hazards through map algebra, in a cartographic information layer of Integrated Risk in Chetumal. This layer allows for the visualization of clear and homogeneous spatial patterns in its generality. Since each layer has been qualitatively and quantitatively categorized, it has been possible to spatially identify zones with a higher probability of a risk scenario occurring per block.

Each of the calculated indices stands for the spatial distribution of the relationship between a given phenomenon (hazard), socioeconomic conditions (vulnerability), and affected systems (exposure). This relationship is established by defining the probability of a disaster or emergency occurring in each location.

Phase V. Territorial Risk Units

The Territorial Risk Units are spaces within the study area that show the hierarchy or priority of each of the hazards occurring there. Thus, the concept of the TRU is based on the integration of the different risks that affect the studied territory, indicating the risks that affect a given space and, at the same time, giving them a hierarchy or priority for attention in terms of planning, policies, risk management, territorial management, and governance.

The purpose of establishing these units of analysis within the city of Chetumal is the zoning of areas considered priorities during the phases comprising emergency response. This zoning is based on the occurrence, magnitude, and intensity of the hazards synthesized in the Integrated Risk Index.

Since the average is available, the tool used to create the groups preceding and deriving the TRUs is *Moran's Cluster and Outlier Analysis* or *Local I Anselin*. This deductive spatial pattern statistic, based on probability theory, evaluates the role of possibility in the analysis results, making it perfect for the study of risks (ESRI, 2016).

To obtain this delimitation, prioritization, and hierarchy of hazards, the multivariate statistical technique called cluster analysis was used as a tool. Objects were classified, and the data's dimensionality was reduced by exploiting the similarities and/or differences between cases. The resulting classification provides relatively homogeneous groups, where the objects in each group tend to be like each other (high internal homogeneity) and different from those in other groups (high external heterogeneity) concerning some predetermined selection criterion. Given a set of weighted entities, it finds entities with high or low values and statistically significant spatial outliers (Figure 6 & Table 1).

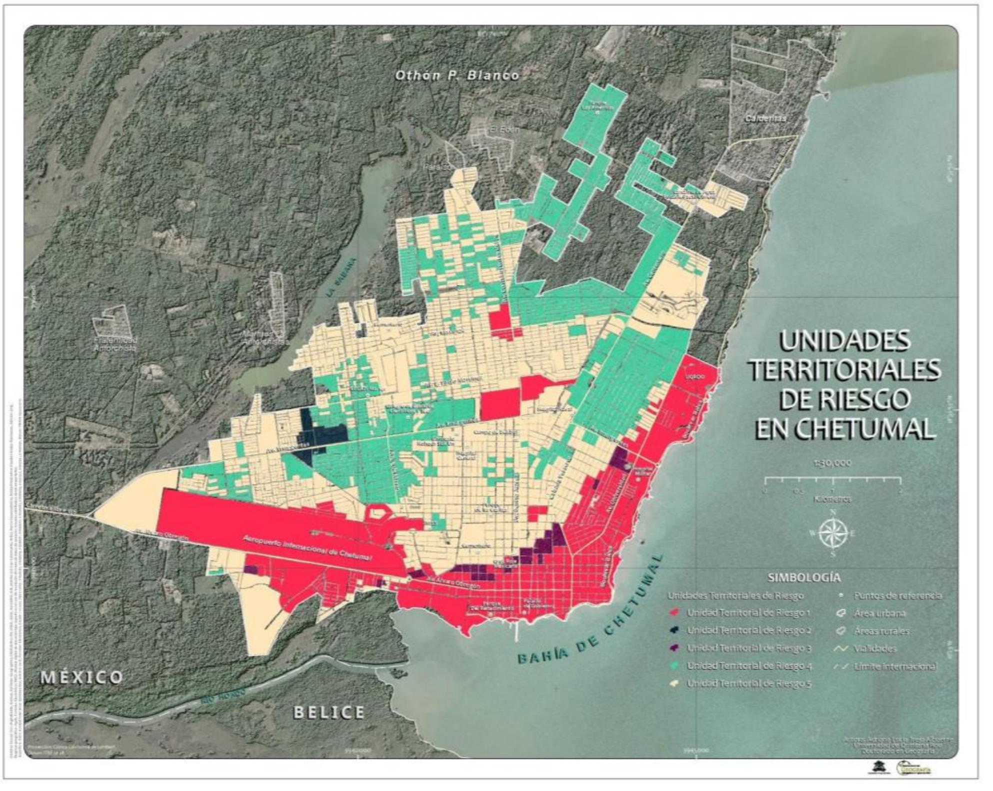


Figure 6. Territorial Risk Units of Chetumal.

Table 1. Integration of risk territorial units and prioritization of their risks.

Territorial Risk Units	Average risk per hazard	Prioritization of risk by hazard	Risk hierarchy by a specific hazard
TRU 1	0.652963	1	Karstification
	0.616679		Earthquakes
	0.586101	2	Pluvial Flooding
	0.530944		Tidal Storm Surge
	0.22293	3	Subsidence
	0.218581		Spills
	0.082955	4	Leakage
	0.06613		Leakage and Transport Spills
TRU 2	0.546341	1	Pluvial Flooding
	0.531707	2	Earthquakes
	0.512195	3	Karstification
	0.360976	4	Spills
TRU 3	0.6	1	Earthquakes
	0.596552	2	Karstification
	0.517241	3	Pluvial Flooding
	0.2	4	Tidal Storm Surge
	0.051724	5	Leakage and Transport Spills
	0.041379		Spills
	0.02069		Leakage
TRU 4	0.488062	1	Earthquakes
	0.453792	2	Karstification

	0.43441	3	Pluvial Flooding
	0.027809	4	Spills
	0.005899		Tidal Storm Surge
	0.000562		Leakage
	0.000281		Subsidence
TRU 5	0.599374	1	Earthquakes
	0.592642		Karstification
	0.58137	2	Pluvial Flooding
	0.091037	3	Spills
	0.014325	4	Tidal Storm Surge
	0.006810		Leakage and Transport Spills
	0.004853		Subsidence
	0.005558		Leakage

Table 1. Integration of risk territorial units and prioritization of their risks.

Discussion and Conclusion

In the case of the municipality of Othón P. Blanco, the occupation and development of settlements in wetlands and water bodies has been allowed, promoting and, in some cases, regularizing informal settlements. These settlements generate a population with a high degree of vulnerability and exposure to some of the hazards described here. This situation, along with physical and social separation, accentuates the socio-economic divisions of the population, generating new population problems in addition to environmental ones.

The current situation of urban planning in the city of Chetumal, Quintana Roo, presents several challenges and issues. Despite the urban growth experienced in recent years, urban planning has been insufficient and, in many cases, deficient. The main problems include:

1. Disordered growth: The city has experienced disordered growth, with the occupation and development of settlements in high-risk areas such as wetlands and bodies of water.

2. Socioeconomic division: The lack of adequate urban planning has contributed to the exacerbation of socioeconomic divisions within the population. The irregular occupation of high-risk areas has led to physical and social segregation, exacerbating existing inequalities.

3. Lack of infrastructure and basic services: Uncontrolled urban growth has resulted in a lack of infrastructure and basic services in many areas of the city, including potable water, drainage, sewage, as well as access to health and education services. This increases the vulnerability of the population to adverse events.

4. Lack of enforcement of regulations: Although urban regulations and standards exist, their enforcement has been inconsistent and, in many cases, ignored. The lack of effective enforcement of these regulations has allowed for the occupation of high-risk areas and the development of inadequate infrastructure.

The current poor urban planning itself represents a risk, as it increases the vulnerability of the population and their exposure to adverse events. Among these, greater exposure, and a higher impact of climate change-related extreme weather events, such as floods and storms, are notable. These events are expected to increase in frequency and intensity. It is essential to improve urban planning and risk management to reduce the vulnerability of the city and increase its capacity to respond to disasters and other adverse events.

According to financial, administrative, and technical ability, the Municipality of Othón P. Blanco must take part in risk reduction works and carry out corrective interventions, to reduce exposure and vulnerability. These actions, translated into general and specific proposals per hazard of each Territorial Risk Unit, must be previously established in the Land Use, Environmental Management, and Risk Management Plans in a transversal, integrated, and equitable manner.

One advantage of the methodological proposal based on Territorial Risk Units for disaster risk reduction at the local level is that it considers the basic conceptual principles of risk management. By considering all the components related to the elements of risk, it is possible to generate an integrated representation of each one, giving the model a systemic rather than fragmented vision, thus considering a total spatial integration closer to reality.

This methodological exercise also has the advantage of using already developed spatial data, which would not require any additional human or financial effort in addition to the investments already made for the generation of thematic information. Furthermore, within its six differentiated methodological phases, it is possible to incorporate a greater number of variables and available information, which in turn makes it possible to transform the model into a more complete and complex one, adapting it to different spatial and temporal scenarios and opening up the possibility of carrying out more detailed comparative analyses.

In this sense, another aspect to highlight in this spatial analysis is that the variables that define the population, and particularly the territory, can be selected, which makes it replicable for other places with different characteristics if the necessary geospatial information is available. On the other hand, if there is not enough up-to-date, reliable data at the required scale, it will be necessary to generate it; otherwise, the model's results will be partial and could provide an inaccurate representation of reality. It would be interesting to consider, in the context of international cooperation, the continuity of the Territorial Risk Units for the country and cities of Belize, with the understanding that this is a common multidimensional problem and not exclusively a political delimitation.

Another virtue of the method is that it does not require advanced knowledge or handling of Geographic Information Systems, making it accessible to a larger number of people interested in its application. Thus, this proposal is a contribution open to multiple interpretations, improvements, and modifications that can be adapted to the needs of users of these computer platforms, as well as risk assessors and planners.

With local methodological tools, such as the one proposed in this research on Territorial Risk Units, it is possible to provide decision-makers from science with a spatial analysis tool that, together with public policies and through development planning and territorial management tools (land use planning, risk management, and environmental management), optimizes time, human and economic resources, and efforts in specific mitigation works for specific risks according to their probability of occurrence.

It is important to set up a medium- and long-term vision and to always keep in mind the need for preventive measures for new facilities in the future to avoid creating new risks, especially with the effects of climate change that are already present.

In conclusion, the needs of the current reality do not correspond to the exercise of policies, planning, or territorial management, reflecting the complexity and dynamism of the processes of risk generation in the territory. Therefore, to make the existing instruments more efficient and comprehensive and to conduct significant processes of disaster risk reduction, aggravated by the hazards of climate change, it is necessary to insist on the usefulness of spatial and territorial analyses.

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