ARTÍCULO CIENTÍFICO

Flood risk in northern basin of Río de las Avenidas in Pachuca's Metropolitan Core using multicriteria decision analysis and GIS

https://doi.org/10.59307/rerne1.15

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Abstract

During the last two centuries, the municipalities of Pachuca and Mineral de la Reforma, Mexico, have been affected by several flood events, causing affectations in infrastructure, local economy, and fringe settlements. Heavy intensity of rainfall, new housing developments covering previously permeable grounds, probably old or bad design drainage systems are the main causes for this situation. This paper presents a simple approach of urban flood hazard assessment in a region where primary data are scarce. The objectives of this study are to develop a GIS-aided urban flood hazard zoning of the two municipalities applying multicriteria decision analysis and to evaluate it by means of uncertainty and sensitivity analysis. The research methodology focused on the analysis of those variables that control the water routing when high peak flows exceed the drainage-system capacity. The model incorporates four parameters: distance to the drainage channels, a social vulnerability index, slope and land use and vegetation. A final hazard map for each category is obtained using an algorithm that combines factors in weighted linear combinations.

Keywords: *social vulnerability, risk,flooding, multicriteria analysis, GIS.*

Riesgo de inundación en la cuenca de Río de las Avenidas en el centro de Pachuca a través de análisis multifactorial y SIG

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Resumen

Durante los últimos dos siglos, los municipios de Pachuca y Mineral de la Reforma, México, se han visto afectados por varios eventos de inundación, causando afectaciones en la infraestructura, economía local y asentamientos marginales. La fuerte intensidad de las lluvias, las nuevas urbanizaciones que cubren suelos previamente permeables, los sistemas de drenaje probablemente viejos o mal diseñados son las principales causas de esta situación. Este documento presenta un enfoque simple de evaluación del peligro de inundaciones urbanas en una región donde los datos primarios son escasos. Los objetivos de este estudio son desarrollar una zonificación de riesgo de inundación urbana asistida por SIG de los dos municipios aplicando análisis de decisión multicriterio y evaluarla mediante análisis de incertidumbre y sensibilidad. La metodología de investigación se centró en el análisis de aquellas variables que controlan el direccionamiento del agua cuando los caudales máximos superan la capacidad del sistema de drenaje.

Palabras clave: *vulnerabilidad social, riesgo, inundación, análisis multicriterio, SIG.*

Introduction

During the last two centuries, the municipalities of Pachuca and Mineral de la Reforma, Mexico, have been affected by several flood events (Menes-Llaguno, 1993), causing affectations in infrastructure, local economy, and fringe settlements. Management of water in urban areas involves control of the wastewater discharges and the modified natural drainage network in which the built-up area is located. Fast-growing cities with increasing populations have many problems with runoff water management during storms (Fernandez and Lutz, 2010). In fact, urbanization aggravates flooding by restricting flood-water flow, covering large parts of the ground with houses, roads and pavement, obstructing channels and building drains to ensure that water will flow into rivers faster than it would under natural conditions (Harris and Rantz, 1964; Konrad and Booth, 2002; Konrad and Booth, 2005). The more people crowd into cities, the more these effects intensify. Consequently, even fairly moderate storms produce high peak flows in the discharge channels because there are more hard surfaces and drains.

The frequency of flood disasters around the world is rising (Douben, 2006). Many hypotheses had been created for explain this phenomenon: increased climatic variability, the expansion of human settlement in flood plains and river courses, and land cover and land use changes together are believed to be increasing human exposure and sensitivity to flood impacts (Kundzewicz & Kaczmarek, 2000). The persistence of loss in face of increased knowledge about the dynamics, drivers, and outcomes of hazards may well signal a significant lack of sustainability in social-environmental relations, as well as a need to reconsider the underlying principles of flood risk management (Eaken and Appendini, 2008). Flood risk is usually defined as the combination of the probability of occurrence of events and the potential consequences on people, environment and anthropic structures (Arrighi *et al.*, 2017), and depends on three factors: hazard, exposure and vulnerability (IPCC, 2012; UNISDR, 2013). Hazard is related to the physical processes with the potential to cause harm ranging from atmospheric via catchment processes to river routing, whereas exposure refers to the elements-at-risk of flooding. Vulnerability is defined as the susceptibility of the elements-at-risk to be adversely affected. Typically, exposure is quantified as the number of people and the assets in flood-prone areas, and vulnerability is represented as the damage ratio. Floods cause damage to people, buildings and infrastructures (Arrighi *et al.*, 20017). Flood damage on structures and infrastructures is classified into direct and indirect, the former being caused by physical contact with floodwater and the latter occurring far from the event, either 30 in space or time (Thieken et al., 2006). On the one hand, direct losses to private dwellings, household contents and economic activities can be estimated through damage curves, which relate water depth to relative losses (Smith, 1994).

On the other hand, urbanization is a necessary process for Mexico's development. Nevertheless, over the years the social and spatial patterns associated with urbanization had been changing. In many regions of Mexico, continued high growth, formerly concentrated in metropolitan cores, is now emerging in small towns and intermediate-size cities (Eakin *et al.*, 2010). In Mexico, Pachuca's metropolitan core (PMC) is located in the most densely populated regions in Mexico – the megalopolis of Mexico City (Eibenshutz, 2010). Now that, the population of PMC of 0.5 million is rapidly encroaching on what remains of Rio de las Avenidas undeveloped floodplain, so that incidence of flood damages is rising. Rural land and urban development and settlement patterns are rapidly evolving, institutions are in flux, and consequently perceptions of flood loss are also changing. Heavy intensity of rainfall, new housing developments covering previously permeable grounds (Pérez *et al.*, 2015), probably old or bad design drainage systems are the main causes for this situation. To date, government's approach to flooding in Río de las Avenidas floodplain has been almost exclusively structural, relying on a series of dams, river straightening and dredging (Romero-Bautista, 2012).

Applied flood risk analyses using GIS technologies, especially in urban areas, very often pose the question how detailed the analysis needs to be in order to give a realistic figure of the expected risk. The methods used in research and practical applications range from very basic approaches with numerous simplifying assumptions up to very sophisticated, data and calculation time demanding applications both on the hazard and vulnerability part of the risk (Apel *et al.*, 2008). The aim of this article is establishing the influence of urban growth on the alteration of hydrological courses in Pachuca´s metropolitan core and their interactions, as well as, know the possible extension of floods, and may identify new risk areas using mulcriteria analysis and Geographic Information Systems (GIS). In addition, this research tries to offer territorial analysis tools to the competent authorities to improve public policies, because throughout the country, disasters natural conditions, the problems derived from erosion, the discharge of the aquifers, the inadequacy of the hydraulic infrastructure among other consequences of serious affectation for mexicans are increasingly more frequent (Alburquerque *et al.*, 2022).

Description of Study Area

The study area covers the municipalities of Pachuca and Mineral de la Reforma that conforms Pachuca´s Metropolitan Core (PMC; State of Hidalgo, Mexico). These cities have a joint population of 500,597 inhabitants spread over 264.72 km^2, thus being the main urban center in State of Hidalgo, and PMC is located in the most densely populated regions in Mexico – the megalopolis of Mexico City (Eibenshutz, 2010). The area is situated at the foot of the Sierra of Pachuca; it varies in topography, population density and land use. Pachuca is one of the most densely populated cities in the State of Hidalgo, with 4959 inhabitants per square kilometer, and it is the political and business center of the state. On the other hand, Mineral de la Reforma, located downhill from the previous one, is mostly suburbs, with industrial facilities. Historically, urban population growth had been confined primarily to the north of the study area. However, in recent years, urbanization has spread rapidly to the southeast with government housing developments and fringe settlements on the city's peripheries. Climate in the area under study is semi-dry with dry winters and a regime of storms in summer, although the city is frequently affected by cold fronts and tropical storms that affect the Gulf of Mexico. Mean annual precipitation is 411 mm, the vast majority of precipitation occurs between the months of May to October.

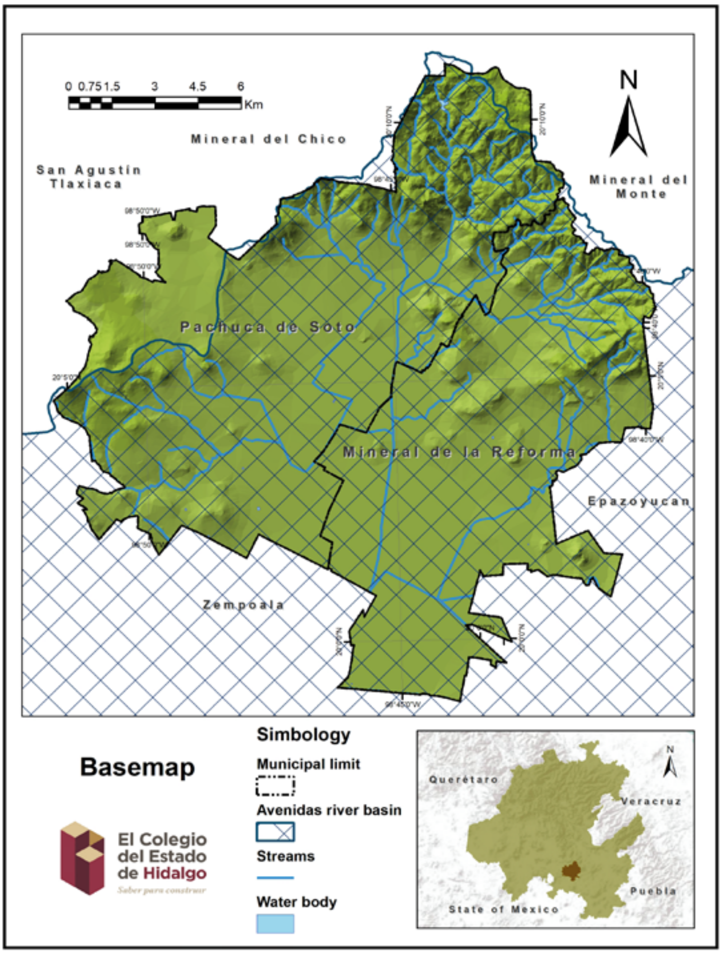
The main pluvial discharge systems that must deal with runoff water in the PMC area have a dendritic design, characterized by two principal channels: the Río de las Avenidas channel and the Río Sosa.

There is also a secondary system made up of small channels and streams that cross the PMC leading water to the main discharge channels. This hydrological system worked efficiently in the past but nowadays, increased paving in urban areas, and storm intensity cause higher flows that exceed system drainage capacity. In recent years, precipitation records have shown that when the intensity of tropical storms exceeds 200 mm/24 h (Hurricane Dean; Hernández-Unzón, 2007), the old drainage system is overwhelmed or cannot drain effectively into an outfall because of waste and debris (Fernandez & Lutz, 2010).

Consequently, excess water flows down roads and other paths of lesser resistance flooding low-lying areas.

Río de las Avenidas basin has a surface of 1,941 km^2 ; 25% of the surface of this basin extends from the Sierra de Pachuca to the north, to the Sierra de Guadalupe near México City to the south (Huizar-Álvarez, 1993). Flooding may take a high toll in damage, distress, and even human lives. The characteristics of the floods are different for both municipalities. In Pachuca the water flows fast and runs with great energy through the avenues and streets due to the steep slopes, however the Río de las Avenidas is tubed throughout its passage through the city. As for Mineral de la Reforma, intense storms cause high peak flows that exceed the drainage system capacity, flooding the streets of the city, especially in the areas with the lowest topographic gradient. Slum areas remain flooded after storms because there are few drains and most of the ground is highly compacted.

Fig 1. Pachuca's Metropolitan Core



Developed by authors based on INEGI (2020).

Metodology

Multicriteria decision analysis (MCDA) provides methodology and techniques for analyzing complex decision problems, which often involve incommensurable data or criteria.

The use of GIS and MCDA has proven successful in natural hazards analysis (Rashed & Weeks, 2003; Gamper et al., 2006) and other geo-environmental studies (Dai et al., 2001; Kolat et al., 2006), but this kind of model must have a procedure to analyze the uncertainty associated with spatial outputs. The purpose of this study is to present an urban flood hazard model using MCDA techniques with GIS support and to evaluate it by means of uncertainty and sensitivity analysis. Extreme events disrupt the occurrence of natural phenomena; whether geological, atmospheric or a combination of both.

Analysis of the factors influencing the susceptibility to flooding

The research process was carried out at three main levels of analysis to evaluate the susceptibility to flooding. In the first instance, a literature review was carried out and the relief mapping was made by processing the digital map with contour lines every 20 meters.

A digital terrain elevation model was developed, obtained by using the Digital Topographic Map from the National Institute of Statistics, Geography and Informatics (INEGI) with a resolution of 20 pixels. The Digital Elevation Models (DEM) are a representation of the surface that is a raster object which combines geospatial information with elevation values. The DEMs were created with the Delaunay triangulation method (Legrá-Lobaina et al., 2014) using TIN (Triangle Irregular Network) by triangulating a set of vertices (points) related to contour lines. Subsequently, a slope raster was created, heuristically reclassifying it to obtain the degrees of inclination of the terrain at different points in the PMC.

The objective of risk assessment and risk mapping is to represent variations in the spatial intensity of both hazard and vulnerability. Thematic risk maps are necessary tools in order to develop more adequate public policies for land use planning. In addition to taking appropriate measures in the event of an emergency (Lirer and Vitelli, 1998). According to the United Nations Office for Disaster Risk Reduction (UNDRO), risk can be defined as the expected number of lives lost, people injured, property damaged and economic activity interrupted due to a particular natural phenomenon (Torrieri, 2002).

Based on the selection of the determining factors that cause flooding processes, weights or weightings are assigned based on their relative influence on instability. Subsequently, the relative weight of each factor with respect to the others was determined, using the multicriteria analytic hierarchy process method by Saaty (1980). With this method, a square matrix is first created, in which the number of rows and columns is defined, in this case by the number of instability factors. Each element of the matrix is assigned a weight, which is a value that represents the relative importance of the factor in its row with respect to the factor in its column in terms of possible instability. The factors and / or variables that were considered to determine the susceptibility to flooding were, type of slope, distance of the discharge channels, social vulnerability and cover type. An important aspect of the method used is the generation of condensed and systematic information on landforms and associated environmental phenomena, all reinforced and verified by field work. The data generated integrated with GIS is useful for the preparation of the risk map with great precision.

Matrix was built with the variables slope, distance of the discharge channels, social vulnerability, and cover type that were compared and weighed. Subsequently, the multicriteria evaluation was continued, which is applied if the criteria have different relevance to the proposed evaluation, and is based on the analysis, discussion and hierarchy of alternatives in order to generate solutions to territorial problems, dangerousness and vulnerability. Based on an objective, which in this case is to evaluate the processes of flooding hazard, a decision rule is chosen and structured to integrate the criteria, which are established from this objective (in this case four), and the selection alternatives that are represented by the spatial objects (pixels) contained in the thematic layers (digital maps).

Each of the criteria constitutes a thematic map of the GIS database, so at this stage it is understood that for the entire evaluation it is crucial to define and make the selection of criteria in an appropriate way. The multicriteria analysis bases its operation on integrating all the variables in a matrix, called decision or evaluation, where the main column contains the criteria, the main row, the alternatives, and inside the matrix are the scores obtained from the criteria. These scores represent the value, level of preference, degree of attraction or significance that each alternative has obtained for each criterion. Thus, in the matrix, quantitative values were assigned to the corresponding categories or classifications of the criteria, since generally in the printed maps or in the consulted bibliographic sources they are dimensioned in nominal or qualitative scale, so they were converted to a common range or quotient scale (Table 1).

Table 1. **Factor comparison matrix to determine flooding susceptibility.**

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
1/9	1/8	1/7	1/6	1/5	1/4	1/3	1/2	1	2	3	4	5	6	7	8	9
Extremly		Strongly		Moderately		Slighty		Equal	Slighty		Moderately		Strongly		Extremly	

This assessment or interpretation allowed, using the GIS, that the cartographic and thematic information of the criteria for each of the alternatives (pixels), was subjected to a series of operations of classification, overlapping, interpolation, calculation of distance or proximity in order to represent the different classes or values of hazards, and that, finally, the alternatives were reclassified into values from lower to higher according to the managed score scale (in this case 1 the lowest risk at 5 the highest risk). Once the evaluation matrix and the thematic maps were established, the relative importance of the criteria was established, because not all of them have the same influence or preference intensity as the type of evaluation projected, and assigned a specific weight or weighting.

This assignment was based on the previous references, views and experience of the specialists (researchers and decision makers), the consultation and opinion poll with experts on the subject, in the literature consulted, for all of which the characteristics of the study area were taken into account. There are different approaches to establish the weights of the criteria, among which one of the most widespread in studies of the territory and in the GIS environment is the one known as Analytic Hierarchy Process (AHP), which was developed by Saaty (1980).

The scale of measurement established for the allocation of weights is a numerical scale of 17 values or hierarchies, ranging from a minimum value of 1/9 (the least important) to 9 (the most important). Obviously on the diagonal of the matrix only values of 1 are assigned, which denotes equality with itself in the comparison of each criterion. Similarly, if two factors have the same importance, they will be given a value of 1. The GIS has a module that allows to perform the automated matrix summation procedure (and consequently maps), by superimposing and multiplying each map by a constant (weight of criteria), producing a new map, in this case the flooding risk map.

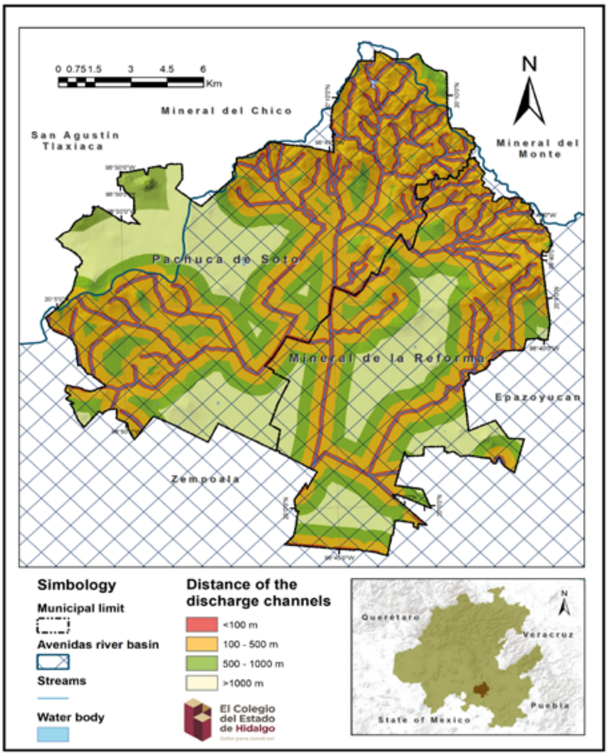
Analysis and results

According to the American Society of Civil Engineers (1996). The process of urbanization and its hydrologic effects are widely known. At an individual development site, trees and natural cover are replaced by buildings and impervious cover. These physical changes result in a loss of interception and depression storage, a decrease in the potential infiltration, and a redirection of principal flow paths. To evaluate the extent of flooding due to the hydrologic impact of the alteration described above, the model incorporates four variables: Distance to the discharge channels, slopes, land use and vegetation and social vulnerability. These variables were selected based on their relevance with respect to the flood susceptibility of the study area and the quality of the data sets that were available. The relevance of the variables and their classification in classes is described below.

Distance to the discharge channels

Distance to the discharge channels has great importance in urban flood mapping, in the case of Pachuca and Mineral de la Reforma. According to the records from the local authorities, the most affected areas during floods are those near these channels, as a consequence of overflow. This layer was created using a multibuffered operation identifying all areas within the specified distances from the channels. The distance intervals used were: <100 m, between 100 and 500 m, between 500 and 1000 m, and >1000 m.

Fig. 2 Distance of the principal discharge streams and channels of Pachuca's Metropolitan Core.



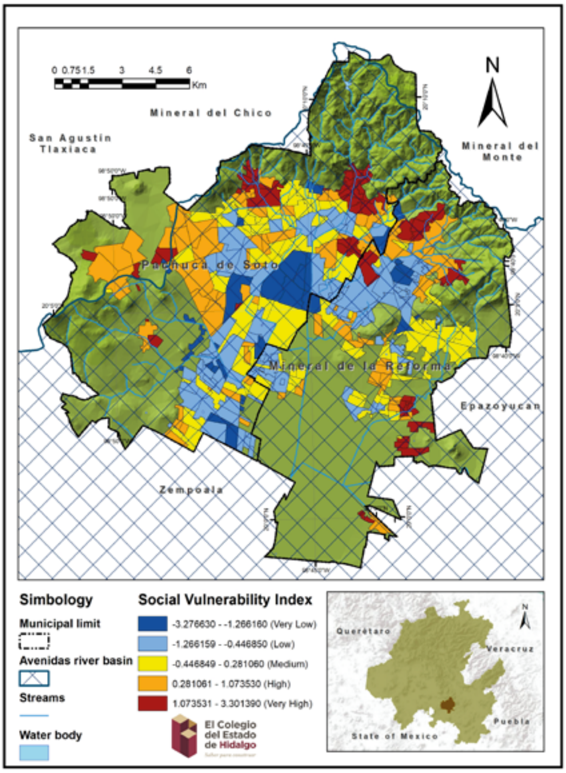
Developed by authors based on INEGI (2020).

Social Vulnerability Index

Measure vulnerability is essential for reducing disaster risk and requires an ability to identify the complexity of this concept to reduce the potentially gatherable data to a set of important indicators that facilitate the estimation of vulnerability (Birkmann, 2013). Some approaches for measuring social vulnerability, define indicators by the spatial level, function, data basis, level of aggregation. Cutter *et al.* (2003) utilizes the hazards-of-place: those characteristics of communities and the built environment, such as the level of urbanization, growth rates, and economic vitality, that contribute to the social vulnerability of places. Model of vulnerability examines the components of social vulnerability; include the individual characteristics of people like age, race, health, income, type of dwelling unit and employment.

The resulting map shows that the areas with less social vulnerability, consisting of residential areas and apartments, are located in the lower areas of the city, occupying the floodplain of the Avenidas river. While the areas with the greatest social vulnerability, made up of popular neighborhoods and irregular settlements, are found in the upper parts of the nearby hills.

Fig. 3 Social Vulnerability Index in urban areas of Pachuca and Mineral de la Reforma.



Developed by authors based on INEGI (2020).

Dwyer *et al.* (2004) is focusing on investigating aspects of social vulnerability and not hazard, two indicators relating to hazard have been included in order to provide a context for investigating vulnerability. The indicator includes variables following a socio-economic criterion to establish the vulnerability of a person within a household to natural hazard impacts, like age, income, residence type, tenure, employment, household type, disability, house insurance, health insurance debt and savings, car, gender, injuries and residence damage. In addition, Aroca-Jiménez *et al.* (2017) raises the need to build a comprehensive indicator which requires an understanding of a social component of risk. This approach has been based on calculating composite indices from sociodemographic and economic characteristics, which considers exposure, sensitivity and resilience. After a thorough selection process, the variables were classified in 8 thematic information blocks: population, dependency, education, employment situation, healthcare services, development and infrastructures, buildings and collective vulnerability.

In addition, Rodríguez (2000), include three dimensions to measure the social vulnerability: 1) Habitat, which is related to the physical state of the house, such as floor materials, number of rooms and services such as electricity, sewer system, water and access to goods and technologies; 2) Human capital, considering individuals over the age 15 with no schooling; 3) In the economic scope (dimension), the occupation status is considered and in the social protection scope (dimension), the population that has no health care access is included. With information from the 2020 Population and Housing Census (INEGI, 2020), the principal component analysis technique is used to create the social vulnerability index (SVI) separated by town and how it affects the territory with Geographic Information Systems (Fig. 3).

Based on existing literature, the variables considered for constructing the SVI are shown below for town in the municipalities of the PMC (Table 2).

The Principal Component Analysis (PCA) measures the proximity between observations and grouping them into clusters according to their characteristics (Alaminos et al., 2015). The objective of the PCA is to reduce the variables in a synthetic indicator that reveals the social vulnerability conditions based on the variables included in the index and the dimensions considered; for PMC locations.

With information from the 2020 Census, a social vulnerability indicator was constructed, which is classified into 5 vulnerability levels using the natural breaks method. The classifications were: very high, high, moderate, low and very low. Geographic Information Systems were used to show the SVI values and their behavior in the territory. Once the existing social vulnerability levels have been identified, an analysis of susceptibility to flooding movements is performed to identify areas that were most exposed to disaster risk.

Table 2. Variables used for social vulnerability models for towns in the municipalities of the PMC (n=364).

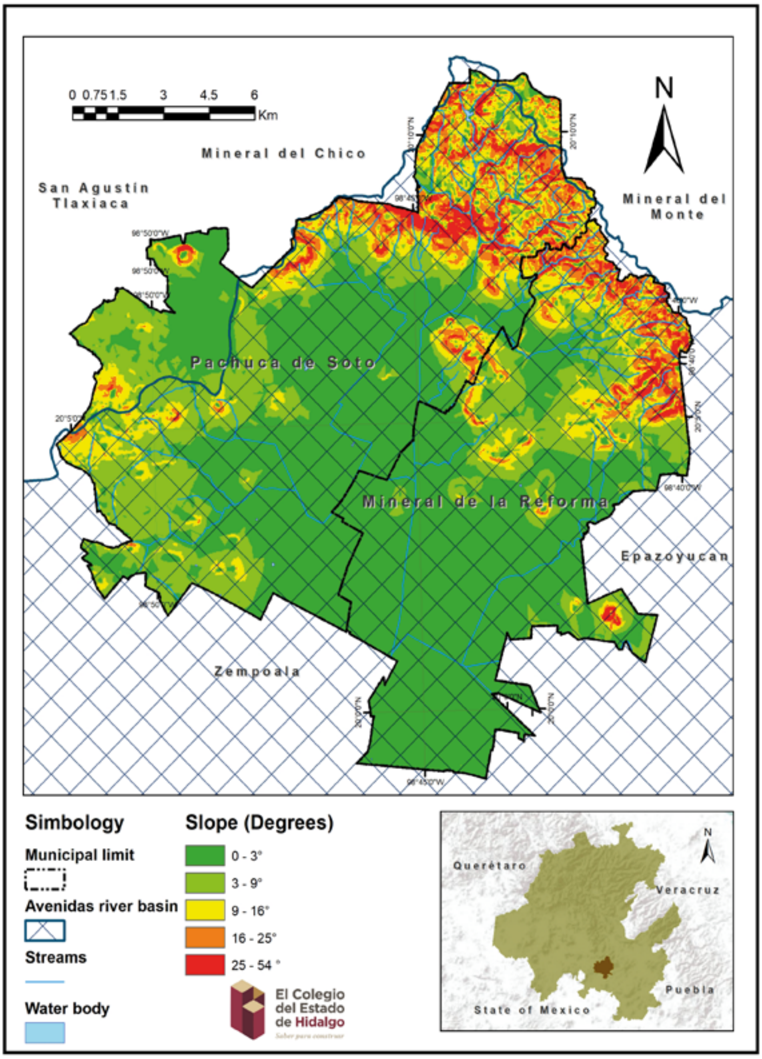
Variable	Indicator
p_unemp	Unemployed population
p_nohealt	Population with no health care access [1]
p15nosch	Population aged 15 years and over with no school
phdf	Private homes with dirt floors
phob	One-bedroom private homes
phnoel	Private homes with no electricity
phnowin	Private homes with no water indoors
phnosew	Private homes with no sewer system
phnoinctec	Private homes without information and communication technologies
phnoas	Private homes with no assets
aver-liv	Average number of people living in the home
depdem	Population aged 0-14 and more than 60 years old
p_female	Female population
density	Percentage of population

Source: Prepared with data from INEGI (2020)

Slope

Slope is an important factor to identify those zones that have shown high susceptibility to flooding over the years due to low slope gradient. The slope of the land in the watershed is a major factor in determining the water velocity. Thus, on very flat surfaces where ponding areas occur, a considerable amount of the surface runoff may be retained in temporary storage (USDA, 1986). The general direction of runoff in the study area is northeast to south and slopes varies from more than 91% along the northern border to less than 3% in the southeast part of the PMC. The slope map was prepared in percent grade using the DEM of the study area. The values were subdivided into five classes as shown in Table 3.

Fig.4
Slope



Developed by authors based on INEGI (2020).

Land Use and Vegetation

Impervious cover (buildings, roads, and parking lots) reduces infiltration capacity and runoff from paved areas can add substantially to total runoff. Urbanization typically leads to a decrease in lag time, an increase in the peak discharge, and an increase in the total discharge for a particular flood (Murck *et al.*, 1996). Land use and vegetation database, based on the soil cover, it was determined that urban areas, deforested zones, agriculture are the most susceptible to flooding processes, areas with no visible vegetation, pastures (grasslands) and rainfed while, oak forests and pine and coniferous forests are the least susceptible (Figure 5).

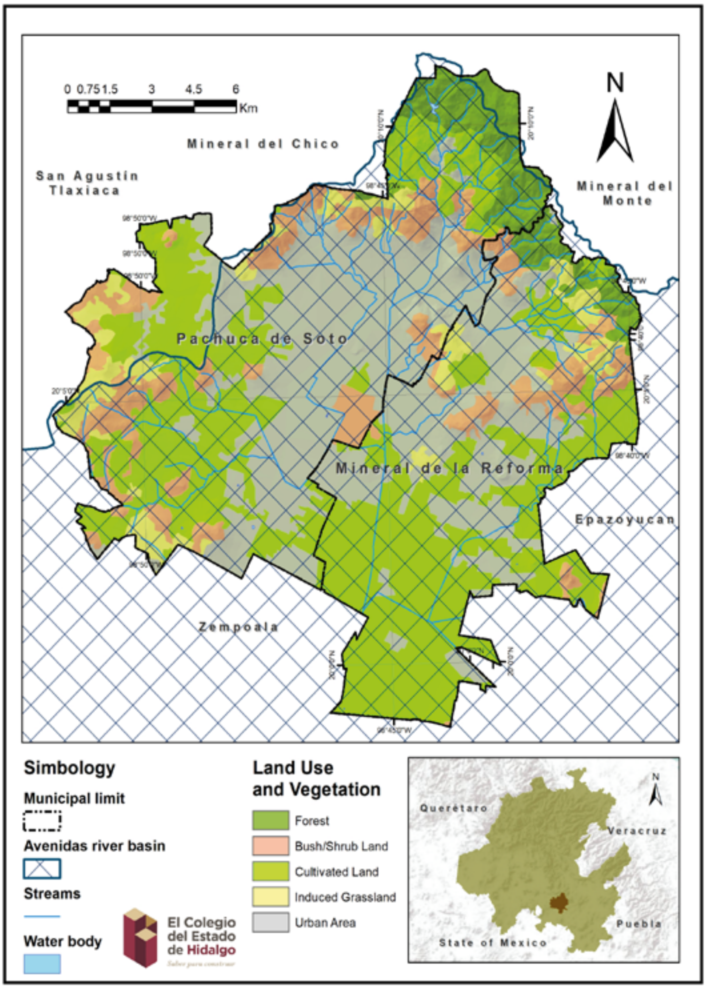


Fig.5 Land Use and Vegetation

Developed by authors based on INEGI (2020).

Development of weights

During the analysis, weight values were assigned to the layers and rank values to the classes of each layer according to their importance in the case study of area floods. The assigned weight and rank values for the layers/classes of the study area based on the local characteristics of each layer and engineering judgment, on the literature, the experience of the researchers and the field work. In the preparation of the risk map, it was decided to use intervals of 1 to 5, assigning the value of 1 to the lowest risk and 5 to the highest risk (Table 3).

The most important layer according to weight was defined as the distance to the discharge channels; because the historical review of flood events reveals those areas near the channels are highly affected as a consequence of their overflow. Slope layers were assigned importance in the accumulation and discharge of the water. The VSI layer is relevant because it defines the degree of exposure of populated areas to flooding. Furthermore, urban areas with high degrees of VSI may have little or no capacity to respond or recover from a flood event. Regarding the use of land and vegetation and based on land cover, it was determined that urban areas and zones where land use changes, they produce less water infiltration and low surface retention. Woods and bush/shrub areas have not suffered changes that can infiltrate water to aquifers and naturally retain it in soil.

We compared the four variables related to the help of a scale or continuous appreciation table (Table 4), which indicates the relative importance of the first variable with respect to the second, this with the third and so on, and allows to form a simultaneous comparison matrix by pairs. The scale varies from 1/9 indicating an extremely low importance of the first variable with respect to the second, to 9 in case the first variable is extremely more important than the other variable. The flooding risk matrix was developed considering 4 variables (distance of discharge channels, slope, social vulnerability index and land use and vegetation). It was established that distance of discharge channel was 9 times more important than land use and vegetation, 7 times more than social vulnerability index, 5 times more than slope; the social vulnerability index is twice as important than slope and 3 times more important than land use and vegetation, and finally, land use is 1/4 less important than slope.

Table 3. Values used to reclassify map contents, which were later used to build the final map through multicriteria analysis.

GridCode (pixel) for design risk level	Distance of Discharge Channels (Classes)	Social Vulnerability Index (Classes)	Slope (Classes)	Land Use and Vegetation (Classes)
1 (Very low)	-	- 3.276630 to -1.266160	25 – 45°	Forest
2 (low)	>1000 m	-1,266159 to -0.446850	16 – 25°	Bush/Shrub Land
3 (medium)	500 – 1000 m	-0.446849 to 0.281060	9 – 16°	Cultivated Land
4 (high)	100 – 500 m	0.281061 to 1.073530	3 – 9°	-Induced Grassland
5 (very high)	<100 m	1.073531 to 3.301390	<3°	Urban Areas

Maps were made that made it possible to form the Factor Comparison Matrix (Table 4) to determine the susceptibility to flooding. The variables that determined the flooding hazard are distance of discharge channel, a social vulnerability index, type of slope and land use and vegetation, are shown in the generated cartography. Condensed information was obtained on geographical features and environmental phenomena that allowed the elaboration of maps showing the risk of flooding. The above constitutes an additional contribution of the present work since it does not exist for the PMC. A very useful supplementary tool for this research was the Geographic Information Systems, which facilitated geomorphological analysis and provided precise and concrete data on geomorphological processes and the phenomena associated with them; as is the case with flooding.

Table 4. Factor comparison matrix to determine flooding hazard

	Distance of the discharge channels	Social Vulnerability Index	Slope	Land Use and Vegetation	Weights
Distance of the discharge channels	1	-	-	-	.6496
Social Vulnerability Index	5	1	-	-	.1632
Slope	7	2	1	-	.6540
Land Use and Vegetation	9	3	1/4	1	.1215

Discussion

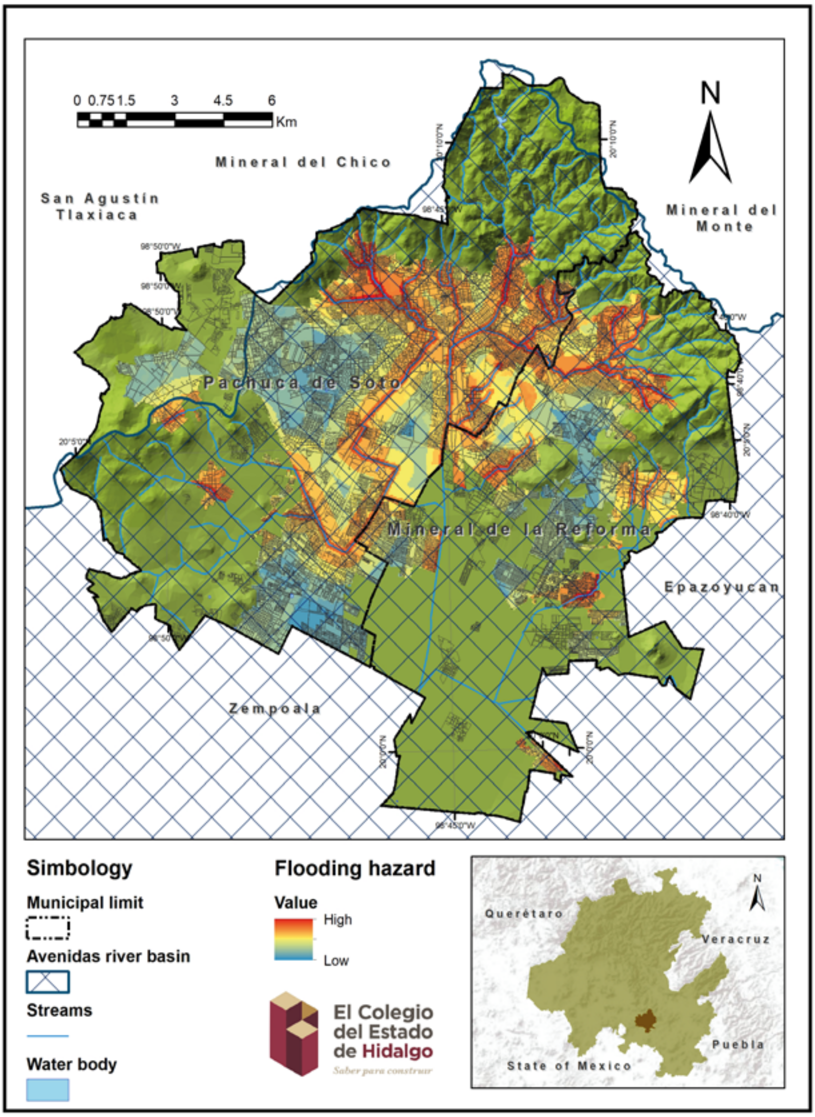
The methodology followed in this paper is simple and was focused on the analysis of those variables that control water routing when high peak flows exceed the drainage-system capacity. Multicriteria MCDA techniques are generally used to rank possibilities, commonly referred to as alternatives within the MCDA field, from most preferred to least preferred. However, MCDA can also be used to identify a single most preferred alternative, to short-list a number of alternatives for subsequent detailed analysis, or to determine acceptable and unacceptable alternatives (Malczewski, 1999). In this case Analytic Hierarchy Process (AHP) was chosen over a variety of MCDA techniques to obtain an urban flooding model of the area. This technique has become one of the most widely used methods for the practical solution of MCDA problems (Cheng, 1997; Chan *et al.*, 2000, Aceves-Quesada *et al.*, 2006; Fernandez and Lutz, 2010, Medina-Pérez *et al.*, 2022) and has gained wide application in natural hazard and suitability analysis (Banai-Kashami, 1989; Dai *et al.*, 2001). However, some disadvantages of this method are that the selection of the flood hazard areas is dependent on the judgment of the experts and can be sensitive to changes in the decision weights associated with criteria (Chang *et al.*, 2008).

The flood hazard map of the study area was divided into five classes as follows: areas with very high to high hazard, areas with moderate hazard, areas with low hazard and areas with very low hazard (Fig. 4). The boundary conditions for the categories were evaluated according to expert judgment. The areas labeled in the map as high hazard are strongly influenced by the discharge channel courses according to the high weight given to this factor in the model (0.6496). The assignment class is due to the great importance of the drainage overflow in the worst flooding events that occurred in PMC.

The final map shows that the north territories in Pachuca and Mineral de la Reforma (nearest Sierra de Pachuca mountains) part has the highest flood hazard over an extended area as a consequence of the combination of lowlands with slopes under 2.87% and the presence of urban stream channels with poor maintenance plan (northeast areas of Mineral de la Reforma known Villas del Alamo and Ciudad del Conocimiento). In this area, several neighborhoods with flood records have been reported in the last years by the local authorities, above statal university installations. During the first half of the 20th century, the historic center of the city of Pachuca suffered catastrophic floods. In the 80's, during the government of Guillermo Rossel de la Lama, the Río de las Avenidas was tubed from Minas de loreto to Madero Avenue and the Río Sosa from the 11 de Julio neighborhood to the Real de Minas. However, the accelerated growth of the PMC invaded new areas of the river floodplain. For this reason, at the beginning of this century during the government of Miguel Ángel Osorio Chong, channels and hydraulic conduits were built in the Río de las Avenidas from Madero Avenue to the south of Mineral de la Reforma (Las Torres). However, the absence of territorial ordering and the excessive growth of the urban area contribute to the persistence of the danger of flooding in PMC.

There are some neighborhoods with historical recorded floods situated in areas that correspond to high hazard in the map, as the cases of El Chacón, Paseos de Chavarría, Tuzos, Forjadores, most of them located in the southern portion of Mineral de la Reforma municipality. Another factor that could be an increasing hazard parameter is the change in local relief as a consequence of bad territorial ordering planning or unfinished civil structure (pipes, drainage system, roads, etc).

Fig. 5 Flooding hazard map in Pachuca's Metropolitan Core.



Developed by authors based on INEGI (2020).

Conclusions

The final urban flood hazard map represents a new tool for the municipalities under study which may assist the planners and decision makers to evaluate those areas in need of revision of discharge infrastructure to reduce the vulnerability of the population to flood events. The map shows that the zones located near the main discharge systems are in danger. Highest-risk areas are those in the north of Pachuca and principal urban areas of Mineral de la Reforma. These are characterized by the confluence of several channels, a lowland topography, and a gentle slope gradient. The model should be used as a first-stage analysis in the problem of floods in the study area. More detailed models will require more reliable information about precipitation and flow peak discharges, as during hurricanes and cold fronts. MCDA techniques within a GIS environment have proved to be a powerful methodology to generate hazard maps with a good degree of precision. In this study, data provided by local authorities regarding neighborhoods affected by floods plotted over the final map showing a remarkable coincidence with the high hazard areas.

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