Modelling a Dam Breach failure: Case of study in the Chaglla Reservoir, Perú.

Fernández - Sánchez, A.[1,2], Bernal López, N.[3], Peña Chávez, E.[1,2], Álvarez Aldegunde, J.A[4]., Vasco Nganhane, H.[5]

1. *Departamento de Geografía. Universidad Complutense de Madrid. España. Calle Profesor Aranguren s/n. 28040, Madrid, España.*
2. *Guías de Espeleología y Montaña. Casilla del Mortero s/n, 28189, Madrid, España.*
3. *Tragsatec. C/ Julián Camarillo, 6B, 28037 Madrid. España.*
4. *Civil Engineering Department, Universidad de Cartagena, St. San Agustín, Cra. 6, Nª 36-100, Cartagena De Indias 130001, Colombia.*
5. *Departamento de Ciencias Naturais e Matemática, Universidade Pedagógica, Moçambique.*
   Correspondence author: adrferna@ucm.es

Abstract

The dam breaching is one of the events with the most catastrophic consequences among the risks due to fluvial flooding, given the intensity, the great extension of the affectation and the speed of the event.

At present, various hydraulic modeling programs are capable of simulating the breach in the wall of a dam, as well as its possible subsequent flooding, granting speeds and drafts in the different study sections. The ability of hydraulic models like Hec-Ras to simulate the behavior of non-Newtonian flows in 2 dimensions improves the modeling carried out in the last decades.

The present work evaluates the flooding produced by a hypothetical phenomenon of breaching of the Chaglla dam, located in the department of Huánuco, Peru. This water reservoir constitutes the largest reservoir of fresh water and human origin in Peru with 308,500 m3 of water, supplying populations such as Tingo - María or Aucayacu. Through the application of a 2-dimensional hydraulic model and the Hec-Ras "Breaching" extension, it is intended to improve the knowledge of flooding due to the Chaglla dam breaching in the Huallaga river valley area, as well as to know the susceptibility to the danger due to the speeds and depths that the sheet of water could reach in this region.

The results show a catastrophic event that would cover a large part of the extension of the defined study area, with maximum depth of 40-20 meters and maximum speeds of 8-5 m/s. All of this could suppose the existence, for the most part, of a susceptibility to the danger of this event characterized as Very Serious. The population that would be in flood zones of any type would be 90,926 people.

1. Introduction

The breaching of the wall of a dam constitutes one of the most dangerous events for inhabited areas downstream of a reservoir. As it is a relatively fast process, the high level of danger will be associated with the sudden and extensive discharge of the dammed water behind the reservoir. This discharge produces flooding downstream with a flood front of high height and extended in practically the entire floodplain (Cai et al., 2020; Li et al., 2019). The consequences of a flood passing through a populated area can be catastrophic.

Various dam break events have occurred in recent history, most of them were caused accidentally, such as the Los Puentes Dam in Lorca (Spain, year 1802), which produced 608 deaths (Ubeda Romero, 1963); the Banqiao dam breaching (China, year 1975), with between 26,000 and 171,000 deaths (Xu et al., 2008); or the Machichhu dam (India, 1979), with between 1,800 and 25,000 deaths (U.S.D.I., 2015).

Other breachings, however, were intentionally caused in war contexts, such as those induced in World War II by British aircraft against German dams (Cockell, 2002), attacks in which 1,600 people perished; or the bombing of 13 reservoirs carried out by the United States during the Korean War (Crane, 2001; Field Jr., 2000), with an unknown but presumably very high number of victims. These acts were prohibited by the Geneva Convention in Article 56 of Protocol I (Protocol Additional to the Geneva Conventions of 12 August 1949, and Relating to the Protection of Victims of International Armed Conflicts (Protocol 1), 1977).

In Peru, dam failure events have occurred less frequently, but they have been noted in specific episodes such as the breaching of the natural dam formed by a landslide that dammed a newly formed lake in Huaccoto (Ponce & Tsivoglou, 1981); or the Huancapetí (Huaraz) mining pond breaching that discharged 50,000 m3 of contaminated water in 2018 (Urbina, 2018). Despite the great environmental cost, these episodes in that country have not led to human losses. The breaching of natural dams of glacial lagoons (such as moraines), however, have had some material and human repercussions. An example would be the breaching of the moraine that dammed the Palcacocha lagoon, producing a flood that killed 1,800 people in 1941 (Stuart-Smith et al., 2021).

The current legislation in Peru determines minimum security for dams and water ponds that include the evaluation, maintenance and management of emergency plans for each dam (ANA, 2019). These emergency plans are based on simulations of accidents that can occur in a dam or pool of water, such as accidental breaks in the dam's glass.

In order to try to reduce the impact of dam failure events, it is necessary to carry out an evaluation of the magnitude of the possible accident, either prior to the construction of the dam or later in the event that they are desired. plan new human activities in the environment.

The best tool to assess the danger of these specific events is the modeling of the effects of the breaching of the dam vessel. This modeling can be done with mathematical simulation programs that collect the topographic characteristics of the terrain and the subsequent water discharge according to various occurrence scenarios.

The Hec-Ras software is a mathematical model based on the use of hydraulic equations (such as the Navier-Stokes equations or the Saint Venant equations (Strelkoff, 1970; U.S. Army Corps of Engineers, 2023) and applied in a one-dimensional or This model can resolve the behavior of a fluvial flood (both of a pluvial nature and the breaching of a dam) from a topography entered in Raster format, generating a map of the extension of the flood sheet as well as spatial results. of maximum drafts and maximum speeds Through the use of Geographic Information Systems it is possible to relate these parameters to generate maps of danger and/or susceptibility according to predefined risk standards.

The objective of this study is to evaluate the flooding of the Huallaga river valley region (Huánuco, Peru) after a breaching event of the Chaglla dam vessel. The flooding will be calculated with a hydraulic modeling software according to various water storage scenarios of the reservoir. The modeling will be carried out without entering into an assessment of the probability of occurrence of the event, a fact that would correspond to the simulation of the breaching of the vessel and temporally non-linear and difficult-to-predict variables, such as the maintenance of materials and security systems. It is because of this lack of probability that this calculation of flooding cannot be taken as a calculation of danger or risk (since there is no social evaluation in this study).

Therefore, the Hec-Ras software, with the Breaching extension, is a very useful program for simulating the effects of flooding that a scenario of breaching of the Chaglla dam in Huánuco (Peru) would have.

2. Location

The flood risk due to the breaching of the Chaglla dam has been calculated along the Huallaga River valley, comprising 121 kilometers of it from the reservoir of the Chaglla dam itself (department of Huánuco, Peru) to the town of Aucayacu (also in Huánuco). The study area would encompass a polygon of 1021.5 km^2 around the Huallaga river valley and the towns surrounding it (Figure 1).

The Chaglla dam (inaugurated in 2011) is located at 9º 41″ 45.7′ S and 75º 50″ 06.05′ W with an altitude of 1000 meters above sea level. It is a three-turbine dam that functions as a hydroelectric power station. Its effective amount of storage is 308,500 m3 and its installed capacity is 456 MW per day 2749 GW per year (Klohn Crippen Berger, 2018; OSINERGMIN, 2020). The dam is made of rock-filled material and a concrete (cement) lining, giving an elevation of 211 meters above the base of the Huallaga River.

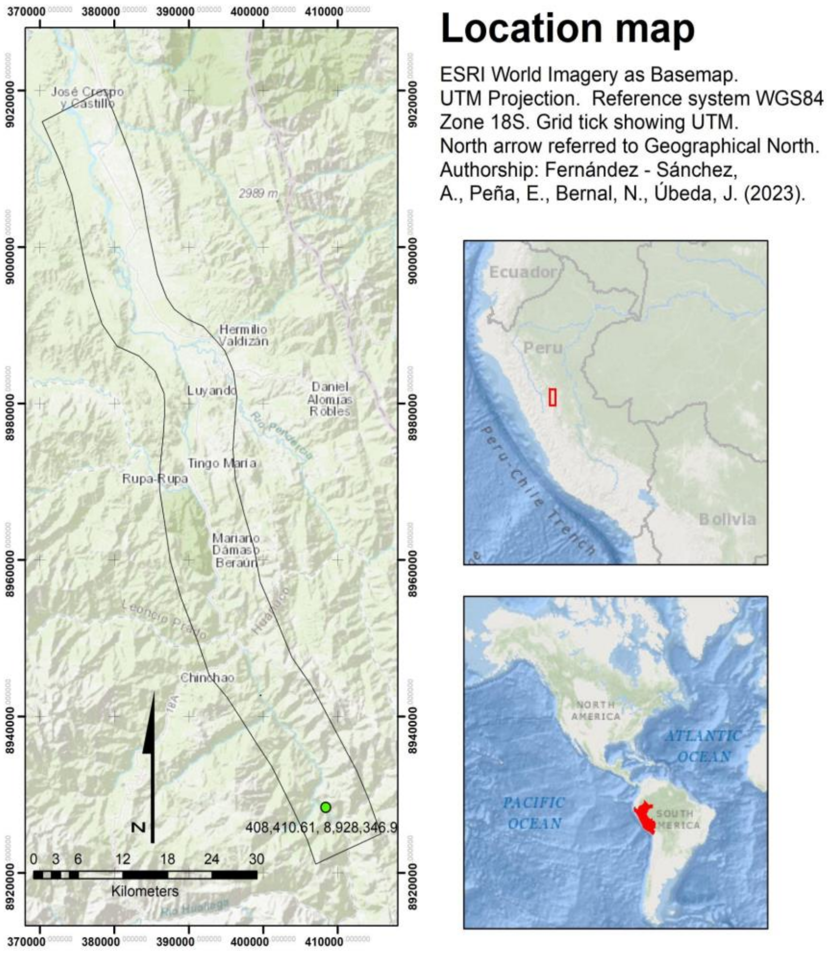


Figure 1. Location map of the study area for the analysis of the breaching of the Chaglla dam.

The study area contains an estimated population of 95,438 people, distributed in several medium-sized cities and smaller population centers. The main localities present in the Huallaga River valley would be Tingo María (46,191 inhabitants), Aucayacu (25,259 inhabitants), Pampamarca (2,241 inhabitants), Mapresa (1,590 people), Pueblo Nuevo (1,376 inhabitants), Tambillo Grande (1,147 inhabitants).), Cayumba (1004 people) or Naranjillo (1126 people) (INEI, 2022). The rest of the towns would be considered populated centers with fewer than 1,000 inhabitants, as well as isolated dwellings. There is, in turn, a permanent camp for the dam workers at the exit of the dam, with some 40 infrastructures.

The Huallaga River is a relatively confined river during most of the study area, with certain lateral sandy bars and a small or almost non-existent flood plain. The average slope of the Huallaga Valley would be 1.39%. After passing through the town of Tingo María, the Huallaga River valley widens creating a floodplain of between 1 and 3.5 kilometers and a channel with greater mobility. The river, in this section, alternates the anastomosed morphology with the meandering with lateral and internal bars. Towards the town of Aucayacu, the Huallaga River increases its flow (both solid and liquid) after the water supply from the Pucayacu River, becoming more meandering with large interior bars in the form of islands and scrollbars.

3. Methodology

3.1. Data source

This study uses a series of data from public bodies and official projects.

The dimensions of the Chaglla dam have been determined based on information from the company Klohn Crippen Berger (2018). The measurements used for the design of the dam wall were: 211 meters high, 273 meters long at the crest, and 11.20 meters wide at the crest.

For the simulation of the flood model, the Digital Terrain Model (MDT) of the ALOS-Palsar program was used as a basis, with a spatial resolution of 12.5 meters. An image obtained on a date corresponding to a dry season (July) was selected in order to best represent the morphology of the Huallaga river bed, as well as the bathymetric morphology of the reservoir as it is at a low level.

3.2. Terrain preprocessing

Despite the fact that the MDT image was obtained during a dry season (the water level of the reservoir is usually at 1,245 meters above sea level and in the MDT it is at 1,114 meters), there were some areas covered by a certain sheet of water, either in the river bed or in the reservoir. Given the inexistence of studies or bathymetric profiles in this area of Peru, it was decided to modify the DTM to provide an estimated bathymetry for both the river bed and the area of the reservoir covered by water in the ALOS-Palsar image. This action was done by creating cross sections in Hec-Ras, modified to give an intuited bathymetry and later exported as a Geotiff.

In turn, the DTM image was preprocessed with the ArcGis Fill sinks tool, which fills very marked depressions to make a hydraulically continuous raster.

3.3. Hydraulic Modelling

The flood sheet modeling was carried out using the Hec-Ras 6.3.1 software. (U.S. Army Corps of Engineers, 2023). This software performs a one-dimensional and two-dimensional

Hydraulic Modeling from a Digital Terrain Model and a flow specified by the user. The calculation of the water sheet is made from the Saint-venant and Navier Stokes equations for the two-dimensional behavior of the water sheet. The Navier-Stokes equations describe the motion of a fluid in 3 dimensions of space according to the conservation of mass and conservation of momentum equations, while the Saint-Venant equations apply the momentum force according to the dimension friction slope and roughness by Manning's N in the river channel (Strelkoff, 1970; U.S. Army Corps of Engineers, 2023).

Hec-Ras has the ability to simulate floods derived from the breach of a dam wall using the Breaching tool. By introducing the measurements of the dam basin, the introduction of breach morphology parameters and the height of the reservoir water sheet, Hec Ras simulates an outflow through the breach, a flood sheet in the terrain and a flood hydrograph.

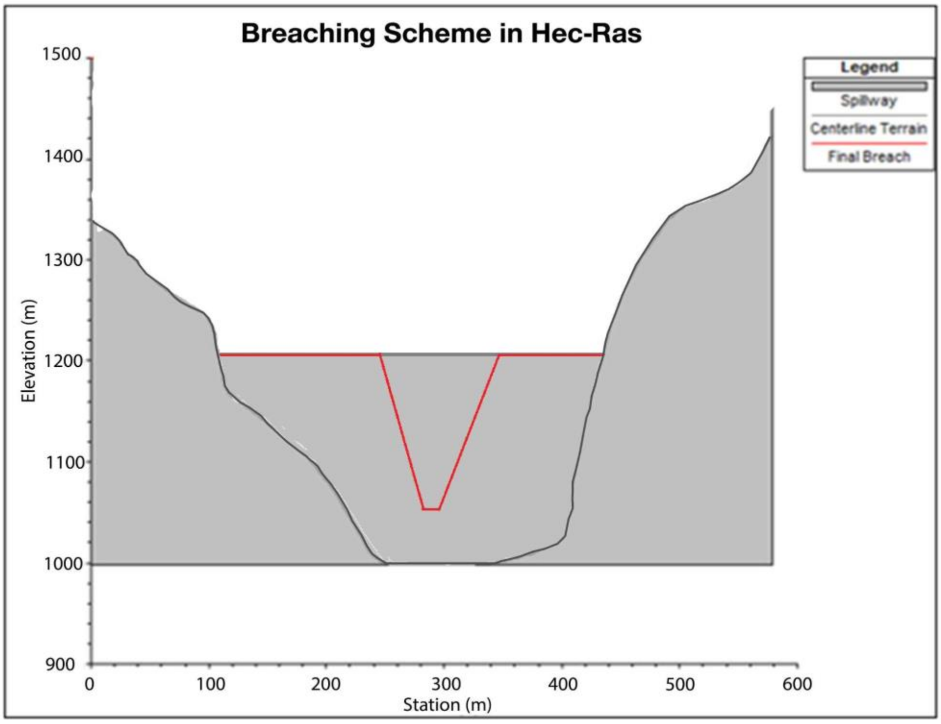


Figure 2. Simulated breach in the Chaglla dam. Screenshot derived from the Hec-Ras Breaching extension.

In the case of the modeling of this study, the dam wall introduced in Hec Ras tried to resemble reality by inserting the same relative measurements. The input parameters of the wall were a height between 211 and 273 meters (1200 meters of altitude), a length of 249 meters and a width of 11.20 meters.

The simulated breach had a trapezoidal, almost triangular morphology (Figure 2) and was located on the center of the dam wall at a distance of 250 meters from each side. The morphology of the simulated breach was 150 meters high, 100 meters wide, 10 meters at the base and its upper part coinciding with the maximum top of the dam wall.

The breach morphology would be difficult to estimate, having chosen an almost triangular Trapezoidal morphology. This morphology would be the simplest for simulation, and the most common in earthen embankment dams (Froehlich, 2008; Morris et al., 2007; Shuibo & Loukola, 1993), such as the Chaglla dam. . In turn, the trapezoidal morphology could occur in different types of accidents such as erosion by overtopping or normal fault.

The breaching process was programmed for a duration of 1 hour, from the incipient breach (the cracking phase) to the full development of the breach, according to the guide of the NWS agency (Wetmore & Fread, 1981) and the FERC. (FERC, 2016). Hec Ras would calculate a first flow of water from the beginning of the breccia, calculating a full flow at the moment in which the breccia would be fully developed. This flow

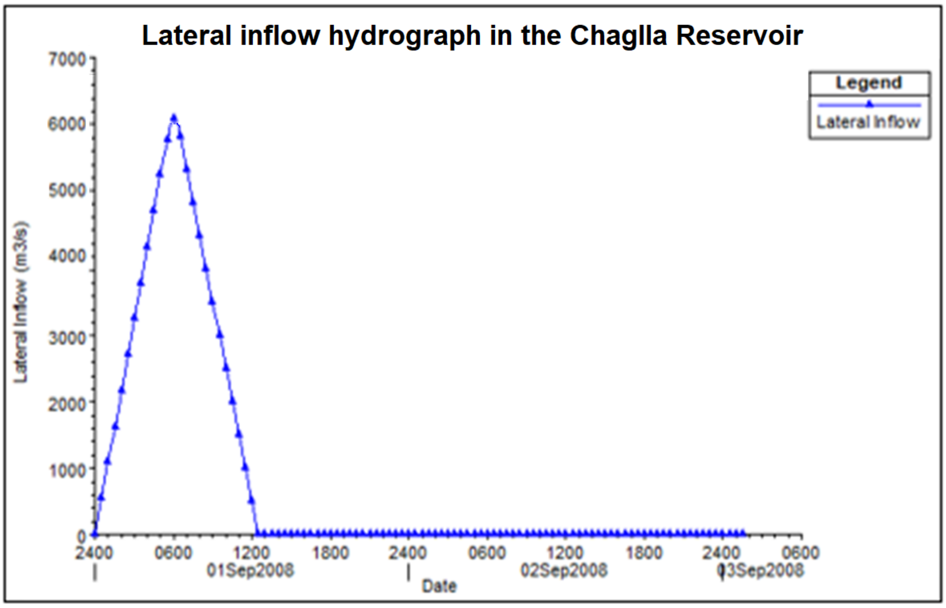


Figure 3. Example of a lateral hydrograph entering the reservoir after the breaching process for the 6000 m3/s scenario.

This flow would function as the input hydrograph for the boundary conditions of the study area and the generation of the flood sheet.

Since the fluvial course of the Huallaga River has a constant flow, the contribution to the reservoir after the breach process would not cease. Therefore, a constant flow has been introduced as Lateral Inflow Hydrograph, in the boundary conditions of the reservoir. This flow was obtained from the data of the Emergency Action Plan for the Operation of the Chaglla Hydroelectric Power Plant (Klohn Crippen Berger, 2018), introducing scenarios 1 and

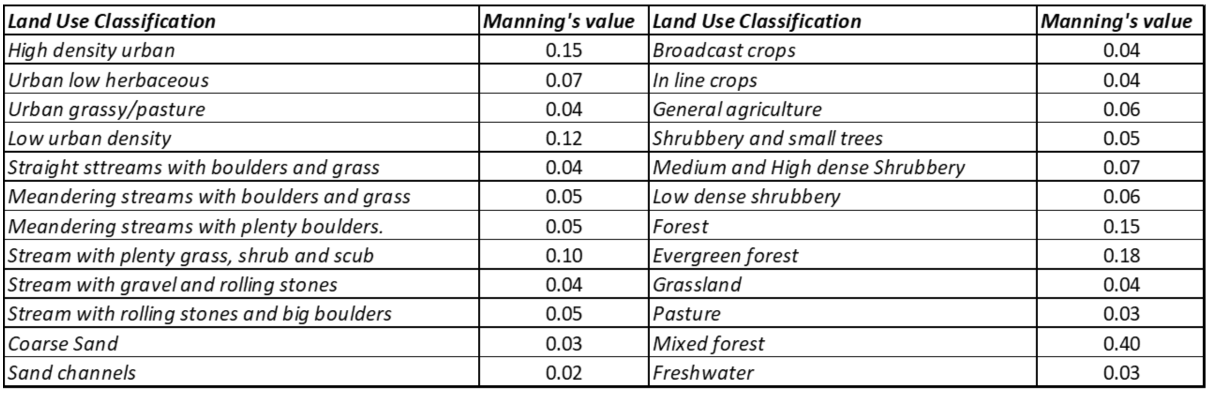
2 of said plan. Flow values were entered as a triangular synthetic hydrograph (Figure 3). With 6,000 m^3/s in the most severe scenario and 2,000 m3/s in the most moderated scenario.

The calculation made by Hec-Ras is displayed in its own .g01 format, which can be exported to different Geographic Information Systems in raster format. Results have been fed into ArcGis Pro software for integrated mapping and analysis.

The results obtained from the modeling included a maximum flood sheet, maximum speed values and maximum draft (depth) values. The maximum speed would be expressed in meters per second (m/s), while the maximum draft would be expressed in meters of height (m) with respect to the surface.

Both results were mapped encompassing various ranges of values. The ranges of maximum speed between 2 and 5 m/s have been represented in intervals of a single unit while the values greater than 5 m/s have been included in the same category to improve the representativeness of the map. In the case of maximum drafts, 8 different classes were created to represent homogeneous heights of the flood.

As a basis for the N-Manning roughness parameter necessary for modeling, a cartography of the study area was carried out, determining the probable roughness from aerial photography interpretation and a description of the occupation or land cover. This cartography was made with the ArcGis Pro software and was imported into Hec-Ras. Given the non-existence of land use or roughness mapping by Manning in Peru, this mapping was carried out solely for the present study.



Land Use Classification	***Manning's value***	***Land Use Classification***	***Manning's value***
High density urban	0.15	*Broadcast crops*	0.04
Urban low herbaceous	0.07	*In line crops*	0.04
Urban grassy/pasture	0.04	*General agriculture*	0.06
Low urban density	0.12	*Shrubbery and small trees*	0.05
Straight sttreams with boulders and grass	0.04	*Medium and High dense Shrubbery*	0.07
Meandering streams with boulders and grass	0.05	*Low dense shrubbery*	0.06
Meandering streams with plenty boulders.	0.05	*Forest*	0.15
Stream with plenty grass, shrub and scub	0.10	*Evergreen forest*	0.18
Stream with gravel and rolling stones	0.04	*Grassland*	0.04
Stream with rolling stones and big boulders	0.05	*Pasture*	0.03
Coarse Sand	0.03	*Mixed forest*	0.40
Sand channels	0.02	*Freshwater*	0.03

Table 1. Land uses and Manning values assigned for the study area.

The mapped parameters were based on urban, agricultural or forest land uses, including areas without land use but with natural cover, such as forest masses or fluvial channels (Table 1). The assessment of the Manning's N classification was made based on the proposals made by various investigations (Barnes, 1967; USGS, 1989; Vásquez-Ramírez & Burgos-Flores, 2021).

3.4. Computation paramathers

Finally, the desired computing characteristics have been indicated in HEC-Ras, which have been the following:

1. The simulation plan options with geometry preprocessor, non-steady state calculation, post processor and mapping of flood zones have been activated.
2. The programmed simulation time has been 29 hours. Therefore, simulating an event lasting 1 day and 5 hours. This time is greater than the concentration time of the basin (estimated at 23.5 hours).
3. The specified compute settings have been:
    - Computation interval: 30 s.
    - Map output interval: 30 s.
    - Hydrograph output interval: 30 min.
    - Interval of detailed results: 30 min.

In Hec-Ras, up to 7 profiles were generated along the floodable area to observe arrival times of the flood wave and maximum discharge. In these 7 profiles, hydrographs were calculated that compared the flow of water in Cm3 and the time in minutes. The hydrographs were calculated only with the 6000 m3/s scenario, in order to know the maximum discharge. Figure 4 shows the 7 profiles generated along the flood section.

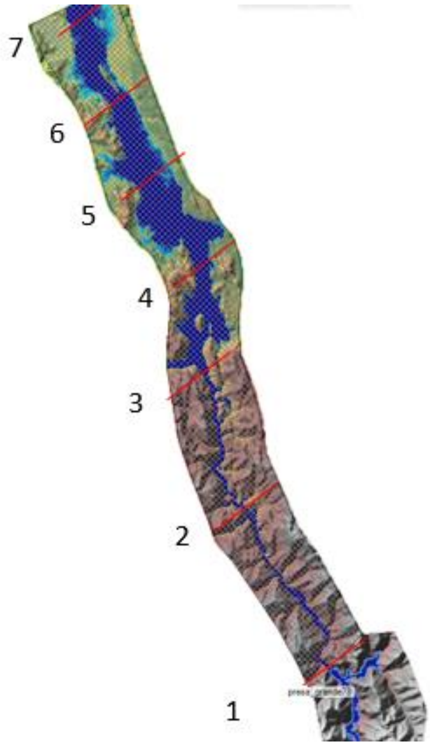


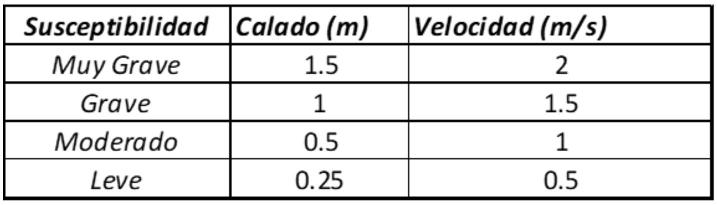
Figure 4. Hydrograph profiles in the study area.

3.5. Susceptibility

Based on the modeling results, an equivalent susceptibility to the affectation of the avenue to the existing population was estimated. This calculation was made according to the ranges of danger due to fluvial floods proposed by the Spanish Ministry of the Environment and the Support Guide to the Regulation of the Hydraulic Public Domain (MAPAMA, 2017). This guide classifies the various hazards (in this study determined as susceptibilities) according to ranges of maximum speed and maximum draft.

Regarding the maximum speed, the limit of the ranges defined for susceptibility has been 2 m/s, speed from which the degree of condition is considered to be "very serious" (MAPAMA, 2017). In turn, drafts greater than 1.5 m carry a degree of affectation also "very serious" against individuals, homes or urban infrastructure.

Lower ranges of maximum speed and maximum drafts (Table 2) would determine less affected susceptibilities, such as severe, moderate or slight. In the Geographic Information System, ArcGis Pro 3.0, the results of maximum speed and maximum draft were spatially related. In this relationship, the maximum value would be chosen from among the drafts or speeds, applying the corresponding susceptibility classification.



Susceptibilidad	*Calado (m)*	*Velocidad (m/s)*
Muy Grave	1.5	2
Grave	1	1.5
Moderado	0.5	1
Leve	0.25	0.5

Table 2. Limits of maximum drafts and maximum speeds for the classification of susceptibility.

4. Results

The most important results are commented below, also expressed in cartographic products. The ranges of values defined in the cartographic representation have followed the following criteria:

4.1. Maximum depth

The results obtained represent the maximum flood depths reached in the surroundings of the Huallaga River when the simulated flows flow through its channel. The drafts have been classified into 8 classes in a GIS. These maximum drafts can be seen in Figure 5.

Of the two scenarios represented, two of them contain very similar results. Even if the flow upstream of the dam were increased, the water would pass through the same geometry of the breach, without modifying the outlet flow.

The maximum drafts of both scenarios occur immediately after the breaching of the dam with values of up to 150 meters in height. Given the narrowing of the Huallaga river valley and the large amount of water released, depths between 100 and 50 meters high are maintained up to the limit of the municipality of Mariano Dámaso Beraún in the center of the study area.

In the city of Tingo María, to the north, the depths reach heights of between 14 and 70 meters. To the north of this population, near Luyando, given the widening of the flood plain, the depths decrease to 40 to 8 meters, to continue decreasing to 25 to 3 meters above the population of Aucayacu.

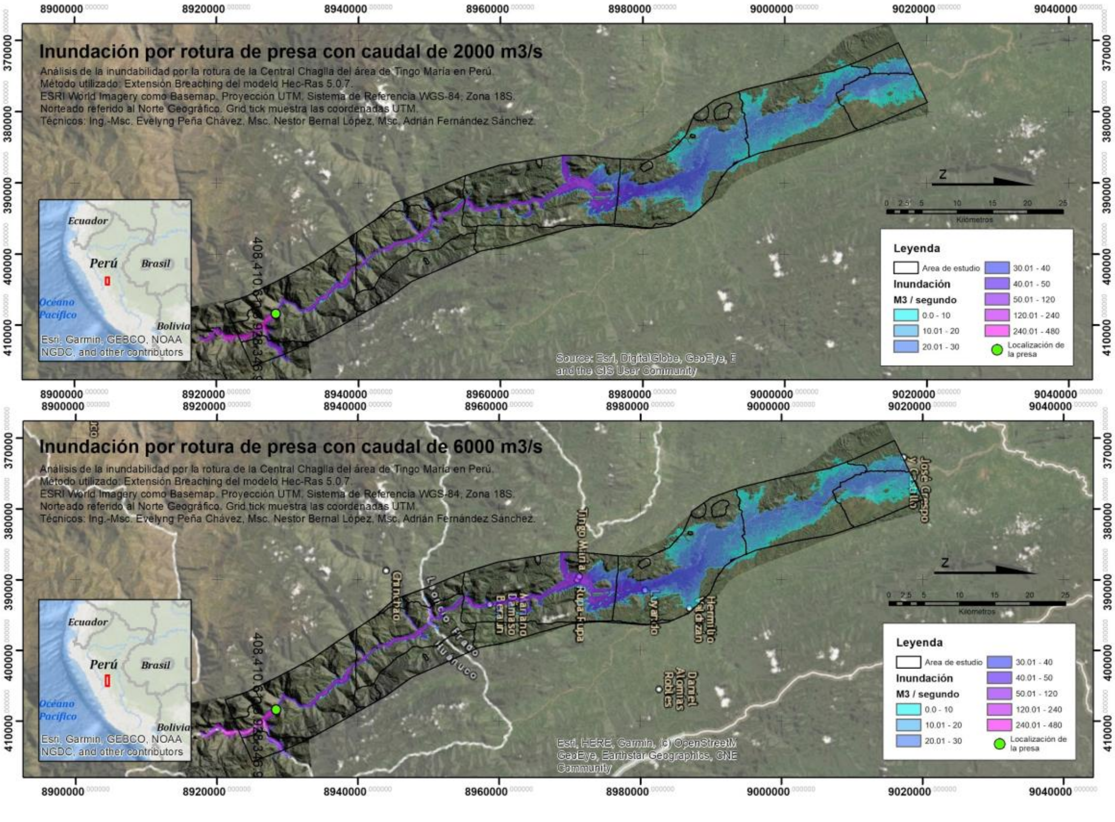


Figure 5. Simulated maximum depths for the flooding due to breaching of the Chaglla dam.

It is possible to observe how some of the tributary valleys to the Huallaga River suffer an elevation of the water sheet that constitutes backwater, since after the passage of the flood wave, the water returns to the main channel of the Huallaga River. Due to the large boxing of the main valley, the flood sheet can rise upslope until reaching a maximum level and then return. The fluvial courses where this fact can be perceived with greater entity are the Monzón

River or the Pachitea stream. This backwater elevation can be confirmed on the velocity map, which is reproduced and commented below.

4.2. Maximum velocity

The mapping of maximum velocities can be seen in Figure 6. The results of the maximum velocities reflect that the locations where the flow circulates faster are, fundamentally, at the outlet of the Chaglla hydroelectric power station, given the fall of the water and the steep slope of the riverbed.

The maximum speed values would reach 450 meters per second, indicating a low reliability of the simulated speed in the first 50 to 80 meters from the exit of the dam. In the first 400 meters of the channel after the outlet of the dam, the maximum speed would decrease to 35 meters per second. Upon reaching 30 kilometers away from the prey, the speed would decrease to 8 to 5 meters per second.

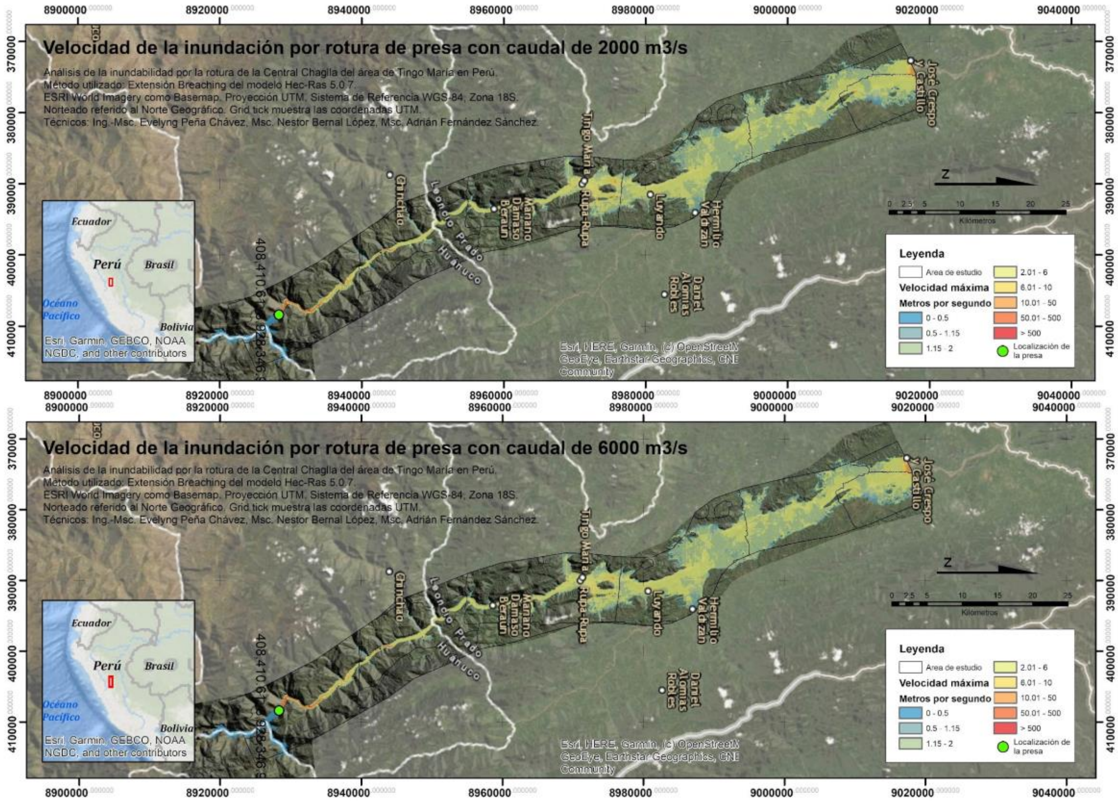


Figure 6. Simulated maximum velocities for flooding due to breaching of the Chaglla dam.

In the flood plain at the height of the city of Tingo María, the flow is slowed down to between 2 and 1 meters per second, with some areas presenting values of between 3 and 5 meters per second.

The tributary valleys to the Huallaga River have maximum speeds that are usually between 2 and 5 meters per second, not exceeding 10 meters per second, not even in the tributary valleys close to the hydroelectric power station. The city of Tingo María would be flooded with speeds of between 1 and 4 meters per second in its central and southern part. In the neighborhoods of PJ 9 de Octubre, AH Raúl Haya de la Torre, the maximum speed would increase to 7 meters per second.

Velocidades Máximas	***2000 m3 (Km2)***	***6000 m3 (Km2)***
0 - 0.5	22.91	26.90
0.51 - 1	126.36	129.00
1.1 - 2	21.07	17.00
2.1 - 5	131.02	136.00
5.1 - 10	12.53	14.70
10.1 - 20	3.10	5.90
20.1 - 30	0.59	2.70
30.1 - 100	0.83	1.20
>100	0.69	1.95
Total	319.09	335.35

Table 3. Extension of the different maximum speeds in the floodable area.

The speeds with a greater extension were from 2.1 to 10 m/s (with 131.02 km^2 in the 2000 m3 scenario and 129.03 km^2 in the 6000 m^3 scenario); and the speed from 0.5 to 1 m/s (with 126 km^2 in the 2000 m^3 scenario and 129.5 km^2 in the 6000 m^3 scenario).

Maximum depth	***Area 2000m3/s (Km2)***	***Area 6000m3/s (Km2)***
0-1	4.46	4.17
1.1-2	4.61	4.21
2.1-10	42.51	41.63
10.1-20	75.59	69.66
20.1-30	94.63	101.78
30.1-100	69.93	76.43
100-150	19.01	19.74
>150.1	8.19	8.33

Table 4. Estimated area of the maximum draft ranges for the two scenarios.

The depths with the greatest extension would be those from 20 to 30 meters deep in both scenarios (29.67% and 31.91% of the total surface), while the second largest extension would be the depths of 10 to 20 meters in the scenario of 2000 m3/s (with 23.7% of the total extension) and drafts from 30 to 100 meters deep in the scenario of 6000 m3/ (23.9% of the total extension), with most of the drafts in the first section of the range, with depths of about 30 meters. Drafts of less than 2 meters would occupy the smallest extensions in both scenarios.

Therefore, as observed in Table 4, the depths would basically be centered at a depth of 10 to 100 meters, with 75.3% of the surface in the 2000 m3/s scenario and a surface of 77.72% in the 2000 m3/s scenario. 6000m3/s.

4.3. Maximum extent

The total extension of the floodable area in the scenario with a flow of 2000 m^3 would be 319.24 km^2, while in the 6000 m^3 scenario this floodable area would amount to 325.95 km^2.

As can be seen, there would be a difference of about 6.7 km^2 in the flood surface between the modeling with one flow and another, the floodable area of the highest flow being greater. However, the difference would not be significant if the flow was doubled between one modeling and another.

4.4. Hydrographs: Reaching times and maximum discarge.

In the first profile (Figure 7), located at the outlet of the Chaglla dam, the Breaching process was simulated with a duration of one hour, which is why the maximum discharge would reach 1:04 hours, being 4 minutes. after the full development of the breaking phenomenon. The maximum discharge would amount to 67,000 Cm^3 of water.

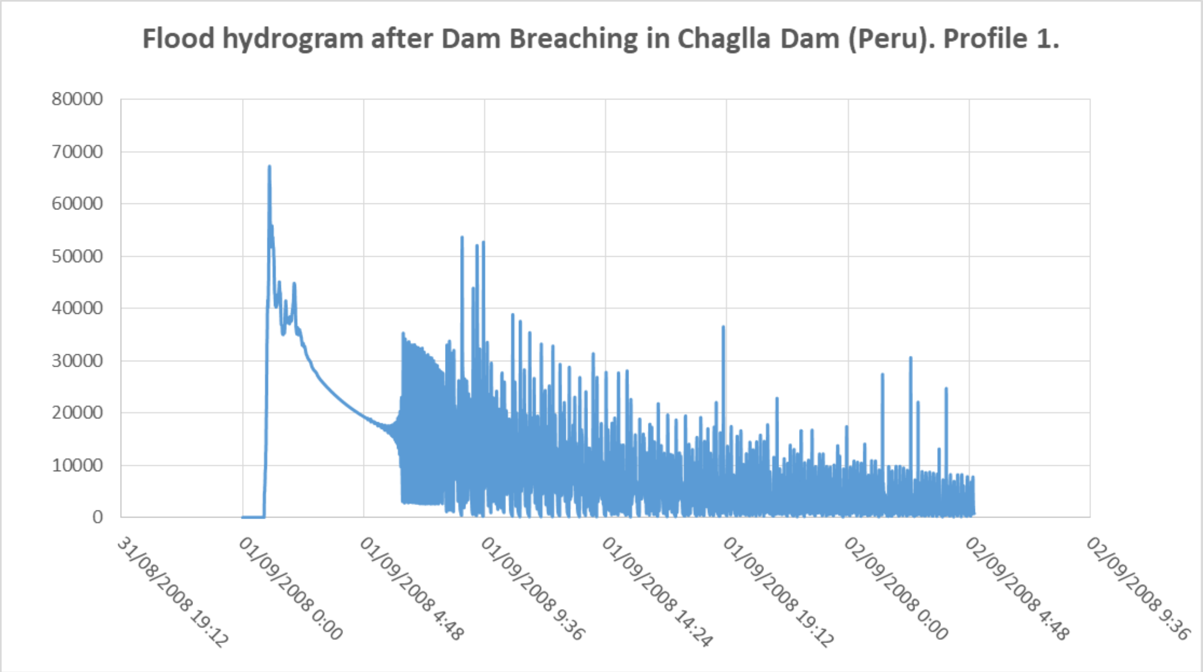


Figure 7. Hydrograph of the flood after the development of the breach in the Chaglla dam.

In profile number 2 (Figure 8), located about 17 kilometers from the dam, the maximum discharge would be about 96061 cm3 of water, with an estimated arrival time of 5:34 hours after the development of the breaching (at 6:34 hours of modeling). There would be a second flood wave at 6:43 hours after the development of the breach, with about 82,800 cm3. The flood would be evacuated progressively, with a long dissipation period, perhaps due to the boxed-in characteristics of the Huallaga River valley.

Profile number 3, located about 25 kilometers from the dam, would have a wave arrival time of about 10:27 hours after the development of the dam break. At this point about 185,000 Cm3 would arrive in a single wave that would be reduced to a minimum about 3 hours later without secondary waves.

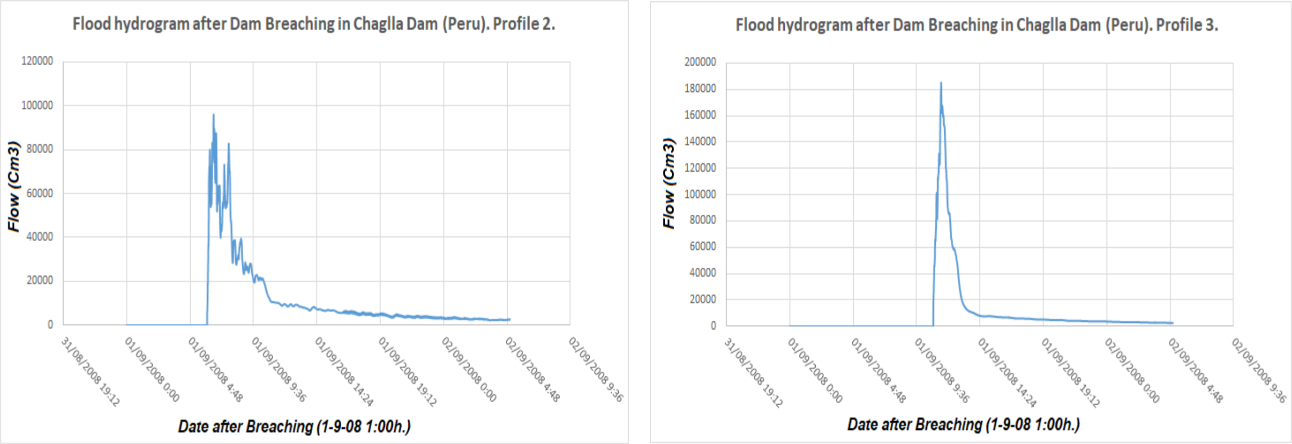


Figure 8. Hydrograph of the flood in profiles 2 and 3 after the breaching of the Chaglla dam.

In profile number 4 (Figure 9), located about 50 kilometers from the dam, the flood wave would arrive at 15:10, 14:10 hours after the dam burst. The maximum discharge would be 125,000 Cm3. The flood would occur in a single wave that would be sudden and dissipate.

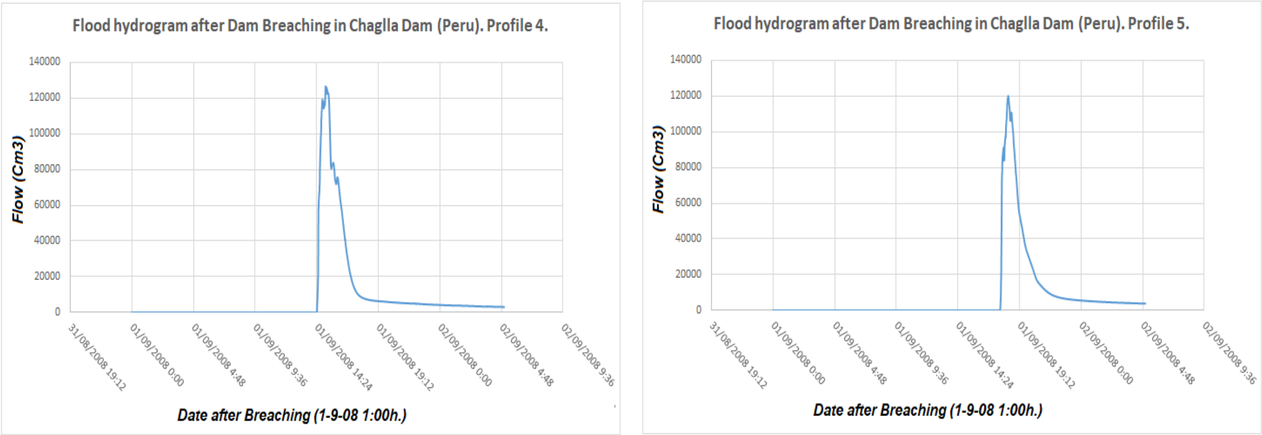


Figure 9. Hydrograph of the flood in profiles 4 and 5 after the breaching of the Chaglla dam.

In the case of profile number 5, located about 63 kilometers from the dam, the maximum discharge would be 119,000 Cm3 of water. The flood wave would arrive at 6:19 p.m., being 5:19 p.m. after the dam broke. This wave would behave like a burst wave, although the dissipation would be slightly more gradual than profile number 4.

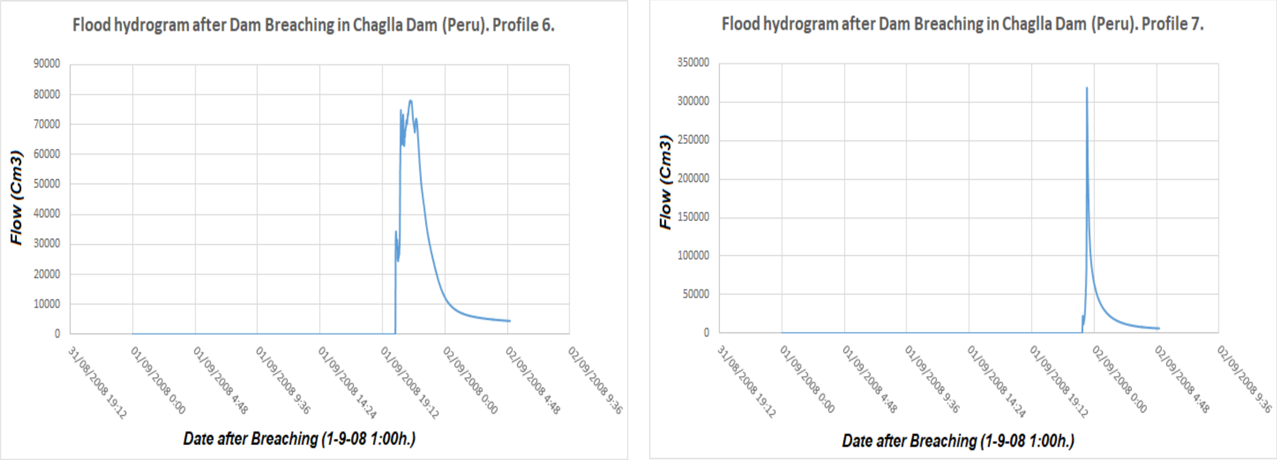


Figure 10. Hydrograph of the flood in profiles 6 and 7 after the breaching of the Chaglla dam.

In profile number 6 (Figure 10), located about 73 kilometers from the dam, the flood wave would arrive at 20:36, 19:36 hours after the dam burst. The maximum discharge would be 77,300 Cm3. The inundation would occur in a single wave that would be sudden, but would crest for an hour and 30 minutes before it also began to dissipate relatively suddenly. In the case of profile number 7, located about 90 kilometers from the dam, the maximum discharge would be 317,000 Cm3 of water, the wave being of the greatest magnitude, perhaps due to the great lateral extension. The flood wave would arrive at 11:26 p.m., being 10:26 p.m. after the dam broke. This wave would behave like a burst wave and the dissipation would also be relatively fast.

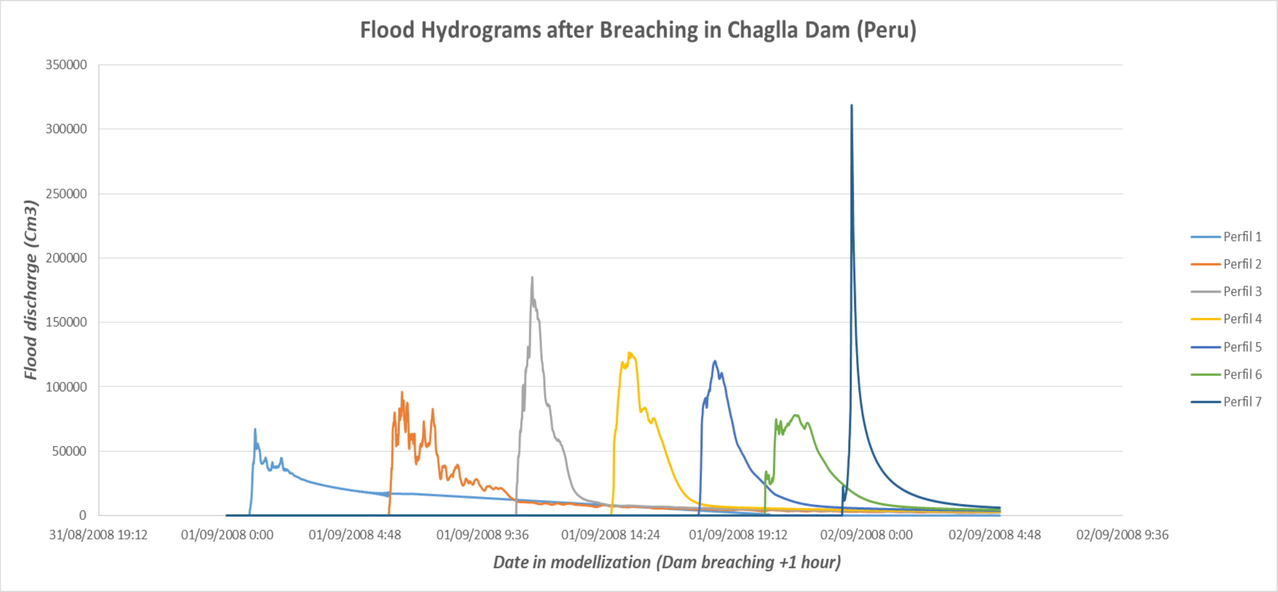


Figure 11. Hydrographs calculated throughout the study area.

The hydrographs calculated for the different profiles (Figure 11) show a common trend in which the start of the flood wave would be sudden in all cases. In the case of Profiles 1 and 2, the dissipation of the flood avenue would be progressive, perhaps due to the boxed-in nature that the Huallaga valley would present in these areas.

The other profiles would have a relatively fast dissipation. The flood waves would arrive progressively at each profile. The flood wave would arrive 4 minutes after the breaching process to profile 1, while to profile 2 it would arrive 5.34 hours later. Profile 3 would see the arrival of the flood wave at 10:27 a.m. after the break, while profiles 4, 5, and 6 would arrive at 2:10 p.m., 5:19 p.m., and 7:36 p.m. respectively. Finally, the flood wave would arrive 22.26 hours after the breach to profile number 7.

The maximum discharges would oscillate between 67,000 Cm3 of the first profile to 317,000 cm3 of water of profile 7. The two profiles (1 and 2) existing within the confined part of the river would be those with the lowest existing maximum discharge (between 67,000 and 74,000 Cm3), while the first profiles at the beginning of the floodplain would be those with the greatest maximum discharge (185,000 and 125,000 cm3), not counting Profile 7, which would have 317,000 cm3 of discharge, surely due to the large extension of the floodplain. flood.

Most of the hydrographs would have an hour of duration for the main flood wave (30 minutes for the shortest, profiles 4 and 5) containing a very long flood dissipation period of several hours. Meanwhile, hydrographs 3 and 7 would have a duration of the flood wave of just 10-15 minutes, with a very rapid dissipation as well. Profiles 4-6 would have a relatively broad crest that would last for about an hour, while Profiles 1 and 2 would have a flood dissipation that could last more than 24 hours in total.

4.6. Susceptibility

In general, most of the flooded area would have a Very Severe susceptibility (Figure 12). This classification would be determined by the height of the sheet of water, given that in most of the floodable area there would be drafts greater than 2 meters, despite the fact that some areas of the floodable area would not have a velocity greater than 1 m/s.

Within the flood prone area, the percentage of the study area with very serious susceptibility would be 96.06% in the 2000 m^3/s flow scenario and 98.07% in the 6000 m^3/s flow scenario. The percentages of surface with severe, moderate and slight susceptibility would be minimal (between 0.58 and 0.67% in the 2000 m^3/s scenario and 0.55 to 0.7% in the 6000 m^3/s scenario) and would be located at the outer limits of the floodable area. for the most part. The Very serious classification would have a greater surface area in the 6000 m^3/s flow scenario with 2% or 6.7 km^2 of surface area.

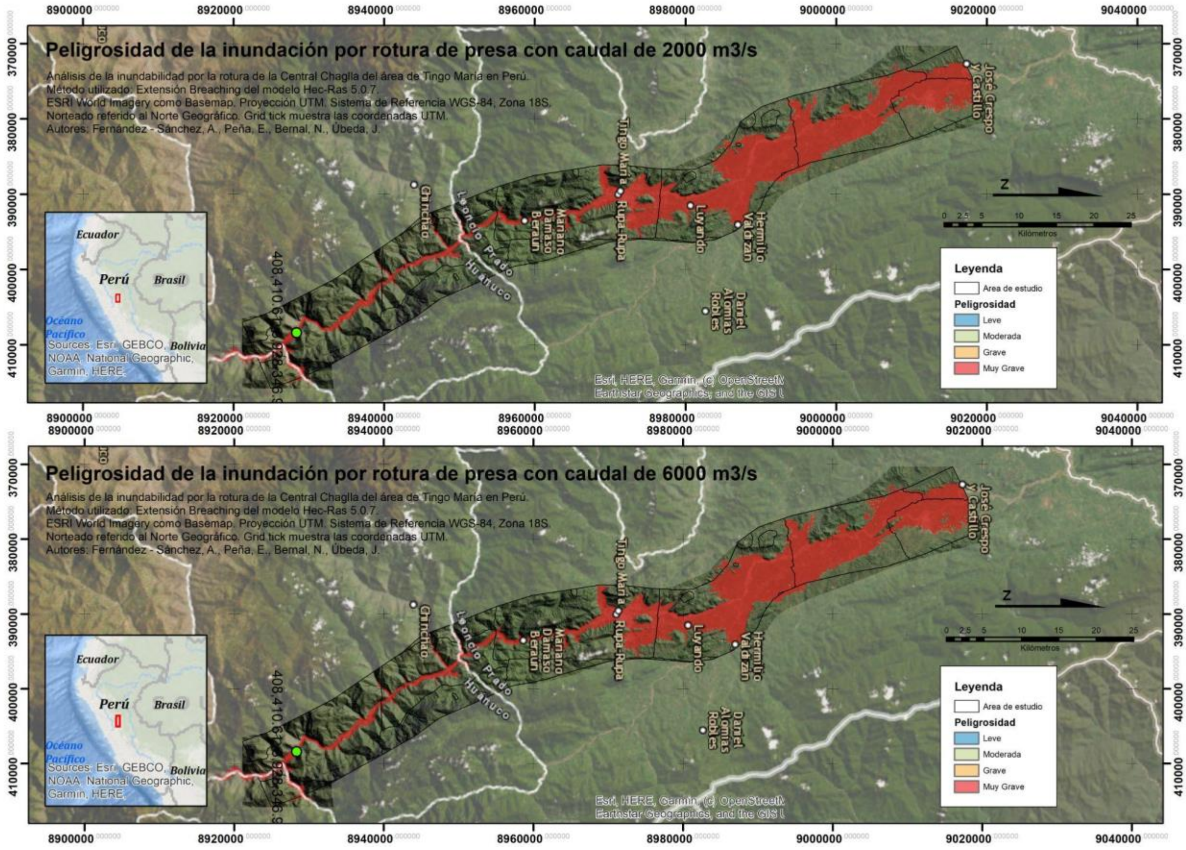


Figure 12: Calculated susceptibilities after the failure of the Chaglla dam.

The flooded area of the modeling in both scenarios would cover the entire flood plain, as well as the boxed bottom of the beginning of the Huallaga river valley. Since the existing populations in the study area are located in the floodplain, most of them would be covered under Very Severe susceptibility.

Of the 98 populated centers, only 20 of them would be free of areas with some type of susceptibility. Most of them are centers located on the slopes and upper parts of the Huallaga Valley, so they have a population structure of less than 350 inhabitants and most of them would be small housing groups. Of the remaining 78, 12 population centers would be affected by a susceptibility of less than 100%, where 3 of them would be covered between 95 and 99% by some type of susceptibility.

The cities of Tingo María and Rupa-Rupa (Figure 13) would be completely covered by a Very Severe susceptibility, except for some isolated buildings on the surrounding slopes. The population of Hermilio Valdizán would also be classified as Very Serious in the North but Mild in the West in both scenarios. The towns of Daniel Alomias Robles and Luyando would not be affected by the flood sheet in any of the calculated scenarios.

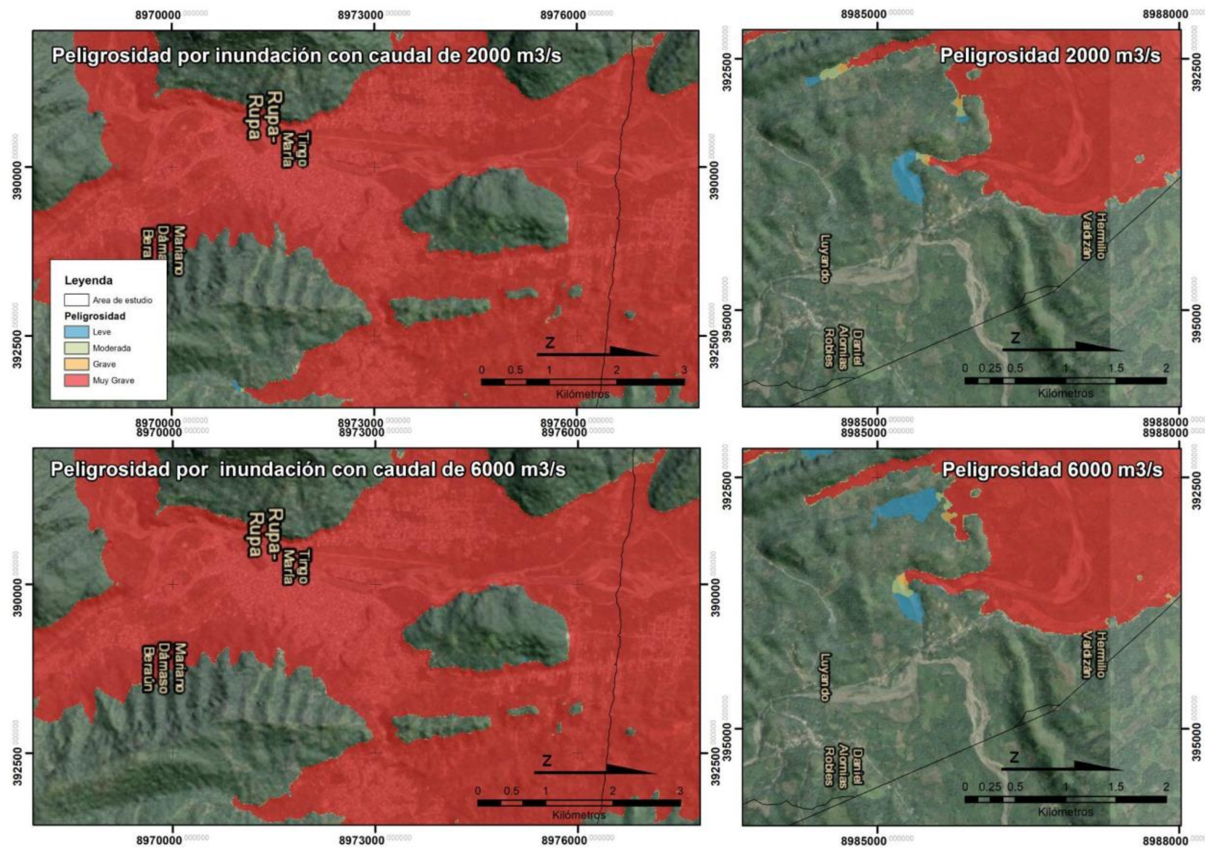


Figure 13. Simulated susceptibilities in the northern zone of the study area.

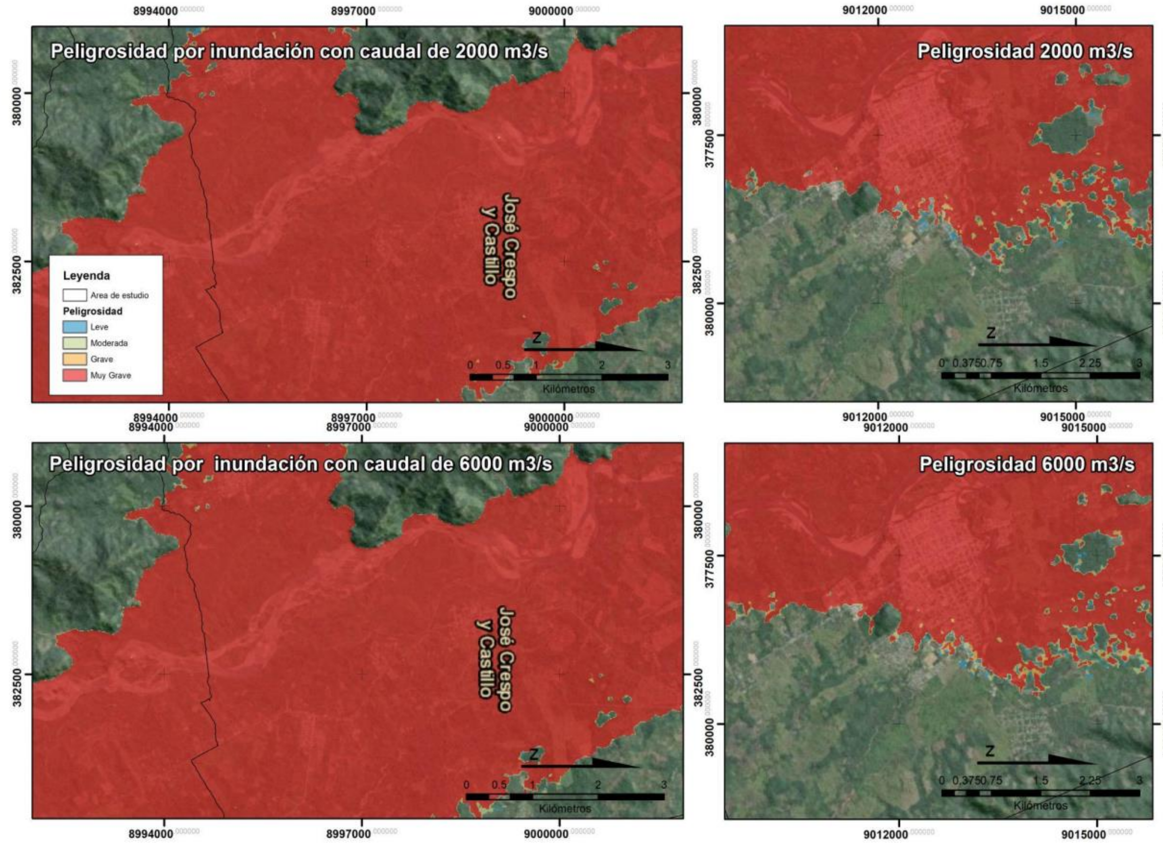


Figure 14: Simulated susceptibilies in the study area center zone.

Most of the populated centers of José Crespo y Castillo (Figure 14) would be completely under a Very Serious susceptibility. The population of Aucayacu would be affected by Very Severe classifications in the West and North of the city, while towards the South there would be a progradation towards slight susceptibilities and towards surfaces without flooding that would be located in the South of the population and in the zone of Yacusisa. The area occupied by flooding in Aucayacu would be 70%.

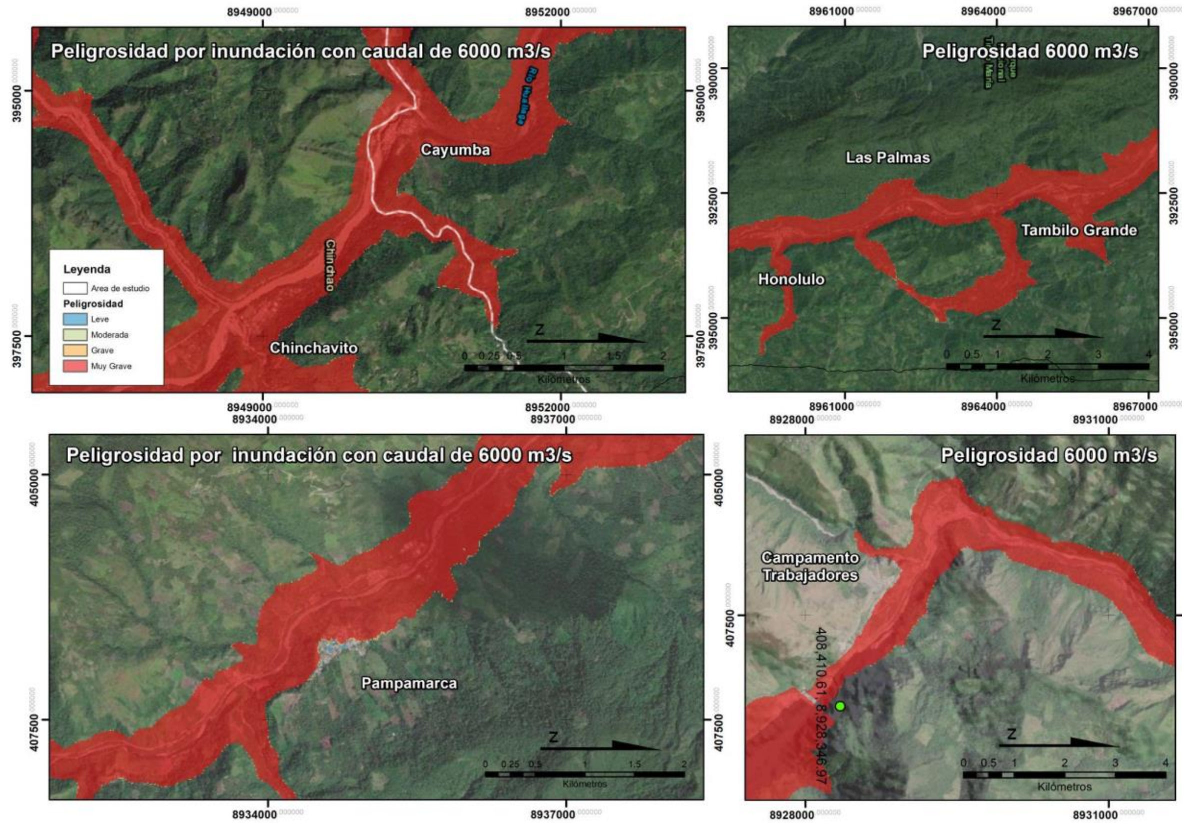


Figure 15. Simulated susceptibilities in the southern zone of the study area.

The populations of Honolulo, Las Palmas, Tambilo Grande, Chinchavito and Cayumba (Figure 15), would be affected by a Very Serious susceptibility. However, the populations of Pampamarca and the Chaglla Hydroelectric Plant workers' camp would have the areas closest to the river with Very Serious susceptibility, reducing said classification towards the outer area of these nuclei. The most remote areas would be left without susceptibility.

5. Discussion.

The different results of arrival times and maximum speeds would make sense of each other when analyzed together. The hydrographs of the selected sections, despite containing a very high arrival time of the flood wave (even 20 hours in the extreme North of the Huallaga Valley), would fit with the calculated maximum speeds, which would be between 3.6 and 7 kilometers per hour. Some initial results of the maximum drafts and maximum speeds would present nonsensical data right at the exit of the dam, at the beginning of the modeling, having obtained depths of 150 meters and speeds of 50 meters per second, surely due to inaccuracies in height between pixels contiguous in the MDT. The maximum drafts, on the other hand, would have been taken as correct given the large amount of water that would exist in the simulation.

5.1. Comparisson between scenaries.

The two modeled discharge scenarios (2,000 m3/s and 6,000 m3/s) would have very similar results in terms of flooding area and hazard area. While the 2000 m3/s discharge scenario would be 96.06% Very Serious, in the case of the 6000 m3/s scenario this percentage would be 98.7%.

The fact that there is not an excessive difference between the two scenarios may be due to the fact that the large amount of mobilized water would cause a certain "saturation" in the levels of water discharge, exceeding the drainage speed of the valley and stagnating the flow in height. Therefore, it becomes clear that, regardless of the size of the dam breach and with a discharge 3 times higher, the hazard scenarios would be relatively similar.

However, a certain difference would be observed between both scenarios in the extension area of maximum drafts. While in the most optimistic recharge scenario (2000 m^3/s) the second largest extension of the maximum depths would be those from 10 to 20 meters deep (75 km^2 or 23.7% of the surface), in the most pessimistic recharge scenario (6000 m^3/s) the second largest extension would be those from 30 to 100 meters deep (76 km^2 or 23.9%). Even so, the greatest extension would be the maximum depths of 20 to 30 meters in both scenarios coincidentally. It is possible to determine that a greater scenario of water recharge of the reservoir after the breaching, could suppose a change in the maximum drafts with a slight increase in them.

5.2. Comparisson with other studies.

The maximum drafts calculated in this study would exceed the maximum drafts of other dam break simulations of a similar size. The low speed and the high draft in the tributary valleys of the Huallaga valley would lead to the hypothesis that the waters that would occupy these valleys would be backwater.

For the simulation of the failure of the Big Bay dam in Mississippi, USA, (Yochum et al., 2008) the maximum drafts would reach 9.3 meters, while in the case of the simulation of the failure of the dam Gidabo in Ethiopia (Desta & Belayneh, 2021), the maximum draft would rise to 12.3 meters.

Some other studies would have obtained maximum drafts of greater magnitude, approaching those obtained in this study. In the case of the depths obtained in the breaching of the Vega de Tera dam (Zamora, Spain) in 1959, they would reach a depth of 24 meters (Prieto Calderón et al., 2017) while the breaching of the dam de Tous in Spain was able to reach depths of up to 20 meters (Alcrudo & Mulet, 2007). The simulation on the breaching of the Yuracmayo dam, Peru, (Bustamante Huaman, 2013) would yield a maximum depth of 35 meters, while in the natural damming in Huaccoto (in central Peru, derived from a landslide) the depths maximums would rise to 22 meters (Ponce & Tsivoglou, 1981).

Certain analyzes would have a similar consonance with the maximum depths obtained in this work. The simulation of the failure of the Kesem dam in southern Ethiopia (Leoul & Kassahun, 2019) resulted in maximum draft values of 64 meters, while the simulation of the failure of the Malpasset dam (France) in 1959, it obtained maximum drafts of between 75 and 81 meters (Valiani et al., 2002) and even 87 meters (Hervouet & Petitjean, 1999).Otros informes realizados para la simulación de la rotura de la misma presa de Chaglla (GEOCID, 2021) mostrarían calados máximos de hasta 164 metros. Este dato sería muy similar al resultado obtenido en el presente estudio de 159 metros de calado máximo, aunque el estudio realizado por GEOCID (2021) se realizó únicamente a partir de la aplicación unidimensional de Hec-Ras. La aplicación unidimensional de HEC-RAS sería correcta para la parte encajonada del valle del río Huallaga, sin embargo, a la altura de la ciudad de Tingo María (donde la llanura de inundación se ensancha) sería recomendable el uso de un modelo bidimensional que obtenga direcciones de flujo laterales (*Guía metodológica para el desarrollo del sistema nacional de cartografía de zonas inundables*, 2011). Este estudio no obtuvo resultados de velocidades.

The Emergency Action Plan of the Hydroelectric Power Plant itself (Klohn Crippen Berger, 2018) carried out certain simulations of the breaching of the Chaglla dam (up to the city of Tingo María), also with a one-dimensional approximation. This study took as a reference various topographic products as a base, such as MDT information from the SRTM program, with 30-meter pixel size; and level curves of 5 meters of equidistance, introducing these data in cross sections every 1 kilometer. Coinciding with the present study, this report assumed a situation of low water in the Huallaga River. The results of this study were depths of about 8-10 meters after the dam broke and a flood sheet that would not cover the entire population of Tingo María (although the flood plains of the confined part of the Huallaga River did), being significantly lower than that calculated under two-dimensional conditions and with a hydrograph product of a breaching process.

The differences between both investigations could be due to a lower spatial resolution of the topographic base in the Klohn Crippen Berger study (Klohn Crippen Berger, 2018), a one-dimensional simulation selected for floodplain areas where lateral flow movements are important. Another very important difference would be the inlet hydrograph used in the aforementioned study, with a hydrograph equivalent to the entire dam discharge at one time (180,000 m3/s), while the breaching simulation would modulate this discharge in the time while the break is generated. In the Klohn Crippen Berger study (Klohn Crippen Berger, 2018), no maximum speed results were obtained.

The maximum speeds obtained in the simulation of the breaching of the aforementioned Kesem dam in Ethiopia would amount to 16.7 meters per second (Leoul & Kassahun, 2019), while those of the simulation in the Big Bay dam (Yochum et al., 2008) would be at a maximum of 9.3 m/s. Both results differ from the data obtained in the simulation of the Chaglla dam in this study, the highest values of which would be at maximum speeds of about 35 m/s if low-reliability data are excluded, although in general the results would be in agreement. at between 1 and 5 m/s.

In the case of the simulation for the breaching of the Yuracmayo dam (in the department of Lima, Peru), there would be estimated maximum speeds between 28 m/s (in section) and 73 m/s (Bustamante Huaman, 2013), while the estimate of the maximum speed produced by the breaching of the Vega de Tera dam (Prieto Calderón et al., 2017), reached 33 m/s. These two simulations would have maximum speeds similar to those obtained in the present analysis, in which 35 m/s are reached. The similar values of maximum velocity between the simulations of the Yuracmayo and Chaglla dams would be justified by having a very similar average slope of the riverbed, with the average slope of Yuracmayo being 1.63% and the slope of the Huallaga River 1.29%. The rest of the commented simulations would have lower average slopes, being 0.37% for the Big Bay damming (Mississippi, USA) or 0.7% in the Tous dam, both with lower maximum speeds as a result of the simulation. However, the simulation of the Vega de Tera dam would run along slopes of 0.39% and would present a maximum speed similar to that simulated in the present study (30 m/s).

5.3. Susceptibility

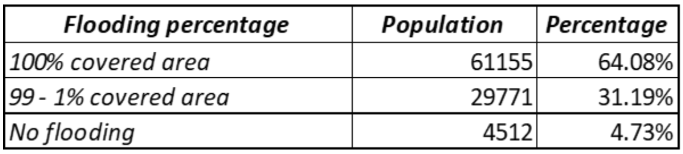
Given the impossibility of obtaining probabilities of recurrence to determine a hazard, susceptibility calculations were made as an approximation in accordance with the Guide to support the application of the Regulation of the Hydraulic Public Domain in the limitations to land uses in the flood zones of origin. fluvial, of the Spanish Ministry of the Environment (MAPAMA, 2017). In Peru, there would be no guidelines similar to those carried out by the Spanish MAPAMA, where various dangerous sections are classified according to maximum speed ranges and maximum drafts.

Therefore, according to the speed and maximum depth parameters and according to the susceptibility results, practically the entire flood prone area would be classified as Very Serious. This susceptibility would be granted mainly due to the Maximum Drafts, which would exceed 1.5 meters in almost the entire territory, with greater heterogeneity in maximum speeds. According to the susceptibility, it is possible to determine that most of the population of the study area would be inhabiting areas with Very Serious affection.

Up to 66 population centers would be 100% covered by some type of susceptibility. Among them would be the populated centers with the largest number of inhabitants in the study area, such as Mapresa, Tingo María, Naranjillo, Las Palmas, Honolulu, Tambillo Grande, Palo de Acero or Venenillo.

All the smaller population centers that are located in the floodplain or the banks of the Huallaga River would be under Very Serious susceptibility. Up to 12 populated centers have a susceptibility of less than 100% (or with Mild susceptibilities), highlighting the populated centers of Aucayacu and Pampamarca. In the case of Aucayacu, only the South of the population would have Mild susceptibilities or areas without flooding, however it would be advisable to be cautious in the external extremes of the modeling, since due to the low resolution of the DTM, it is not possible to know exactly where would stop the flow of the flood. The population of Pampamarca would be free of susceptibility from the eastern half of the urban nucleus, surely due to being on an old river terrace. The workers' camp of the Hydroelectric Power Plant itself would be classified as Very Serious, although it would have 60% coverage.

The population that would inhabit the 12 nuclei with a flood area of less than 100% and greater than 1% would be 29,771 people (Table 5). Excluding the populated center of Aucayacu, the population would amount to 4,512 people. The 20 populated centers free of flooding would have a low habitability density (none would exceed 350 inhabitants) and together they would have a total population of 2,503 people. The rest of the area's population, 61,155 people, would remain under the flood sheet and mostly in Very Serious susceptibilities.



Flooding percentage	***Population***	***Percentage***
100% covered area	61155	64.08%
99 - 1% covered area	29771	31.19%
No flooding	4512	4.73%

Table 5. Population affected by the different percentages of flood coverage.

It is recommended that new homes and residences in urban centers with Very Severe susceptibilities be built on hills located above the floodplain. It is recommended, in turn, to review the existing evacuation plan (Klohn Crippen Berger, 2018), since the extensions of the flood sheet and the maximum depths would be greater in the present study. At the same time, it is recommended that the Evacuation Plan consider the installation of audible alarms and signaling of evacuation paths to the highest possible places, since in a hypothetical case of the

Chaglla dam breaking, the affectation to the population of the study area would be generalized. The results have shown that the delay in the arrival of the flood wave to the main towns with the greatest susceptibility would be several hours, so there would be a high probability of being able to apply successful evacuation plans. Specifically, the flood wave would have an estimated arrival time of between 6 and 10 hours to the city of Tingo María.

However, the towns closest to the hydroelectric plant, such as Chinchavito, Cayumba, Honolulo, Las Palmas, Tambillo Grande or other dispersed towns, would have an estimated time of arrival of the flood wave of between 10 minutes and 5 hours, for Therefore, these populations would have greater problems to carry out evacuations, especially the plant workers' camp, which would be just minutes from the arrival of the avenue or Pampamarca, which would be about 30 - 50 minutes for the arrival from the Avenue.

Smaller and closer populations would be especially vulnerable to the arrival of the flood wave, also due to the impossibility of having their own emergency plans for evacuation and acoustic alert systems, as these are mainly intended for larger population centers. .

It is recommended that in the towns of Aucayacu, Pampamarca and Hermilio Valdazán, future urban developments or housing construction take place in areas outside the floodplain to avoid exposure to the risk calculated here.

5.4. Shortcomings.

Hydraulic modeling should be assumed to be estimates based on the topography assumed by the model and general hydraulic equations. This Chaglla dam failure modeling is based on a 12.5 meter DTM topography, which is the highest resolution available to date. Given the drafts generated and the wide extension of the modeling, this resolution, although low, would be acceptable. However, if better MDTs are obtained, mainly in areas surrounding the populations of the study area, it would be recommended to carry out detailed analyzes to observe the flood behavior more precisely. As data input, the hydrographs resulting from the modeling of this study could be introduced. The results modeled here should be taken into account as estimates and recommendations for territorial decision-making.

In any case, it is recommended that in the future, if there are DTMs with a higher spatial resolution, the hydraulic modeling be carried out again in order to improve the accuracy of the analyses.

The Breaching process of the dam (1 hour duration with a trapezoidal shape) would have been chosen according to the current knowledge of the formation processes of dam breaks in masonry-type dams. However, it is not possible to accurately predict the type of geometry and duration that the dam breach would have, so in a hypothetical emergency, the flooding rate could vary according to the breaching process that would take place.

There would be some results of maximum speeds and drafts that would be modeling errors. Certain decreases in maximum speed in the northern section of the study area (downstream of Tingo María) could be due to the progressive disenclosure of the Huallaga River and the decrease in slope. The high speeds (up to 450 m/s) in the first section behind the dam wall would indicate that the simulation is not reliable in that location. This fact would call into question the result of 159 meters of maximum draft that exists right at the exit of the dam break, which remains in the first 80 -120 meters of distance. The results downstream, around 100 meters of maximum draft, could be possible due to the great boxing in of the Huallaga river valley.

It must be taken into account, in turn, that the modeling carried out here would be for a Newtonian-type fluid. It would not be ruled out that the flow coming from the hypothetical breaching of the dam behaved as a non-Newtonian fluid type debris flow or mud flow in certain areas due to the erosion capacity and the sediments that make up the study area, although this option could be ruled out given the large volume of water that would be in motion and that would reduce the proportion of clay or silt per cubic centimeter, necessary for the generation of these fluids. It is recommended that future projects carry out sedimentological profiles at various points in the section of the Huallaga River that can clarify the amount and size of sediment that could be set in motion, as well as take into account the surrounding vegetation that could move as a solid flow.

6. Conclusions

The modeling with Hec-Ras allowed us to simulate the flooding caused by a trapezoidal breach in the Chaglla dam basin, in Huánuco (Peru), according to two discharge scenarios.

The simulation showed a flood area along the Huallaga river valley of 319.24 km^2 and 325.95 km^2 depending on the scenario. The maximum depths would be between 100 and 40 meters high in the confined part of the river and between 12 and 20 meters high in the floodplain (where most populations are located). The maximum speeds calculated would be between 35 and 2 meters per second, with speeds of 8-5 m/s being more common in the first stretch of the simulation and 3-2 m/s in the floodplain area.

Various simulations carried out on the same Chaglla dam would reveal maximum depths similar to those of the present study, while the safety plan for the Chaglla dam would have estimated an extension of lower flooding up to the Tingo María area. The methodology in the present study would have been two-dimensional modeling with the "Breaching" extension of

Hec-Ras, an unprecedented methodology in the study area given that the previous works and the security plan would have been modeled in a one-dimensional way and without software extensions. .

The susceptibilities calculated for the entire area would be classified fundamentally as Very Serious in the scenario of greatest discharge, occupying an extension of 98.07%, while in the scenario of least discharge the situation would be very similar, with an extension of 96.06%.

The inhabitant population in populated centers fully covered by the flood prone area would amount to 61,155 people, while the population of the study area located in non-flood prone areas would be 4,512 inhabitants.

The revision of the safety plans of the dam and the placement of acoustic signals, as well as the revision of the evacuation paths, are urged. Given the characteristics of the flooding, the arrival times of the flooding would be quite lax in most of the populations (even greater than 10 hours), so that the evacuation plans could be quite successful.

It is also urged to carry out a Risk study that includes the probability of the dam breaking, as well as social dimensions of exposure and vulnerability.

BIBLIOGRAPHY

Alcrudo, F., & Mulet, J. (2007). Description of the Tous Dam break case study (Spain). *Journal of Hydraulic Research*, *45*(Extra), 45-57.

ANA. (2019). *Reglamento de seguridad de presas públicas de embalse de agua* (p. 37). Autoridad Nacional del Agua de Perú. http://repositorio.ana.gob.pe

Barnes, H. (1967). *Roughness Characteristics of Natural Channels* (UNITED STATES GOVERNMENT PRINTING OFFICE, p. 219). U.S. Geological Survey 1849.

Bustamante Huaman, Y. A. (2013). *Modelamiento Numérico de una Onda de Avenida Generada por la Rotura de una Presa de Tierra y su Estimación de Riesgo. Aplicación a la presa Yuracmayo.* Universidad Nacional Mayor de San Marcos.

Cai, Y., Cheng, H., Wu, S., Yang, Q., Wang, L., Luan, Y., & Chen, Z. (2020). Breaches of the Baige Barrier Lake: Emergency response and dam breach flood. *Science China Technological Sciences*, *63*(7), 1164-1176. https://doi.org/10.1007/s11431-019-1475-y

Cockell, C. S. (2002). The science and scientific legacy of Operation Chastise. *Interdisciplinary Science Reviews*, *27*(4), 278-286. https://doi.org/10.1179/030801802225005734

Crane, Co. (2001). The Air Campaign Over Korea: Pressuring the enemy. *Defence Technical Information Center*, 78-85. ADA405213.

Desta, H. B., & Belayneh, M. Z. (2021). Dam breach analysis: A case of Gidabo dam, Southern Ethiopia. *International Journal of Environmental Science and Technology*, *18*(1), 107-122. https://doi.org/10.1007/s13762-020-03008-0

FERC. (2016). *Engineering Guidelines for the Evaluation of Hydropower Projects* (p. 200). Federal Energy Regulatory Commission. https://www.ferc.gov/industries-data/hydropower/dam-safety-and-inspections/eng-guidelines

Field Jr., J. (2000). *History of U.S. Naval operations: Korea* [Blog]. https://www.history.navy.mil/research/library/online-reading-room/title-list-alphabetically/h/history-us-naval-operations-korea.html

Froehlich, D. C. (2008). Embankment Dam Breach Parameters and Their Uncertainties. *Journal of Hydraulic Engineering*, *134*(12), 1708-1721. https://doi.org/10.1061/(ASCE)0733-9429(2008)134:12(1708)

Guía metodológica para el desarrollo del sistema nacional de cartografía de zonas inundables (p. 349). (2011). Ministerio de Medio Ambiente y Medio Rural y Marino; ISBN 978-84-491-1136-5. http://publicacionesoficiales.boe.es/

Hervouet, J.-M., & Petitjean, A. (1999). Malpasset dam-break revisited with two-dimensional computations. *Journal of Hydraulic Research*, *37*(6), 777-788. https://doi.org/10.1080/00221689909498511

Protocol Additional to the Geneva Conventions of 12 August 1949, and relating to the Protection of Victims of International Armed Conflicts (Protocol 1), (1977), Diplomatic Conference on the Reaffirmation and Development of International Humanitarian Law applicable in Armed Conflicts. https://www.ohchr.org/en/instruments-mechanisms/instruments/protocol-additional-geneva-conventions-12-august-1949-and

INEI. (2022). *Censo de Población y vivienda*. Instituto Nacional de Estadística e Informática. https://m.inei.gob.pe/estadisticas/indice-tematico/poblacion-y-vivienda/

Klohn Crippen Berger. (2018). *Plan de Acción de Emergencias para Operación de la Central Hidroeléctrica Chaglla* (ZC6†66.A66; p. 110). Empresa de Generación Huallaga S.A.

Leoul, A., & Kassahun, N. (2019). Dam Breach Analysis Using HEC-RAS and HEC-GeoRAS: The Case of Kesem Kebena Dam. *Open Journal of Modern Hydrology*, *09*(04), 113-142.

https://doi.org/10.4236/ojmh.2019.94007

Li, Wang, Ge, Wei, & Li. (2019). Risk Analysis of Earth-Rock Dam Breach Based on Dynamic Bayesian Network. *Water*, *11*(11), 2305. https://doi.org/10.3390/w11112305

MAPAMA. (2017). *Guía técnica de apoyo a la aplicación del reglamento del Dominio Público Hidráulico en las limitaciones de usos del suelo en las zonas inundables de origen fluvial.* (p. 74). Ministerio de Agricultura y Pesca, Alimentación y Medio Ambiente. http://publicacionesoficiales.boe.es/

Morris, M. W., Hassan, M. A. A. M., & Vaskinn, K. A. (2007). Breach formation: Field test and laboratory experiments. *Journal of Hydraulic Research*, *45*(sup1), 9-17. https://doi.org/10.1080/00221686.2007.9521828

OSINERGMIN. (2020). *Central Hidroeléctrica Chaglla: Detalles Técnicos.* (p. 1). Organismo Supervisor de la Inversión de Energía y Minería.

Ponce, V., & Tsivoglou, A. (1981). Modeling gradual dam breaches. *Journal of the Hydraulics Division*, *107*, 829-838. https://doi.org/0044-796X/81/007-0829/$01.00

Prieto Calderón, J. L., Marínez-Alegría López, R., Taboa Castro, J., Montequi Martín, I., & Sanz Lobón, G. (2017). Rotura de la presa de Vega de Tera, simulación hidráulica de la propagación de la avenida (Zamora, España). *DYNA*, *84*(203), 45-54. https://doi.org/10.15446/dyna.v84n203.60544

Shuibo, P., & Loukola, E. (1993). *CHINESE-FINNISH COOPERATIVE RESEARCH WORK ON DAM BREAK HYDRODYNAMICS* (p. 92). Vesi- ja ympäristöhallitus, National Board of the Waters and the Environment; 0786-9592. http://hdl.handle.net/10138/29795

Strelkoff, T. (1970). Numerical Solution of Saint-Venant Equations. *Journal of the Hydraulics Division*, *96*(1), 223-252. https://doi.org/10.1061/JYCEAJ.0002262

Stuart-Smith, R. F., Roe, G. H., Li, S., & Allen, M. R. (2021). Increased outburst flood hazard from Lake Palcacocha due to human-induced glacier retreat. *Nature Geoscience*, *14*(2), 85-90. https://doi.org/10.1038/s41561-021-00686-4

Ubeda Romero, E. (1963). La rotura del Pantano de Puentes en Lorca 1802. *Revista Murgetana*, *21*, 5-33.

Urbina, L. (2018, marzo 5). Áncash: Reportan derrame de relave minero en Recuay. *El Comercio*. https://elcomercio.pe/peru/ancash/ancash-reportan-derrame-relave-minero-recuay-noticia-502049-noticia/

U.S. Army Corps of Engineers. (2023). *HEC-RAS User's Manual* (6.3; p. 732). United States Army Corps of Engineers.

U.S.D.I. (2015). *Dam Failure and Flood Event Case History Compilation. RCEM – Reclamation Consequence Estimating Methodology.* United States Department of Interior: Bureau of Reclamation.

USGS. (1989). *Guide for selecting Manning's roughness coefficients for natural channels and flood plains*. United States Geological Survey. https://doi.org/10.3133/wsp2339

Valiani, A., Caleffi, V., & Zanni, A. (2002). Case Study: Malpasset Dam-Break Simulation using a Two-Dimensional Finite Volume Method. *Journal of Hydraulic Engineering*, *128*(5), 460-472. https://doi.org/10.1061/(ASCE)0733-9429(2002)128:5(460)

Vásquez-Ramírez, L., & Burgos-Flores, N. (2021). Correlación entre el coeficiente de rugosidad de Manning y el diámetro representativo del material de arrastre en lechos de ríos de alta montaña, Cajamarca—Perú. *Revista Ingeniería UC*, *28*(2), 265-273. https://doi.org/10.54139/revinguc.v28i2.25

Wetmore, J., & Fread, D. (1981). NWS Simplified Dam-Break Flood Forecasting Model. *Engineering, Environmental Science*, 27.

Xu, Y., Zhang, L., & Jia, J. (2008). Lessons from Catastrophic Dam Failures in August 1975 in Zhumadian, China. *GeoCongress 2008*, 162-169. https://doi.org/10.1061/40971(310)20

Yochum, S. E., Goertz, L. A., & Jones, P. H. (2008). Case Study of the Big Bay Dam Failure: Accuracy and Comparison of Breach Predictions. *Journal of Hydraulic Engineering*, *134*(9), 1285-1293. https://doi.org/10.1061/(ASCE)0733-9429(2008)134:9(1285)