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Vulnerability curves for masonry buildings affected by hyperconcentrated flows as natural disaster risk management tools for the quantification of material damage

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Vulnerability curves for masonry buildings affected by hyperconcentrated flows as natural disaster risk management tools for the quantification of material damage

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Abstract. The damage assessment caused by floods, earthquakes, hurricanes among others phenomenons in the world are analyzed with methodologies such as "Vulnerability curves". In Peru, disasters caused by hyperconcentrated flows are alarming due to a climatic variability such as the "El Niño Costero" phenomenon. Therefore, this research has developed vulnerability curves for 1 and 2-story confined masonry buildings in Urb. San Idelfonso, Ica - Peru; linking the variables: flow depth, associated with the event produced by heavy rains at the top of the "Quebrada Cansas" caused by the "El Niño Costero" phenomenon in 2017, and the percentage of the damage based on the methodology of the United States Army Corps of Engineers (USACE), whose formula is the repair value and total building value. The monetary amounts and items of the buildings are obtained from the RM 415-2017-VIVIENDA of the Ministry of Housing, Construction and Sanitation of Peru. The process consisted of hydrological modeling in HEC-HMS, hydraulic modeling in FLO-2D, damage percentage estimate and vulnerability curves production. Finally, the vulnerability curves for hyperconcentrated flows were contrasted with similar studies regarding curves for flooding and debris flow. The results of the investigation showed that the "El Niño Costero" phenomenon in 2017 had an economic impact of at least 1.3 million soles in Urb. San Idelfonso. In addition, at least 24 buildings had a complete damage and 21 buildings an extensive damage.

1. Introduction

Heavy rains in usually dry places tend to generate floods in rivers, activation of streams and "huaycos" so, due to climate change, notable impacts should be expected to increase frecuency; as [1] mentioned in relation to disasters caused by heavy rains in countries such as Bolivia, Ecuador, Colombia and Peru, frequently affected by floods, hyperconcentrated flows and interannual events such as "Fenómeno El Niño Costero (FENC)", consequence of climate variability. On January 24, 2017, the "Quebrada Cansas" was activated as a result of heavy rains in the upper part of the basin, originating the hyperconcentrated flow that affected the sectors of Chanchajalla, La Tinguiña and San Idelfonso in Ica with a total of 4225 affected people [2]. For this reason, research has been used regarding methodologies for the assessment of damage by hyperconcentrated flows from the generation of vulnerability curves.

The occurrence of these events in urban sectors not only causes structural damage to buildings or material losses, it also immobilizes the inhabitants for blocking roads and for the common activities of the sector, negatively affecting the region's economy [3]. The quantification of economic losses allows us to determine which structures and areas are most affected hence, vulnerability to flooding and hyperconcentrated flows is associated with the assessment of damage caused [4]. Various authors, including [5][6] develop vulnerability curves for homes against debris flow by establishing critical referential heights to allocate 100% damage depending on the depth of the flow reached in the building. Finally, quantitative risk assessments against hazards related to the removal of land masses in relation to heavy rainfall are becoming more relevant to determine the absolute risk and under this approach provide tools for emergency prevention and allow better urban planning in advance [7]. The literature review has shown that the generation of vulnerability curves allows to quantify the damages in buildings, this information will be used as a tool so that the authorities in charge of the Prospective and Reactive Management of risks can foresee the possible damages associated with their occurrence.

Through a hydrological and hydraulic study, it is possible to generate a map of flow depths for the San Idelfonso sector affected by the activation of the "Quebrada Cansas" in 2017, the contrast of this map with the estimate of damage in the area allows to generate the vulnerability curves for the identified buildings.

The contribution of the research lies in the need to improve vulnerability and hazard assessment methodologies in Peru, in such a way that they allow to estimate the damages under methodologies used in other countries through vulnerability curves that establish a relationship between the depth flow and the percentage of damage to the buildings [8].

2. Materials and methodology

2.1. Study area

The "Quebrada Cansas" is located within the basin of the Ica River in southern Peru that flows into the Pacific Ocean. When extraordinary rains occur at the head of this dry ravage, hyperconcentrated flows originate that overflow the main channel and mainly affect the district of La Tinguiña – Ica causing material and economic losses in the urban areas located within the old channel of the "Quebrada Cansas" as the San Idelfonso sector on which this research is based. Figure 1 shows the study area in which the Ica River and the "Quebrada Cansas" can be observed. Figure 2 shows the detailed study area, in which you can see buildings that were affected by the 2017 event.

Figure 1. Location of the study area.

Figure 2. Study area detail.

2.2. Methodology

This research focuses on the "Quebrada Cansas"; For this, the flood map of the hyperconcentrated flow caused by "Niño Costero" from 2017 formulated by the National Center for the Estimation, Prevention and Reduction of Disaster Risk (CENEPRED) was taken as the basis of analysis.

This research used HEC-HMS and FLO-2D for its development. The first was HEC – HMS (Hydrologic Engineering Center's - Hydrologic Modeling System) to simulate the precipitation process – runoff from dendritic watersheds [9] and the second was FLO-2D, which is a two-dimensional hydrological - hydraulic model that allows to simulate the propagation of water floods, debris flows, mud flows, hyperconcentrated flows (non-newtonian fluids) in basins, in addition to their interaction with the structures and obstructions present [10].

To better understand the development of the paper, a flow chart has been developed explaining the procedure in Figure 3. We start with everything that corresponds to the hydrology part, that allowed us to carry out the modeling in HEC HMS and obtain the first output: liquid flows for different return times and for the 2017 event.

To carry out the hydraulic modeling, a review of the general characteristics of the "Quebrada Cansas" is necessary, such as geology, geomorphology, topography and previous studies that allowed us to define the concentration of sediments and rheological parameters. We also require the Manning roughness and the digital topography in pts format, all these data will serve us (in conjunction with the liquid flows) to generate the FLO-2D modeling of the "Niño Costero" event and, if the flow-depth obtained in the model are not similar to those obtained in the field, we must calibrate the sediment concentration until a similar flood-map is obtained. Once this is achieved, we can validate the flood-map for each of the return period.

Then we estimate the percentage of damage for the buildings identified and classified in Urb. San Idelfonso during a field visit. To estimate the damages, we require the definition of damage evaluation criteria, information on monetary amounts proposed by the "Ministerio de Vivienda del Perú", and define the exposure index for each item analyzed. Once the results of damage percentages were obtained, we made them compatible with the depth-flow to finally obtain the vulnerability curves, which have allowed us to make damage maps for each analyzed scenario.

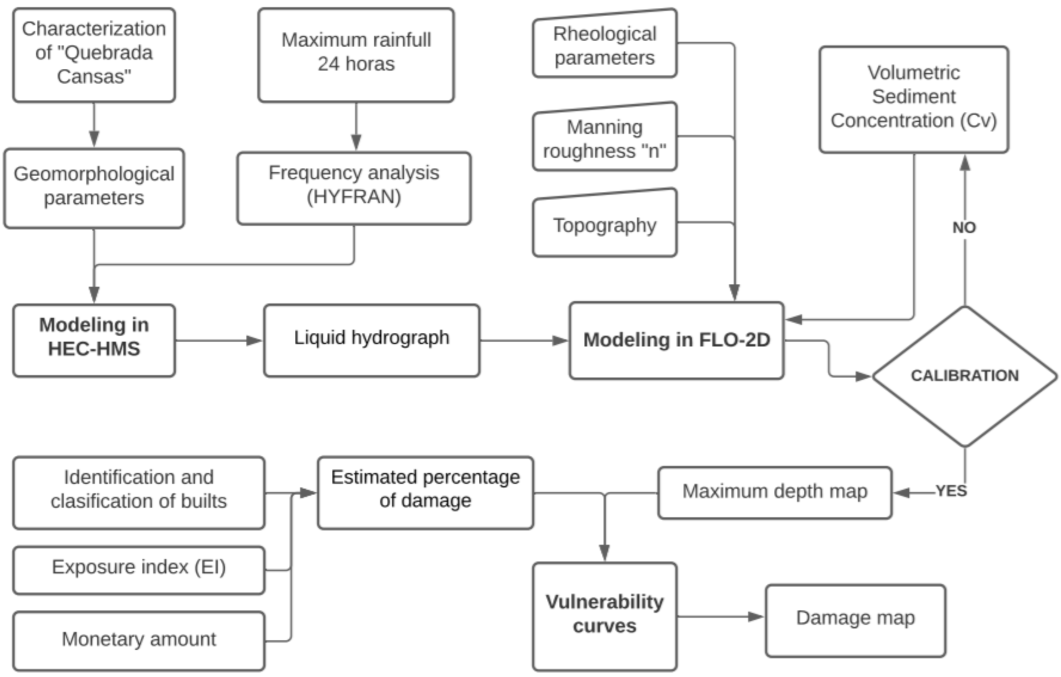

Figure 3. Flowchart for the generation of curves proposed by this research.

2.3. Modeling

The modeling stage had two main parts: hydrological and hydraulic. Both were used in order to know the liquid flows to then determine the depths of the hyperconcentrated flow for the "El Niño Costero" event in 2017.

2.3.1. Hydrological modeling. This modeling aims to obtain the flows and hydrographs for the "El Niño Costero 2017" event. The processing for the delimitation of the "Quebrada Cansas" was carried out in ArcGIS, where satellite images of ALOS PALSAR were used with a resolution of 12.5x12.5m taken from the ASD Alaska Satellite Facility portal. This delimitation gave us the Quebrada Cansas' main geomorphological parameters such as an area of 163.83 km2, length of the main channel equivalent to 41.55 km and an average slope of the basin equal to 40.68% which then will help us determine the rest of the parameters shown in the following Table 1.

Table 1. Morphological Parameters.

Morphological Parameters		
Description	Unit	Value
Surface		
Area	Km2	163.83
Perimeter	Km	91.88
Main course length	Km	41.55
Medium width	Km	3.94
Form factor	-	0.09
Compactness coefficient	-	2.01
Relief		
Middle elevation	m.n.s.m	182.36
Slope basin	%	40.68
Drainage		
Bifurcation	-	0.478
Density	-	4.54
Slope	%	1.23

The maximum rainfall in 24 hours between the periods of 1965 – 2012 obtained from the National Service of Meteorology and Hydrology (SENAMHI) was analyzed across different weather stations near the "Quebrada Cansas", of which, based on a graphical analysis, the Tambo station is selected because it has the largest extent of data and a better distribution of the maximum rainfall series in 24 hours over time relative to the peak events that occurred previously.

Finally, the parameters required in the HEC-HMS model were introduced to generate the liquid hydrograph for the "Fenómeno El Niño Costero 2017" event, resulting in a liquid flow of 61.4 m3/s shown in Figure 4.

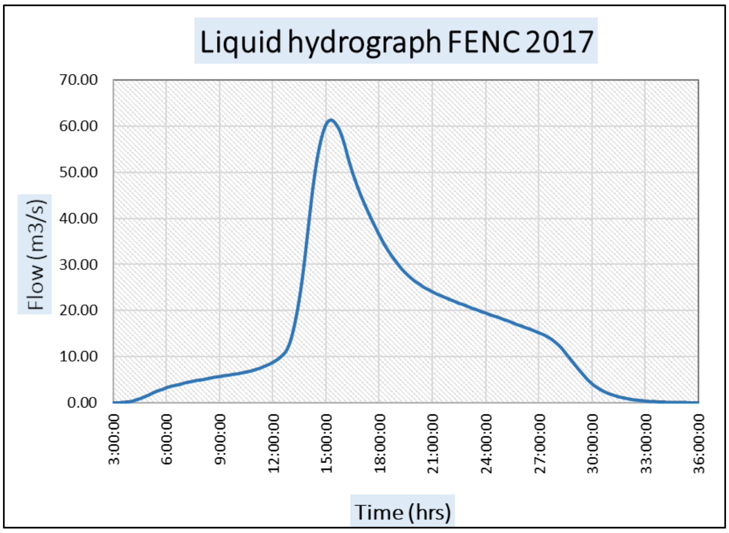

Figure 4. Liquid hydrograph “Fenómeno El Niño Costero 2017”.

2.3.2. Hydraulic modeling. Hydraulic modeling is developed in order to determine the depths of the hyperconcentrated flow that affected each building within study area. This model requires information such as the topography of the site, Manning's roughness coefficient, rheological parameters and previously generated liquid hydrographs. The contour lines were obtained by drone flight provided by SIGRID (Disaster Risk Management Information System). FLO-2D software was used to model the hyperconcentrated flow.

- FLO-2D model

According to its web portal, this is a two-dimensional hydrological and hydraulic model that allows to simulate avenues, debris flows, mud flows, hyperconcentrated flows, all of them characterized by being non-Newtonian fluids and approved by FEMA (Federal Emergency Management Agency). The model requires as input data the topography of the terrain, geometry of the channel, roughness of the channel and flood plain, hydrographs of entry (liquids and solids), precipitation and rheological properties of water-sediment mixture [9].

In the case of the “Quebrada Cansas”, according to the 2001 report of [11], the amount of fine materials does not exceed 5% (silts and clays), also in accordance with [10] in the application of a numerical model for the “Quebrada Cansas”, recommends using the Glenwood sample 2 due to the characteristics found in the dejection cone because it presents greater amount of gravels and sands. The other parameters that were used for modeling in FLO2D are shown in Table 2.

Table 2. Parameters to FLO-2D.

Parameters to be used in the simulation of FLO-2D		
Type	**Symbol**	**Value**
Volumetric concentration	Cv	0.22 - 0.35
Sample	-	Glenwood 2
Roughness channel	n_1	0.029
Roughness agricultural	n_2	0.04
Roughness scrub	n_3	0.05
Roughness abandoned plots	n_4	0.03
Laminar flow resistance	K	2480
Specific gravity os sediment	S.G	2.65

The surface for the modeling was generated by unifying the 3 contour lines obtained through the drone flights published in the SIGRID portal and were processed in the Civil 3D software.

The sediment concentration value used after calibration was variable, which varies progressively according to the flow rate, using a starting value of 0.22 to the breaking point of the maximum flow arriving with a concentration of 0.35 associated with a maximum mixing flow of 94.46 m3/s seen in Figure 5. As a result, the following flood spot corresponding to the "El Niño Costero 2017" event observed in Figure 6 was obtained.

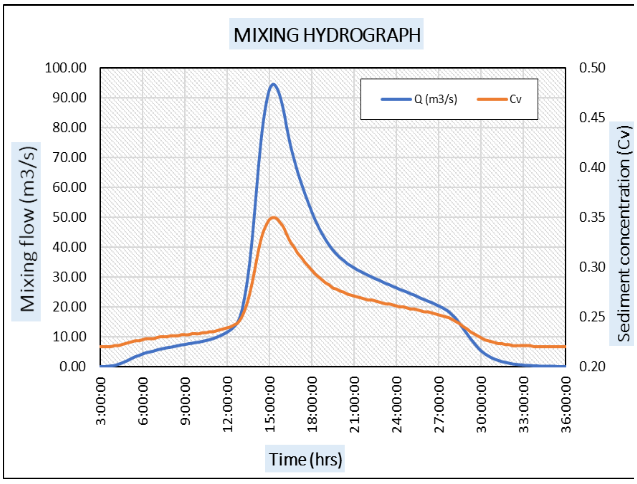

Figure 5. Mixing hidrograph.

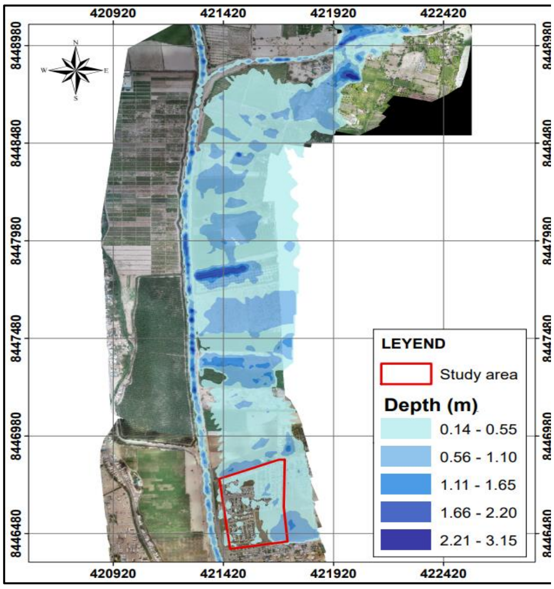

Figure 6. Maximum depth map.

2.4. *Damage estimate*

The U.S. Corps of Engineers adapted formulation is used to determine the percentage of damage, representing the cost of repair in the building versus the presence of the hyperconcentrated flow between the total value of the building. Where the repair cost includes parameters such as exposure index and starting unit price as detailed below:

$$\%\text{Damage}=\sum\frac{EI_i\times UP_i+EI_j\times UP_j+\ldots+EI_n\times UP_n}{\text{Total value}} \quad (1)$$

EI_i: Exposure Index for item "i".
UP_i: Unit Price for item "i".

2.4.1. Types of buildings. According to field interviews and satellite images of the sector on the date of the event analyzed, only two types of buildings were found present. All are composed of typical modules of confined masonry built as part of the project "Urb. San Idelfonso" of the company CLASEM EOM SAC, which delivered lots with a module that had two bedrooms, kitchen, living room, bathroom and laundry. The buildings are 1 and 2 levels, they have water, drainage, and electricity services and its characteristics are described in Table 3.

Table 3. Building classification.

BUILT			
Description	-	One floor	Two floors
Code	-	VIV-TIP-1	VIV-TIP-2
Total area	m^2	110	110
Built area	m^2	33	220
Height	m	2.6	5.2
Material	-	Confined masonry	Confined masonry

2.4.2. Unit prices. The most significant items in the structural and economic part of a masonry house were analyzed, which are walls / columns, ceilings and cladding. Table 4 shows the unit price of these items was assumed from ministerial resolution RM N°415-2017-VIVIENDA, which is renewed every year for the different areas of the country.

Table 4. Cost of items.

ITEM	DESCRIPTION	COST (S/.)
Walls and columns	Masonry or similar walls with reinforced concrete columns and tie beams.	S/213.23
Ceiling	Concrete slab with horizontal reinforcement	S/157.29
Cladding	Rubbed scrape or plaster with washable paint	S/58.78

2.4.3. Exposure index (EI). According to [1] this index considers the vulnerability that an exposed element could present in the face of the materialized threat, this depending on the intensity and proximity of the event. The index is expressed as a function of the depth of the flow, among others that are obtained from the results of the FLO-2D model and is developed for the items mentioned above in Table 5.

Table 5. Variation of the exposure index according to items.

	VIV-TIP-1	VIV-TIP-2
Walls and columns	$if\ h < 1.00m;\ EI(\%) = 1.49\left(\frac{h}{0.692}\right)^{1.938}\left(1+\left(\frac{h}{0.692}\right)^{1.938}\right)^{-1} x100$ $if\ h \geq 1.00m;\ EI(\%) = 100$	$if\ h < 3.63m;\ EI(\%) = 1.49\left(\frac{h}{2.513}\right)^{1.938}\left(1+\left(\frac{h}{2.513}\right)^{1.938}\right)^{-1} x100$ $if\ h \geq 3.63m;\ EI(\%) = 100$
Ceiling	$if\ h < 0.50m;\ EI(\%) = 0$ $if\ 0.50m < h < 1.00m;\ EI(\%) = [0-100]$ $if\ h \geq 1.00m;\ EI(\%) = 100$	$if\ h < 2.10m;\ EI(\%) = 0$ $if\ 2.10m \leq h < 3.63m;\ EI(\%) = [0-100]$ $if\ h \geq 3.63m;\ EI(\%) = 100$
Cladding	$if\ h < 1.00m;\ EI(\%) = \frac{(h+10)}{2.60}$ $if\ h \geq 1.00m;\ EI(\%) = 100$	$if\ h < 3.63m;\ EI(\%) = \frac{(h+10)}{5.20}$ $if\ h \geq 3.63m;\ EI(\%) = 100$

2.5. Vulnerability curves

The vulnerability curves or depth-damage functions represent a mathematical relationship of the hydraulic variable flow depth with the percentage of damage to the building caused by the presence and impact of hyper-concentrated flow [12][13]. In this way, the graph of the vulnerability curve according to type of building is generated. The depths of the flow are extracted from the hydraulic modeling in FLO-2D and the damage percentages associated with this hydraulic variable are obtained from the formulation (1) according to the exposure index, unit prices per item and the total value of the building.

2.6. Damage map

To assess the damage in the study area and make a damage map according to the percentage of damage caused by FENC 2017 [5] presents a range of values to classify the damage levels as shown in Table 6.

Table 6. Classification of damage to building to the hyperconcentrated flow.

Damage	Leyend		Description
0% - 30%	Slight		Slight non-structural damage, stability not affected, damage to furnishings or fittings
30% - 60%	Moderate		Cracks in the wall, stability unaffected, reparation not urgent, flooding of the internal rooms and damage to the furnishing
60% - 80%	Extensive		Partly destroyed, loss of parts of external and internal walls, evacuation necessary, reconstruction of destroyed parts
80% - 100%	Complete		Partly or totally destroyed, evacuation necessary, complete reconstruction

3. Results

3.1. Flow-depth map

From the Figure 7, it was obtained that the depths of the flow that affected the buildings were in a range of 0.0 m to 1.20m, where there is accumulation of the flow in the upper part, because the buildings are located perpendicular to the direction of the flow. In addition, a greater depth of flow is shown in the lower right limit due to the topography of the terrain that tilts the flow along “Avenida Siete”.

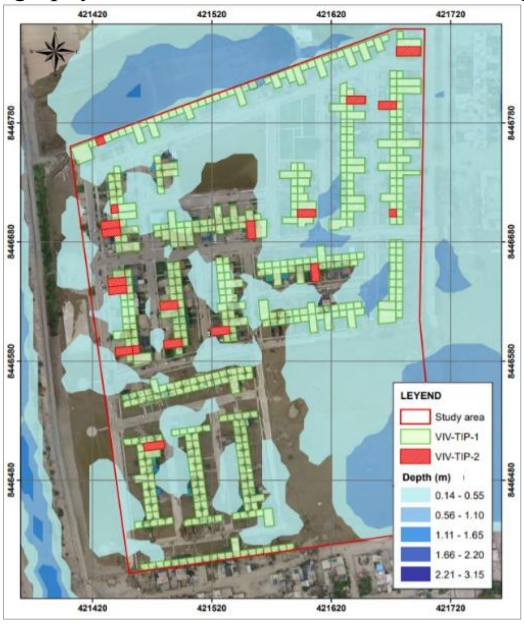

Figure 7. Maximum depth map in study area.

3.2. Vulnerability curves

The vulnerability curves were generated with a 10 cm separation in flow Depth. This way, a damage assessment across the building was obtained until the flow gets to its maximum height. As a result, two types of curves were obtained, corresponding to the two types of buildings existing on the day of the "FENC 2017" event.

It can be seen in Figure 8 that in the case of the VIV-TIP-1 curve when it exceeds the critical height of 1.00 m, the percentage of damage is equal to 100%, this is because this critical height compromises the most important item in the unit prices analysis: walls and columns. This item has a direct impact on the others because its instability as a result of the high depth of the flow ends up affecting the other items and the total reconstruction of the building would be necessary. The same for the case of the VIV-TIP-2 curve in Figure 9 which, when exceeding the critical height of 3.63 m, achieves 100% damage.

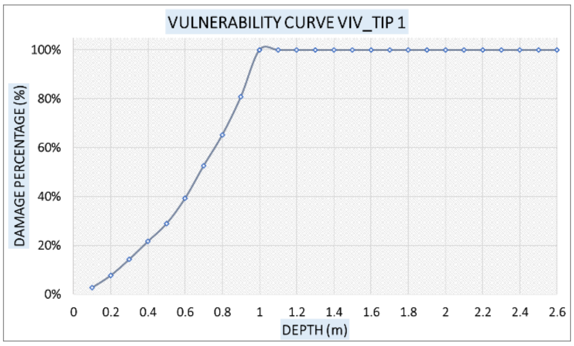

Figure 8. Vulnerability curve of VIV-TIP-1.

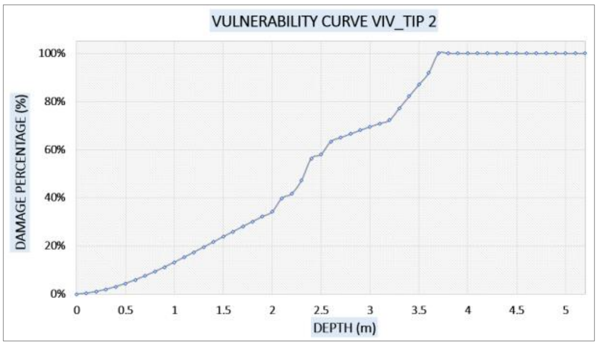

Figure 9. Vulnerability curve of VIV-TIP-2.

3.3. Damage map

In Figure 10 the level of damage for each building is observed in the presence of the hyper-concentrated flow caused by the "El Niño Costero" phenomenon of 2017. By knowing the depth of flow present in each building, it was possible to determine the percentage of damage dealt using the vulnerability curve according to the type of building. This percentage can be classified to determine the level of damage to the building as indicated in Table 4.

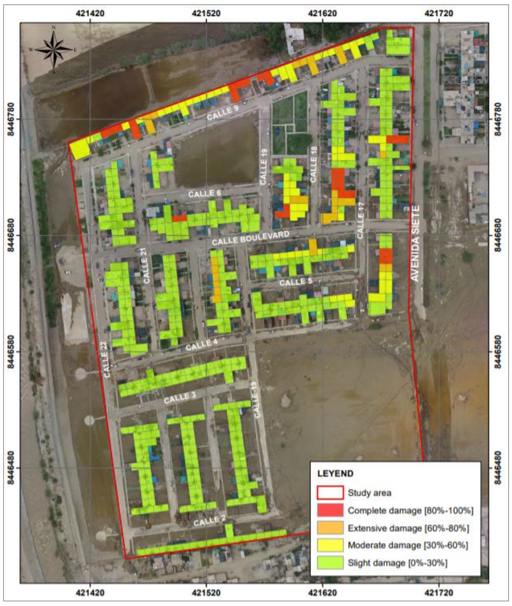

Figure 10. Damage map.

4. Analysis and interpretation of results

The criteria adopted for the realization of the vulnerability curves were contrasted with the results of other related investigations. Although no evidence of curves was found for hyperconcentrated flows with sediment concentration (Cv) between 0.22 to 0.35, evidence of vulnerability curves for floods (Cv < 0.20) and debris flows (Cv > 0.40) was found. It was found, for both cases, that the intensity of the impact is partially different from the case study; however, this was a point of comparison to consider validating the proposal.

On the one hand, from Figure 11 it can be seen that the VIV-TIP-1 vulnerability curve for hyperconcentrated flows is slightly higher than the HAZUS and CAPRA curves that were developed for floods. This can be attributed to the fact that the impact of hyperconcentrated flows on confined masonry buildings is greater than in the case of a flood.

On the other hand, from Figure 12 it is evident that the effects caused by the same flow depth have a different result depending on the type of event, resulting in that the vulnerability curves developed by [5] [6] [8] for debris flow would have a higher percentage of damage for the same flow depth than in the case study, which is a hyperconcentrated flow with a (Cv) between 0.22 - 0.35.

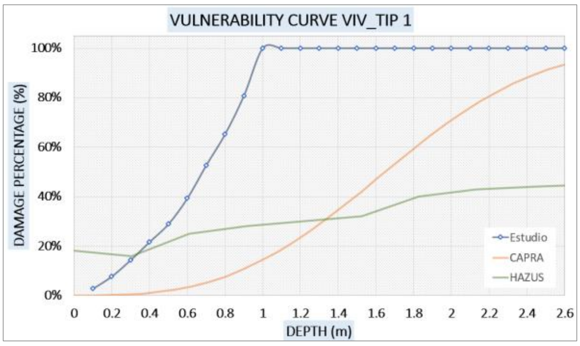

Figure 11. Comparison of different vulnerability curvesVIV-TIP-1.

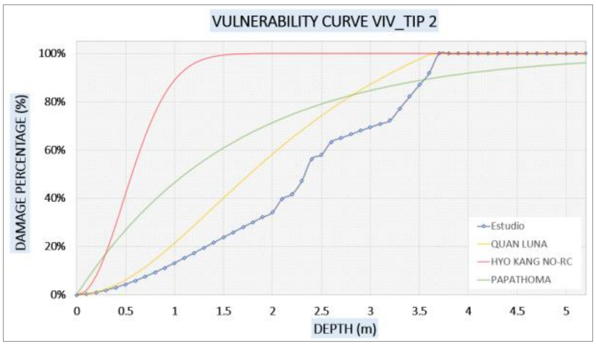

Figure 12. Comparison of different vulnerability curvesVIV-TIP-2.

5. Model validation

The vulnerability curve methodology mainly requires two inputs, the flow depth map and the damage percentage. For this reason, to validate the hydraulic model of the "El Niño Costero 2017" event, the flow depth values corresponding to the event were compared at 08 points located in Urb. San Idelfonso as seen in Figure 13; information collected in the field through interviews with local residents. The calibration of the model allowed modifying the (Cv) for hyperconcentrated flows until presenting a flow map similar to that described in the field and to SIGRID (CENEPRED).

Figure 13. Location of calibration points.

6. Conclusions

- Different sediment concentrations (Cv) were used, from constant values to variable values in a range of 0.22 - 0.35, which were modified until they resembled the flood map that was presented for the analyzed event. Using a constant Cv of 0.22 until the breaking point where the flow increases, reaching a maximum Cv of 0.35 for the peak flow and decreasing proportionally to 0.26 for the first break point after the maximum flow and 0.24 for the second change point.
- The final flood map of the model was validated according to the affected area present in the SIGRID platform for the event studied. For this, there were 8 calibration points located in different places within the sector, from which the depth of the flow reached on the day of the disaster was obtained with information collected in the study area.
- The vulnerability curves obtained show a difference in the maximum point of damage in the building, which corresponds to a height of 1.0 m for the VIV_TIP_1 curve and 3.63 m for the VIV_TIP_2 curve. This is due to the fact that 2-story buildings have a higher cost in the items because they are divided into two levels and the depth flow present in the building has to damage the second level for its total loss.
- In accordance with the damage classification [Table 6], These results show that, at least 24 buildings had a complete damage level; 21 buildings, extensive level; 55 buildings, moderate level and 184 buildings a slight damage level.
- In addition, since the damages relationship is based on monetary amounts, the total economic damages caused by the hyperconcentrated flow of 2017 could be estimated, amounting to approximately 1'303,881 soles or USD 407,463 considering the exchange rate in January 2017 (1 USD = 3.20 soles).

Author’s comments about the research

The vulnerability curves for hyperconcentrated flows should be generated for a greater number of building typologies due to the great variety of existing constructions in the country, such as ‘adobe’, wood, ‘quincha’ or other materials. In this way, a methodology will be needed to assess damages in any area of our country regardless of the type of building; However, this would mean carrying out research for each type of construction due to the difference in materials used. The applied method makes it possible to assess the vulnerability in similar situations of terrain and hazard elements but it cannot be easily generalized.

The methodologies for the elaboration of vulnerability curves in developed countries use information from insurance companies that collect information through post-event surveys, in Peru, the damage information registry is in the SINPAD (Sistema de Información Nacional para la Respuesta y Rehabilitación), therefore, based on all the information collected in this restricted access platform, it could start with the formulation of vulnerability curves for different types of phenomena since there is valuable information that should be used for the production of new methodologies.

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