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Vulnerability Assessment with Scarce Information for a Quantitative Flood Risk Model. Case Study Monteria-Colombia

Haider Hoyos ¹, Blanca A. Botero ²

¹ Corporación Autónoma Regional de los Valles del Sinú y del San Jorge – CVS.
Montería, Colombia

² Engineering faculty. Universidad de Medellín. Medellín, Colombia

babotero@udem.edu.co

Abstract. A quantitative flood risk assessment requires that vulnerability and hazard be evaluated quantitatively as well. In our research, we assess the flood risk of a south-east suburb of the city of Montería Colombia. We proposed to assess vulnerability through damage functions development and their incorporation in the flood risk assessment. Risk is quantifying as expected annual economic loss. Vulnerability is estimated based on the relationship between the physical condition and the contents of the households, with their ability to resist flooding. Flood damages in movable property, structures and public areas were established through depth-damage functions. Data for construction of these depth damage functions were obtained through a survey and field observations of the entire selected area. In order to identify damage, we have taken advantage of the recent memory of the communities regarding their perception of real damages during a flood occurred in July 2010. Structural elements and movable assets were classified in categories and people were asked about damage in these categories. Additionally, the water marks on walls, doors and other structural elements were identified. In order to quantify hazard, we calibrate a simple hydrological model and a hydraulic model, based in the records and water marks left by the July 2010 flood. A quantitative risk model was applied that incorporates the quantitative risk and vulnerability estimation. Depth- damage functions developed are a useful tool that can be used in other regions in Colombia and Caribbean with similar socioeconomic and climatic conditions. Results shown that it is possible to typify the houses and the movable property by means of the construction of functions and it is possible to obtain the quantitative risk, contributing a practical tool for the urban planning of this zone of the city.

1. Introduction

Risk assessment from a quantitative approach allows obtaining values that can be included in a cost-benefit analysis to evaluate different risk reduction alternatives. One way of representing risk quantitatively is to estimate the annual economic losses, in such a way that the risk can be transferred through mechanisms as flood insurance. For a quantitative flood risk assessment, it is necessary to quantify hazard and vulnerability as well. However, risk models have the greatest uncertainties when quantifying vulnerability in terms of losses and damages [1]. Flood damage estimation is a key step to assess the annual economic loss and it is useful for mobilizing investment and developing policies for flood loss prevention [2].



In [3], vulnerability is defined as the characteristics and circumstances of a community, system or good that make them susceptible to the harmful effects of a hazard. Physical vulnerability is the predisposition or physical susceptibility that a community has, to be affected or to suffer damages in case a natural or anthropic destabilizing phenomenon manifests itself [4]. For the assessment of physical vulnerability, [5] established flood damage by analysing the height-damage scenario and the relationship between different flood parameters and land use characteristics. [6] presents a vulnerability analysis based on the identification of direct and indirect, tangible and intangible damages, finally selecting the tangible direct damages for their accuracy when measuring them. To [4] tangible damages are related with direct effects (losses of capital, existence and production). [7] defines direct damages as those caused by direct physical contact between water and the elements that are in its way. For the quantification of tangible direct damages, [6] determines the exposure and the damage assessment. The susceptibility of the exposed elements is expressed through damage functions, specifically the depth-damage functions. From these curves and from the economic assessment of the damage, it is possible to estimate the risk of flooding, such as the damage in terms of economic losses that will occur for each flood map and the expected annual economic loss.

In this paper, we assess flood risk, as expected annual economic loss, spatially distributed over the south part of Montería City, specifically in a suburb named Villa Jimenez. La Niña event during 2009 and 2010, caused serious emergencies in Colombia due to floods, especially in the northern area of the country where the city of Montería is located. In July 2010, Villa Jimenez was flooded for more than three days. The level reached by the water in the houses was marked on the walls, as it produced deterioration of the paint and the wood that forms the walls of the different types of housing. This flood event, that we called, reference flood event, was also recorded in the memory of the inhabitants of the area and was documented in several local newspapers. Vulnerability is evaluated as potential flood damage and local depth-damage curves are developed, as an example of how to take advantage of the recent memories of the floods. Depth-damage curves here can be used in other similar regions with scarce information. Quantitative flood risk can be a practical tool for the urban planning of this zone of the city.

2. Methodology

Methodology is divided in three main phases, a) quantitative estimation of hazard, b) physical vulnerability estimation and c) Risk estimation as the discrete solution of the risk integral. At forward subsections we explain these phases in more detail.

2.1. Flood Hazard

Flood hazard is quantified by mapping the different areas flooded obtained through hydraulics modelling of maximum discharge of return periods of 10, 25, 50, 100 and 500 years.

We used a digital elevation model (DEM) obtained from topography at a detailed scale of 1: 750 for the flooded area and another DEM from a scale of 1: 10000 for the morphometric characterization of the basin. The resulting drainage network is compared with a drainage network previously established in studies of official entities.

In our case study, we do not have IDF curves in the area and nor rainfall data at hourly scales. From the series of maximum rainfall in 24 hours available for the basin, a frequency analysis is performed and by means of non-dimensional conversion factors between the maximum rainfall in 24 hours and those of shorter durations built by [8], it is estimated the maximum rainfall associated with each return period. For the case study, duration of rainfall corresponds to the concentration time of the basin that drains to the flooded area.

There are no discharge series that allow obtaining the maximum discharge for the selected return periods by a statistical method. Therefore, the methodology employs a rainfall-runoff model to obtain the maximum discharge of the given return periods. The hypothesis that supports this methodology establishes that a maximum rainfall estimated for a given return period produces a maximum discharge for that same return period. This hypothesis has been widely used and accepted in the hydrological

design when there is no flow data to perform a frequency analysis. Starting from this hypothesis for the generation of hydrographs, a departure error is incurred and accepted, since the estimated discharge associated with a certain return period may be different from the discharge for that same return period if estimate from statistics method of maximum in the area. The rainfall runoff model used is the Unitary Snyder Synthetic Hydrograph, having as input the maximum precipitation for each return period, with duration equal to the time of concentration of the basins contributing to the area.

Hydraulic modelling was carried out with the IBER 2.3.1 model [9]. The calibration of roughness coefficient was made by modelling the reference flood event, from which, based on the survey made to the population, the depth reached by the water was determined. Hydraulic model was calibrated, in such a way that the water heights reported both in the press and by the inhabitants of the neighbourhood were obtained for the rain reported on the day of the event. With calibrated hydraulic model, the inputs hydrographs were run for each return period, thus obtaining the flooded area as a representation of the flood hazard.

2.2. Vulnerability

In this study, we exclusively estimate the physical vulnerability, based on the calculation of the damages produced by a flood, obtained from the depth-damage curves constructed for the specific area of the study. The analysis of tangible direct damages is performed. The estimation of the physical vulnerability due to floods was made under the premise that the human settlements in the alluvial valleys are exposed to water for prolonged periods, since in these valleys, slow floods achieve the accumulation of large amounts of water reaching considerable heights [10].

2.2.1. Exposure identification. Following the methodology used by [6], the damage assessment is done by subdividing the tangible direct damages into classes and categories, and then establishing a damage function for each class evaluated. In this study, three classes represent the first level of hierarchy: make up elements for the structure of the houses, movable property in homes, and public areas. The categories represent the second level of hierarchy, which in the case of movable property are the types of goods: living room and / or dining room furniture, refrigerator, stove, beds, sound equipment, television, washing machine and others. Make up elements for the structure of the houses are: floor, walls, windows, doors and roof.

A survey was applied to the 801 households in the neighbourhood, in which data for identification of the current characteristics was collected and additional questions were asked to obtain data to construct the depth-damage functions specific to the area, based on the flood event of reference. The following specific questions were asked for the survey: a) Were you living in the neighbourhood during the flood of 2010? b) What was the height reached by the water in your home during the reference flood event of 2010? c) Did the water enter to the house by the front door or the yard? d) How long did the evacuation process of the water take in the flooded area? e) What furniture was damaged? f) Which of these make up elements for the structure of the house were damaged or affected? (The 5 main elements were described at this point), g) How much money was spent cleaning and fixing your house?, h) For which specific activities was that money spent?. The depths referred by the inhabitants were validated in the field by following the marks left by the water in the dwellings.

2.2.2. Depth-damage curves. From the hydraulic modelling, is obtained the flood that match the water depth reported in the press and in the survey, for the reference event. Absolute damage functions are generated, which evaluate the damages of individual property in a unitary area. For the evaluation of the damages, it is required to obtain information in a same spatial scale defined by the hydrodynamic analysis of the flood, which is expressed in a grid or pixels and that will later be added to the scale of the property.

To calculate the damage on a detailed residential scale, we must start from the general expression of the unitary damage proposed by [6] as presented in the following equation:

$$D_u = S_u(h_u) \quad (1)$$

Where:

D_u = damage of unitary element

S_u = susceptibility of unitary element. In this study is the damage obtained from the depth-damage curve.

h_u = flood depth of unitary element.

Total damage of all exposed elements is:

$$Dt = \sum_{k=1}^n \sum_{u=1}^m D_{k,u} \quad (2)$$

Where:

Dt = total damage

u = unitary element in a class or category

m = total number of elements in a category or class

k = category or class of the exposed element

n = total number of category or classes

$D_{k,u}$ = unitary damage of the u -element in the k -category or class .

Derived from equation 2, damage for movable property can be estimated by equation 3, and for make-up elements for the structure, by equation 4:

$$Dt_{bm} = \sum_{u=1}^m D_{bm,u} \quad (3)$$

$$Dt_e = \sum_{u=1}^m D_{e,u} \quad (4)$$

Where:

Dt_{bm} = total damage of movable property at unitary dwelling.

m = total number of elements in the category.

u = unitary element of the category.

$D_{bm,u}$ = unitary damage of the u -element of one of the movable property categories.

Dt_e = damage of make up elements for the structure at unitary dwelling

$D_{e,u}$ = unitary damage of the u -element of one of the make up elements for the structure categories.

For damages in streets and public areas, it is proposed equation 2 applied with a different methodological approach, because few elements are identified exposed in these areas. The objective is to calculate the damages caused in these exposed elements for zones with similar features. In this sense, [6] proposes to account for damages from the costs generated by the removal of sediments and the rehabilitation of these areas. The damage estimation in streets and public areas are based on the depth of the reference flood event, assuming that in the case of any increase in flood depth the percentage of increase is equal to the expected damage percentage.

2.3. Flood risk quantification

Damage caused by the floods, is related with the monetary value of repair in the case of the make-up elements for the structure and it is related with the total value of the movable property. The unitary economic loss is calculated for a given return period according to equation 5, presented in [7]:

$$De(t) = \sum_{c=1}^m D_{cu}(h, t) * (VT_c) \quad (5)$$

Where:

$De(t)$ = unitary economical loss in a unitary area for a period of time.

D_{cu} = percentage of total damage for a residential urban damage class c in a unit element at a depth h

h = water depth for a return period t

VT_c = economic value of the elements in a c class

m = total number of class.

In the case of public areas, the economic value is replaced by recovery cost of the affected area, leaving the expression as:

$$Dep(t) = D_{au} * CR_a \quad (6)$$

Where:

$Dep(t)$ = economical loss in the public areas and streets for a specific return period t .

D_{au} = expected damage in percentage of each unit of public areas.

CR_a = cost of recovery of the affected area.

Total loss for a specific return period is calculated with equation 9, given by [6]:

$$Dt_{Tr} = \sum_{pr=1}^m De_u(h, t) * (N^oVi) \quad (7)$$

Where:

Dt_{Tr} = total economic loss for a return period

De_u = unitary economic loss per unitary area for a given return period.

h = depth of water producing losses at the given return period t

N^oVi = number of dwelling or residential units exposed at h depth.

Finally, based on the equation for the discrete solution of the risk integral, the total annual economic loss can be calculated as:

$$DT = \sum_{i=1}^k Dt_{Tr} [i] * \Delta p_i \quad (8)$$

Where:

$Dt_{Tr} [i]$ = risk or total economic loss for a return period between two known points of the curve.

Δp = probability of the interval between these two points.

3. Results

From the DEM in a scale of 1:10000, we obtained drainage network and basins. Flood at the zone, begins with the input of water from a principal drainage of a sub-basin area of 1.03 km². A secondary drainage that enters to the zone through the south-west also runs directly to Villa Jiménez with a basin of 12.3 km² (See figure 2).

3.1. Flood Hazard estimation

From the series of maximum monthly rainfall in 24 hours, the respective precipitation depths are obtained for each return period. For secondary drainage, a concentration time of 2.7 hours is estimated and for the main drainage a concentration time of 1.5 hours. These concentration times are considered as the duration of the rain. By means of the correction factors method [8], the precipitation depths for these durations are obtained for each return period. Effective precipitation is calculated by Soil Conservation Service (SCS) method of abstractions. From the soils and vegetal coverage maps and with antecedent humidity condition III, a CN of 93.08 is obtained, associated with bare soil and pasture. Finally, the hydrograph for each return period is set by the Snyder unit hydrograph, both for the main and secondary drainage (see figure 1).

3.1.1. Reference flood event. Hydraulic model calibration and depth-damage curves were developed based on reference flood event. From precipitation recorded by the meteorological governmental institution (IDEAM), four maximum daily precipitations for July were identify: 60.4 mm, 11.1 mm, 73.8 mm, 75.2 mm recorded at 10, 11, 16 y 17 of July 2010 respectively. Flood caused by these precipitations, were reported by a local and a regional newspaper. At 22th July, local newspaper reports a flood with maximum depth over 1.40 m. The maximum depth reported by inhabitants matched the one reported by press. Based on these two sources of information, we set the reference flood event as the flood caused by precipitation of 17th July 2010.

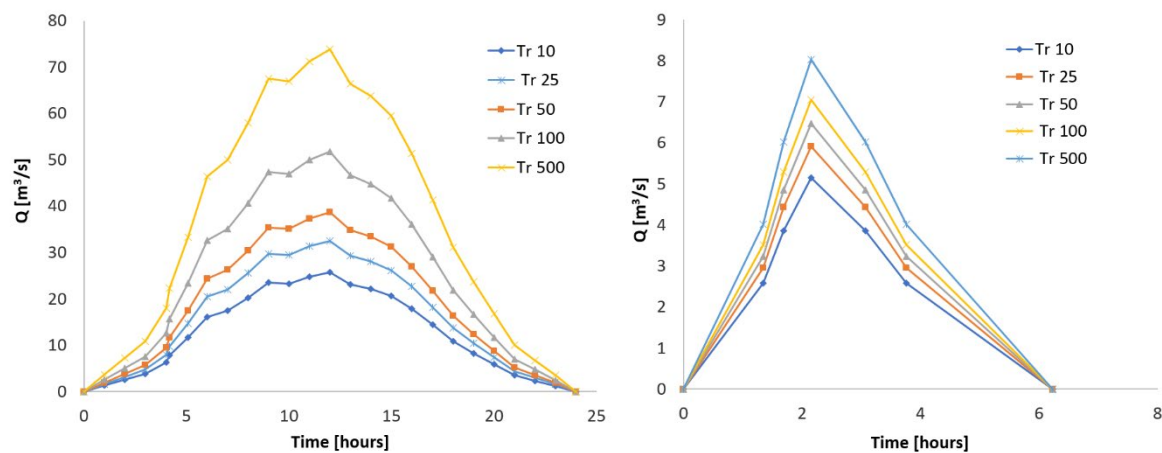


Figure 1. Flood hydrographs. Left, secondary inflow to the zone. Right, principal inflow to the zone.

The flood reported in the newspapers and by the inhabitants of the neighbourhood, not only obeys the rain of July 17, but is conditioned by the rain of the previous days, which contributed to the saturation of the soil. This condition of soil saturation is considered, when calculating effective precipitation. From the rainfall record published by the IDEAM for that date, a precipitation event with a depth of 75.2 mm and a duration of 12 hours is reported. From the SCS method, an effective precipitation of 56.48 mm is estimated. From the Snyder unitary hydrograph, with the duration of the rain equal to the actual duration, the flood hydrographs are obtained with maximum flow rates of 16 m³/s and 2.5 m³/s for the secondary and principal drainage respectively. According to the results for the different periods of return, the reference flood event has a return period of less than 10 years.

3.1.2. Hydraulic model calibration. With the reference event hydrograph, hydraulic modelling is performed, calibrating the roughness coefficient of the model, in such a way that the maximum flood depth obtained coincides with the maximum depth of the flood reported by the press and the communities for the event. In figure 2, the flood resulting from the reference event is shown. The maximum level reached is 1.48 m, which matched with the press reports and with the answers of the inhabitants in the survey conducted in this investigation.

3.1.3. Flood hazard maps. Once the model was calibrated, it was run with the hydrographs for the return periods of 10, 25, 50, 100 and 500 years. For the flood of 10 years, 37.5% of the area reached depths greater than 1 m, for the 100 years' flood, this area increases to 84% and for the flood of 500 years, it extends to 86% of the area. The sector of the neighbourhood that registers the most critical depths is the eastern side, because in that sector there are the lowest elevations of terrain.

3.2. Vulnerability estimation

Depth-damage curves and vulnerability were performed using information recorded from the survey mentioned in section 2. Curves were developed from the answers of the community to the question related with the damage and water level during reference flood event.

3.2.1. Depth-damage curves estimation. For movable properties, the survey determined that there are 8 types of goods most likely to be found: Furniture (living room and / or dining room), refrigerator, stove, beds, sound equipment, television, washing machine and others. According to the results of the survey, for any type of house that has been exposed to flood, the threshold of minimum damage or the depth of water in which damage to begins to occur is 4 cm, starting hence the damages are progressive depending on the type of movable property. Depth-damage curve for movable property is presented in figure 3.

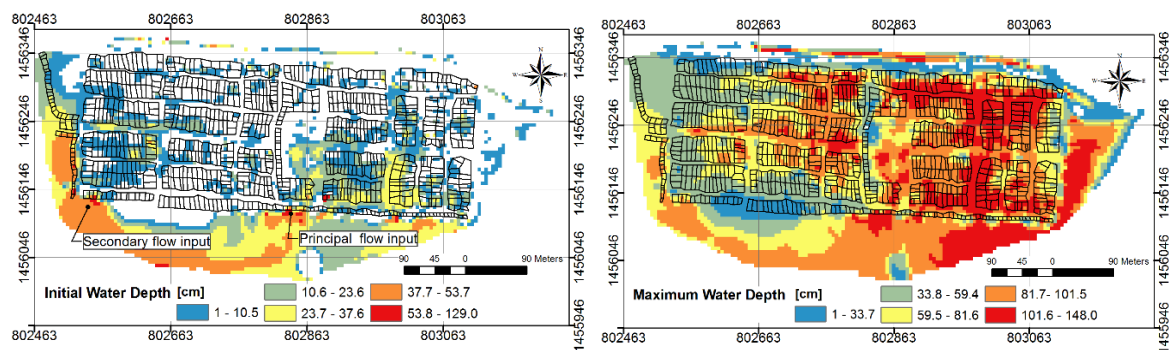


Figure 2. Reference flood event. Left: flow inputs at the begin of modelling. Right: maximum water depth.

To estimate damages on the houses, five make up elements for the structure are defined: floor, walls, doors, windows and roof. In the survey, information was collected on the damage suffered by these elements during the reference flood event. With this information, a damage function was built for each of the 3 housing types found in the area, which are: non-traditional material houses, wood houses and masonry houses. Non-traditional material houses are built with cardboard panels, zinc panels, and other material from recycling. In figure 3 and figure 4 are shown depth-damage curves for each type of houses.

As can be seen, for the movable property the damage of 100% of the appliances is reached for a water depth of 50 cm, which implies that at this point, the types of furniture considered were replaced. For dwellings of non-traditional material, the make up elements for the structure of the house are completely affected from a water depth of 50 cm. For wooden and masonry houses the results show that there is a range between 20 cm and 100 cm, where the percentage of make up elements for the structure of the house is affected by 60%. From 100 cm, the percentage of damaged increases to 80%, but does not reach 100% under any depth, indicating how it was expected, that these types of houses are less vulnerable to flooding.

3.2.2. Susceptibility to damage on streets and public areas. Considering that the study area is located in an almost rural environment (surrounded by paddocks, wet areas and mud flats) where the floods drag a large volume of sediments, due to the geomorphological and hydraulic characteristics of the area, we propose that streets and public areas could suffer damage when the water depth reaches a level over 1 cm.

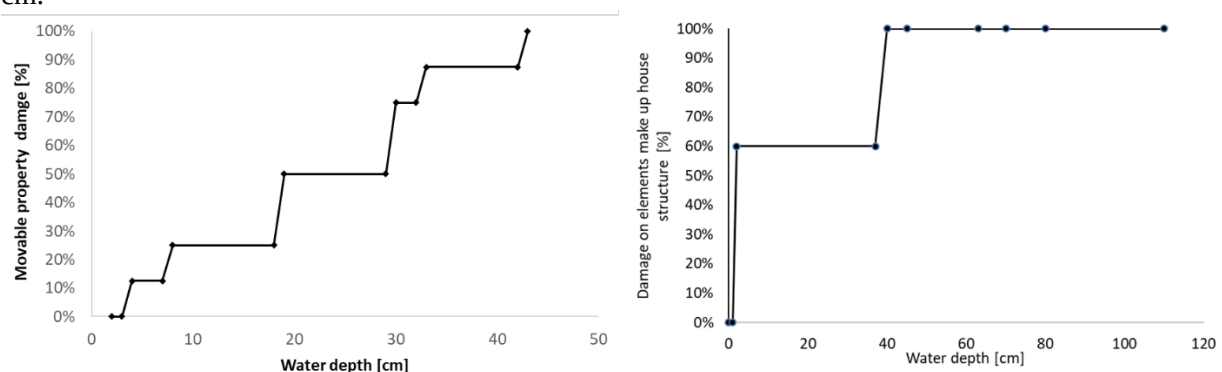


Figure 3. Depth-damage curves. Left: Percent of damage for movable properties. Right: Percent of damage on make up elements for the structure of non-traditional materials houses.

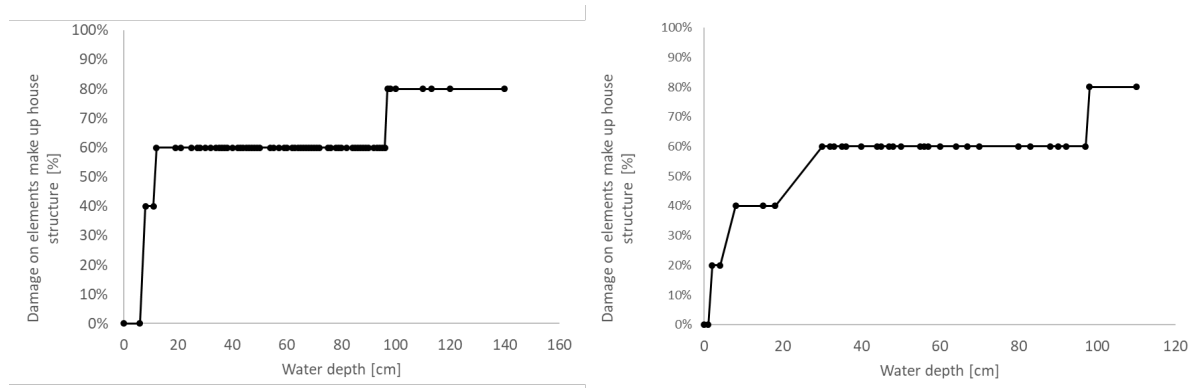


Figure 4. Depth-damage curves. Left: Percent of damage on make up elements for the structure of wood houses. Right: Percent of damage on make up elements for the structure of masonry houses.

3.3. Risk Estimation

From the flood map for each return period, it could be established according to the thresholds defined at depth-damage curves, the percentage of damage in make up elements of the structure of the houses, in the movable property and in the streets and public areas, and therefore the economic losses. The houses were classified according to the type and its elevation with respect to the level of the street was defined from the field visit. From the flood maps, the depth of the water to which the houses were exposed for the different return periods is established, and with the depth-damage curves, the percentage of damage for each of the properties is obtained. The economic loss is obtained by multiplying the damage by a value of repair of these goods obtained through the elaboration of a budget with prices of the region. For movable property, the percentage of damage obtained was multiplied by a commercial value of these elements subject to depreciation for use. Losses in public areas and streets were estimated from a general budget with the costs of maintenance, improvement and conservation of roads and recreation areas, multiplied by the percentage of expected damage per square meter. Losses in public areas and streets were estimated from a general budget with the costs of maintenance, improvement and conservation of roads and recreation areas, multiplied by the percentage of expected damage per square meter.

Figure 5 shows maps of economic losses for return period of 10 years and 500 years. As expected, the economic losses increase as the return period of the flood increases, but there is little difference between the maximum value of the return period of 10 years and that one of 500 years. This is explained because of the greatest contribution to these economic losses are the movable property, no conventional material houses and public areas. For movable property, there is total damage from 50 cm, this depth is already reached with the 10 years return period in many of the houses, contributing with a high percentage to the total losses. The expected annual economic loss for Villa Jiménez is estimated at US \$ 1'094590. Figure 6 shows the spatial distribution of it.

4. Discussion and conclusions

Following the methodologies of [7] and [6], a quantitative risk assessment was performed, in terms of the expected annual economic loss. The estimation of the hydrographs that are part of the hazard was made using the rainfall-runoff method of the Snyder unitary hydrograph. However, this method is susceptible to improvement, if a distributed hydrological model is used. For hydraulic modelling, buildings should be incorporated in the future, as part of the topography, since this may increase the heights obtained in this study.

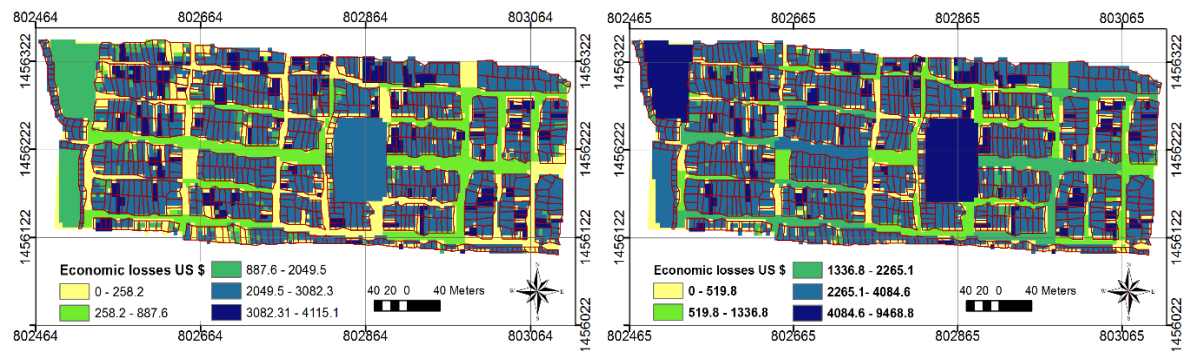


Figure 5. Economic losses for 10 years of return period (left) and for 500 years of return period (right).

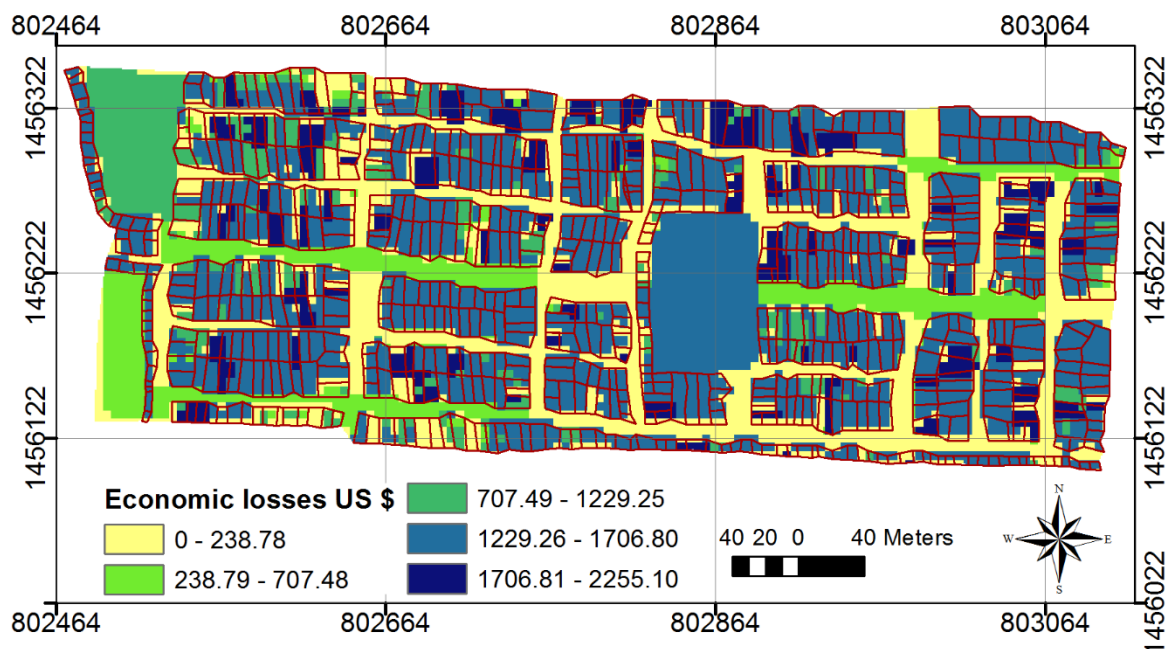


Figure 6. Expected annual economic loss

Usage of inhabitant's memories of past events allowed the construction of depth-damage curves. These curves are a key step in assess quantitative vulnerability and consequently quantitative risk assessment. The replicability of these curves in other contexts is subject to similar socio-economic conditions and slow flood conditions, since the damage reflected in them is only due to the action of the water level. In other areas where the physical, hydroclimate and socioeconomic characteristics are different, two scenarios may occur. First one, the curves underestimate risk when dealing with an exposure condition and inherent susceptibility to the loss of human life in areas with torrential floods. The second one, the curves overestimate risk in areas where communities have a better knowledge of emergencies and are prepared for the response to a disastrous event.

Depth-damage curves in this research must be re-evaluated periodically, since the actions aimed to mitigate risk, can result in changes in the idiosyncrasy of the population, leading to new parameters of construction and adaptation to the environment that modify these curves. Many flood events have occurred in Colombia and may still be recorded in the memory of the inhabitants. Therefore, they could be exploited for the construction of their own depth-damage curves. Question focus in the application of the adequate procedures for the census information survey, in such a way that the level of detail of

the identified damages coincides with the scale of spatial representation of the flood. The gathering of information in the field constitutes an appropriate methodology for the construction of damage functions typical of a region, which can be used in areas with a similar typology to that study area. This tool is proposed in an environment where the management of risk is increasing and the methodology for quantifying it lacks real models that can be applied to our environment.

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