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Research Article

Study of Flood Risks in Urban Zones of the Mexican Republic

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Abstract

The objective of this article is to give an understanding of a methodology for the generation of risk, hazard and vulnerability maps due to flooding in urban areas. This work is part of an update of the Flood Risk Atlas of Mexico. Models with a two-dimensional (2D) structure that includes the tie rod and velocity are used simultaneously. The foregoing will permit flood risk prevention to the local infrastructure. With this methodology, flood zones can be prioritized to assess flood damage so as to mitigate the loss of economic resources. Simulations with one dimensional model are considered for this, as well as two dimensional (2D) simulations for the generation of flood maps. This will help as a decision-making tool for flood control in urban zones. This methodology is applied in the city of Tuxtla Gutierrez, Chiapas to demonstrate its scope and benefits.

Introduction

Throughout its history, Mexico has been affected by the inclemency of meteorological phenomena due to its geographical location. Among the principal problems that are generated by the meteorological phenomena of unusual intensity are extreme precipitation, hurricanes, storms and tropical depressions just like convective phenomena. Such precipitation generates floods that often cause severe damage to the population, roads, urban infrastructure, hydro-agriculture, wildlife, as well as diverse economic activities and may even lead to human casualties.

Floods in cities can be caused by overspill from rivers, rising sea levels, broken earth dikes, dams, or water discharges from reservoirs. This is due to the accelerated growth of urban areas, generating irregular human settlements in stream beds; invasion of federally protected areas; and the absence of an urban development plan that takes risk zones into consideration. Thus, it can be said that flood problems are due to three factors: a) human, b) natural and c) structural failures of hydraulic works.

Whatever the factors are, it is important to determine, by means of some mathematical calculation, the costs due to flood damages, both to household furnishings and to the structural nature of homes, as well as public and private buildings. Other damages include the deterioration of streets and bridges, economic losses to businesses and industries, the halt of the student population's academic activities, loss of life caused directly by the flood or through diseases produced from the contamination of the water (often associated with the destruction of the city's water distribution and sanitation infrastructure)

Given this situation, having a methodology to generate flood risk maps is decisive to propose actions that lead to the mitigation of this risk and consequently the reduction of damages caused by surface runoff.

Methods that are used for the estimation of the costs caused by flooding

Within the literature, there is a variety of methods that are used for the estimation of the costs caused by flooding. These methods are described in the following:

Historical Method

Historical data shows the water depth reached in flood-prone areas that cause damage to infrastructure, flood damage costs can be inferred from said data. Land use changes over the course of time, however, and therefore the cost with past events vary.

Empirical Method

The empirical method, similarly to the historical, is based on the relation between the hydrological characteristics and the historical damages for different periods of return. Its precision depends on the quality of the information and is only applicable in the same region that is studied, which is why it cannot be generalized in a spatial or temporal manner [1].

Correlation Method

Based on an aggregate formula, this method uses a relationship that directly estimates damage costs caused to a property in relation to the height the flood water reached. This formula is obtained from an analysis of the correlation between the estimated damages from a field study, the hydrological characteristics, and the inundated area's economics [2].

Integrated Linear Method

This method consists of combining diverse factors, with which costs are calculated for the damages caused by the flood [3].

Equation 1

$$C_d = K_d * U * M_s * H * A$$

Where:

C_d = Damage costs caused by a specific flood ($/m)

K_d = Damage caused to the structure in accordance with the depth the water reached (%)

U = Proportion of the flooded area with urban development (%)

M_s = Market value of the flooded infrastructure per square meter ($/m^2)

H = Average water depth of the flooded area (m)

A = Total flooded area (m^2)

INRS-ETE/MEF Method

The method used by the National Institute for Scientific Research (INRS) Water, Earth and Environment (ETE) of the Finance and Economy Ministry of Canada is based on the depth of water reached in homes (submergence) which is determined with the aid of a hydrodynamic model or some other approximation that establishes the relationship: level-flow. The damage associated to each possible flood event is relative to the replacement value of the residences and the flow depth reached on account of flooding

The depth of water submergence in buildings affected by floods is the most known variable for calculating damages or risks, although efforts are currently underway to combine this information with water velocity, erosion and rubble content. The method consists of predicting the average damage index in buildings according to the local submergence level of each home or infrastructure based on the following equation [2]:

Equation 2

$$D = \frac{K \lfloor e(-\beta H) * e(-\alpha) - 1 \rfloor}{(e(e(-\alpha)) - 1)}$$

Where:

D = Residential Damage to the building linked to a rain event ($)

K = Replacement value of the home ($)

H = Height of submergence (m) in respect to the building floor

β = Calibrated coefficient

α = Calibrated coefficient

With the use of the previous equation, behavior curves were made for damage assessment (unitary damage) in relation to the submergence height of a building for each type of residence.

CENAPRED Method

In keeping with CENAPRED [4], risk is defined by the combination of three factors:

The value of goods exposed C, vulnerability V, and the probability P that a potentially damaging event occurs to the exposed goods. Symbolically:

Equation 2

Risk = C P V

The risk estimation can be made at a housing level, so that when added to that of other homes an idea of the risk in a locality is found. This in turn, in aggregate, would provide an estimate of the risk for a municipality and onward. In this manner, hazard, vulnerability and risk maps can be created according to the aforementioned ranges.

To say that a risk of flooding exists in any municipality of the Mexican Republic, a high probability of heavy rainfalls must be observed within it that exceeds its threshold in the 24 hours that follow, and that it is classified with a high or medium vulnerability to where adverse effects could be expected in the community or its assets.

Method proposed by Ribera [5]

The risk maps or potential damage maps due to flooding can also be defined as a situation likely to cause damage as a consequence of a rain event that presents itself in a vulnerable environment, for example: the area of some neighborhood or area of a city. In this way, risk can be formulated as the product of the affected area by the threat of the event, the number of elements (houses, people, etc.) that are in jeopardy and their vulnerability [5].

Equation 3

$$Risk = AffectedArea * Threat\ of\ the\ Event * Elements\ in\ Play * Vulnerability\ of\ the\ elements$$

To make risk maps, four maps must be available: the map of potential flood areas, the hazard map, the exposure map, and the vulnerability map. The first two serve to locate and characterize the event and allocate a place in the hazard map. The third and fourth maps serve to locate and characterize the elements at risk that ultimately lead to the final vulnerability map.

Methodology

The method proposed by IMTA [6] bases itself on articulating hazard and vulnerability maps to later be able to generate the costs for damages associated with floods and areas at risk (Figure 1).
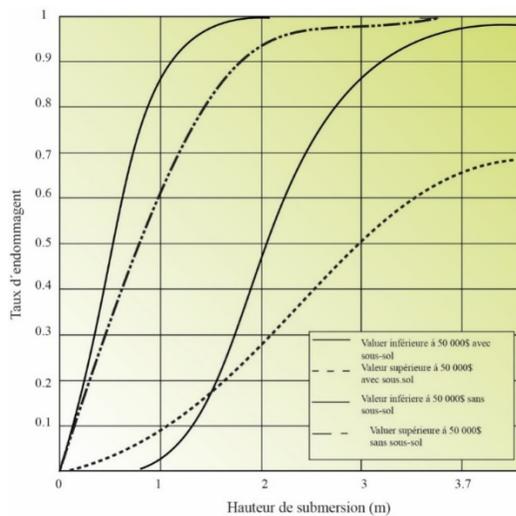

Figure 1: Damage behaviour curve [2].

Flood Hazard Maps

The risk of flooding can be defined based on certain criteria; these can be the flow-depth and the velocity of water reaching the streets, rivers or streams. The overflow of the natural river channels is known as river flooding. Rainfall runoff excesses within an urban area, after saturating its soil, may remain for hours or days and is called a storm flood. Other phenomena exist that can provoke a flood, like high tides, which result in the average sea level rising, causing a coastal flood. Other phenomena that can provoke a flood are tsunamis or the failure of a hydraulic work [7].

Hazard maps for a flood are a graphic representation of the results of excess rain, river overflow, an increase in the surf, a breach in a dam, etc., in which the water level reached and the velocity of the drainage within an urban area, river bed or lagoon are overlapped.

The following is a description made of the different criteria used at an international level for the definition of hazard map.

Method Proposed by the IMTA [3]

Yamanaka and et al. [8] states that (hazard) maps are obtained through three principle aspects, which will provide the basic information for the construction of the numerical surface runoff model. The first aspect is based on analyzing the precipitation in order to establish the spatial and temporal behavior of the rain. The second aspect, takes into account the urban infrastructure of the region being studied. Finally, the third aspect refers to the delimitation of sub-basins and micro-basins of studies considering the geomorphologic parameters (area, perimeter, width, principle channel's length, etc.), see Figure 2.
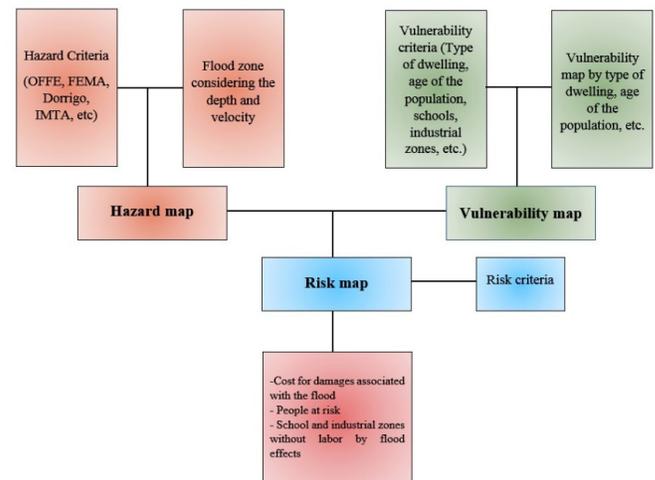

Figure 2: Methodology to define risk maps [1].

The analyzed scenarios correspond to 2, 5, 10, 20, 50, 100, and 200-year return periods. As a result of each scenario, a grid of velocities and flood flows is generated which permits the creation of hazard maps. The map is plotted and generated with this data according to Table 1, where, unlike other methods, slippage and overturning provoked by floods are taken into account.

Level	Height (m)	Overturning (m²/s)	Slippage (m³/s²)
Null	h < 0. 3	vh < 0. 3	v^2h < 0. 2
Low	0. 3 ≥ h < 0. 5	0. 3 ≥ vh <0. 5	0. 2 ≥ v^2h < 0. 5
Medium	0. 5 ≥ h < 1. 5	0. 5 ≥ vh< 1. 5	0. 5 ≥ v^2h <1. 23
High	h ≥ 1. 5	vh ≥ 1. 5	v^2h ≥ 1. 23

Table 1: Established parameters for the construction of hazard flood maps.

Vulnerability maps of urban zones prior to the effects of floods

Vulnerability is the measure of the susceptibility of a property or asset exposed to the occurrence of a destructive phenomenon [4] of two exposed assets, one is considered more vulnerable if it suffers bigger damages under the same rain intensity. This is different to risk, which is defined by climate patterns (nature) and due to this it is difficult to modify. Vulnerability is one variable that man has the possibility to diminish.

The calculation for vulnerability is limited to the direct damages that properties or houses may experience, however, indirect damages are not taken into account like the psychological tolls exacted on people who find themselves affected by a rain event or very specific damages to businesses or industries [5]. This vulnerability calculation is very complex, specific or not quantifiable because it involves aspects such as loss of human life or damages to the environment.

Method to construct vulnerability maps proposed by CENAPRED

CENAPRED proposes criteria to evaluate physical vulnerability derived from the location of the houses and property in relation to the proximity to streams, and the characteristics of dwellings [7]. Vulnerability refers only to the assets of the population or household furnishings. Types of dwellings are divided into nine categories depending on the type of walls they have from M1 (cardboard and plastic) to M9 (bricks or concrete). The roofing materials of the dwelling are defined by six categories from T1 (cardboard and plastic) to T6 (slabs of connected concrete).

Based on the dwelling's wall and roof materials, CENAPRED presents a series of combinations between the nine types of walls and the six types of roofs of the dwelling for a total of 24 combinations. From these, four color coded levels of vulnerability are derived and defined as follows (Table 2):

Dwelling Construction in housing area	Color	Description	Vulnerability	Household Furnishing Costs (in $ dollar)
Type I	Red	The ratio between the numbers of private dwellings inhabited with a single room to the total number of dwellings was considered as an indicator. If the ratio for the block is greater than 0. 20 then the block's construction is considered as Type I.	High	$ 665. 24
Type II	Orange	The ratio between the numbers of private dwellings inhabited with two rooms to the total number of dwellings was considered as an indicator. If the ratio for the block is greater than 0. 20 and is not in Type I then the block's construction is considered as Type II.	Medium	$ 2 660. 98
Type III	Yellow	The ratio between the numbers of private dwellings inhabited with three or more rooms to the total number of dwellings was considered as an indicator. If the ratio for the block is greater than 0. 50, then the ratio between the economically active populations to the total population, which should be less than 0. 4, the block that fall in Types I and II should be discarded.	Low	Furnishings for a two-story house $ 8009. 59 Household furnishing damage here is considered to be half as much since these homes have two stories

Type IV	Green	The ratio between the numbers of private dwellings inhabited with three or more rooms to the total number of dwellings was considered as an indicator. If the ratio for the housing area is greater than 0. 50, then the ratio between the economically active population to the total population, which should be greater than 0. 4, must be excluded from Type I, II and III categorizations.	Very Low	Furnishings for a two-story house $ 15 965. 94 Household furnishing damage here is considered to be half as much since these homes have two stories
*Considered 1 dollar = 18. 79 Mexican pesos				

Table 2: Vulnerability by type of dwelling obtained from the analysis of the information contained in the AGEB [3].

Flood Risk Maps

To generate risk maps, the criteria for risk shown in Table 3 is defined in accordance to vulnerability based on dwelling type in the Table 2 and hazard obtained in the two dimensional hydraulic analysis for the city.

Four ranges define the risk criteria: Null Risk is defined by areas where the hazard result was null or for very low vulnerability and low hazard. Low Risk is those areas in the city that present a low hazard and a low to medium vulnerability or a medium hazard and a very low vulnerability. For this type of risk, household furnishings loss is considered to be 10%. Medium Risk in cases of low hazard and high vulnerability, medium hazard and low to medium vulnerability, or in high hazard and very low vulnerability considers losses in household furnishings at 50%. And ultimately High Risk is when hazard is medium and high vulnerability or high hazard and low to high vulnerability, household furnishings loss results is at 100% (Table 3).

Vulnerability by Type of Dwelling	Hazard			
	Null	**Low**	**Medium**	**High**
Very Low (Type IV)	Null Risk NR (0%)	Null Risk NR (0%)	Low Risk LR (10%)	Medium Risk MR (50%)
Low (Type III)	Null Risk NR (0%)	Low Risk LR (10%)	Medium Risk MR (50%)	High Risk HR (100%)
Medium (Type II)	Null Risk NR (0%)	Low Risk LR (10%)	Medium Risk MR (50%)	HR (100%)
High (Type I)	Null Risk NR (0%)	Medium Risk MR (50%)	HR (100%)	HR (100%)

Table 3: Risk criteria in function of hazard and vulnerability and per cent loss of household furnishings [6].

Results and Discussion

Case Study: Tuxtla Gutiérrez, Chiapas

Description of study area

The ZMTG is almost entirely within the basin of the Sabinal River (Figure 3), which is located in the Hydrographic Region RH30 "Grijalva-Usumacinta" and is within the Hydrological Subregion 30A "Alto Grijalva. 43. 129% of the basin lies within the municipality of Tuxtla Gutiérrez, 30. 39% is within Berriózabal, 23. 54% is within San Fernando and 2. 95% is within Ocozocoautla de Espinosa.
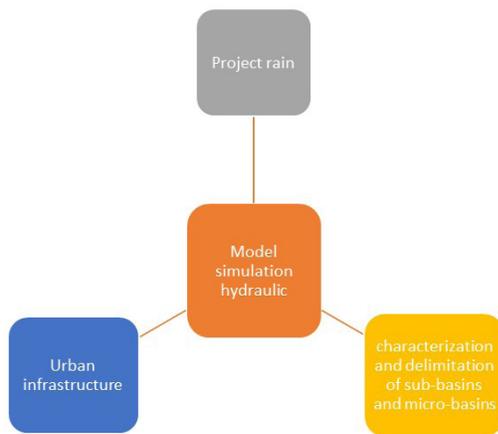

Figure 4: Study Area Location.

Flood Vulnerability Map

This methodology is an adaptation of the CENAPRED proposal, in keeping with the information contained in the AGEB. It was possible to consult, by housing area, the number of private dwellings with one room, private dwellings with two rooms, private dwellings with 3 rooms or more, in addition to the economically active population. With this information, the types of dwellings and therefore, the degree of vulnerability of the constructions for the city of Tuxtla Gutiérrez, Chiapas, as indicated in the Figure 5 and the vulnerability map of the city as shown in Figure 5 is generated based on the characteristics found.
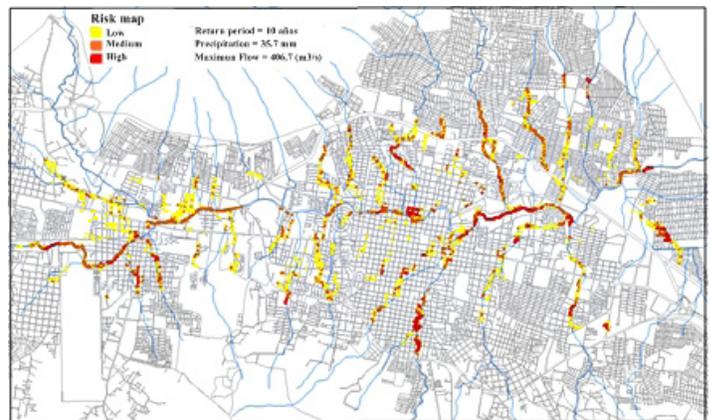

Figure 3: Essential variables for the two-dimensional hydraulic simulation [6].

Flood Risk Maps Construction

Generation of risk maps is done in line with the suggestions of Rodríguez and al., (2015) where the basic criteria are established in order to first construct the hazard maps and subsequently the vulnerability maps. Having the maps together, the process to construct the risk maps is carried through a matrix analysis.

Flood Hazard Maps

The Figure 4 flood risk maps generated from the 1D-2D simulation model in accordance to the criteria set forth in Table 2 are presented. As can be observed, the risk map for a 2-year return period starts to indicate the margins of low to medium hazard streams. This agrees with the field trips made in the streams in which the invasion of constructions was observed in practically all the stream beds.

Figure 5: Flood risk map for a return period of 10 years.

Flood Risk Maps

The Figure 6, 7 present the flood risk maps generated from the 1D-2D simulation model in accordance to the criteria set forth in Table 4 are presented. As can be observed, the risk map for a

2-year return period starts to indicate the margins of low to medium hazard streams. This agrees with the field trips made in the streams in which the invasion of constructions was observed in practically all the stream beds.
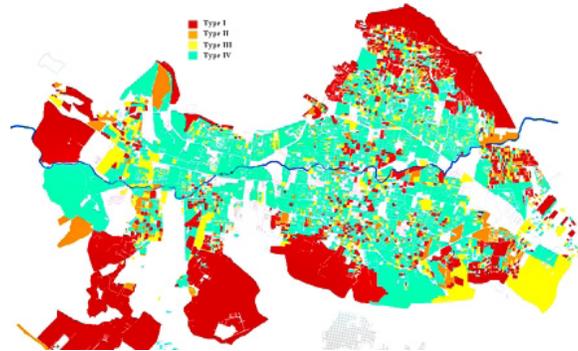

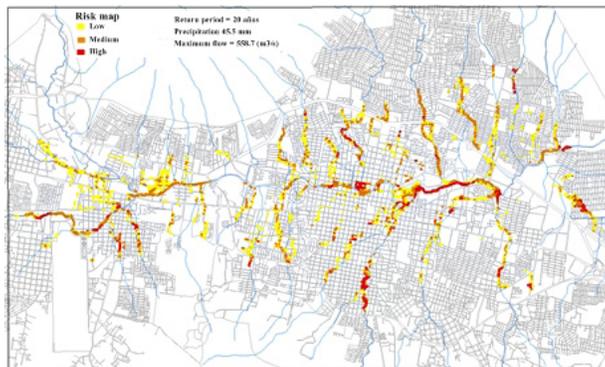**Figure 6:** Vulnerability map by type of dwelling.

Figure 7: Flood risk map for 20-year return period.

Damage Assessment and Shelter Relocation

Flood Risk Evaluation (damage to household furnishings and to the population)

At the Civil Protection Institute [9] a study was done with resources from the Fund for The Prevention of Natural Disasters (FOPREDEN) and the Government of the State of Chiapas to analyze alternatives for solving the flood problem caused by rains in the city of Tuxtla Gutiérrez. The corresponding report details flood damage costs for different return periods, see Table 4. The costs estimated by the Civil Protection Institute are compared with the costs estimated using the 1D-2D model.

Return Period in years	Damage Costs calculated by the Civil Protection Institute	Damage Costs calculated with 1D-2D model	Spending in (m³/s) considered in the analysis of damages by the Civil Protection Institute	Spending (m³/s) calculated with the 1D-2D model
	($ in millions of dollars)	($ in millions of dollars)		
2	-	5. 5	-	6. 9
5	10. 0	9. 6	12. 5	15. 1
10	16. 8	12. 8	19. 1	21. 6
20	21. 6	17. 1	26. 3	29. 7
50	25. 4	22. 4	36. 7	49. 5
100	27. 9	26. 5	45. 0	56. 0
200	-	27. 8	-	70. 2

500	33. 3	34. 2	66. 2	90. 7
1000	35. 6	37. 1	75. 7	107. 8
*Considered 1 dollar = 18. 79 Mexican pesos				

Table 4: Comparison of flood damage costs in accordance to the analysis by the Civil Protection Institute and the 1D-2D simulation model.

Conclusion

Different methods exist to estimate the damage costs associated with flooding, including: the historical method, empirical, correlation, integrated linear, INRS-ETE/MEK and CENAPRED. Any of these methods can generate a relationship between the events and the costs they can generate.

A criterion is proposed for the generation of flood risk maps in urban areas through a matrix linkage of the vulnerability and hazard maps. Set in 4 ranges: null, low, medium and high risk.

In addition, a calculation method is proposed for the analysis of damage to household furnishings and to the dwelling's infrastructure; and a simplified probabilistic evaluation of flood risk is made, where the excess-loss curve is obtained for the city in question.

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