Hazard map based on the simulation of sludge flow in a two-dimensional model, Case Quebrada Malanche-Punta Hermosa -Lima-Perú

Luis Jimenez Garcia
School of Civil Engineering
Universidad Peruana de Ciencias aplicadas
Lima, Peru
u201513699@upc.edu.pe

Osnar Iruri Guzman
School of Civil Engineering
Universidad Peruana de Ciencias aplicadas
Lima, Peru
u201416480.@upc.edu.pe

Sissi Santos Hurtado
School of Civil Engineering
Universidad Peruana de Ciencias aplicadas
Lima, Peru
pccissan@upc.edu.pe

Abstract— This research presents the numerical simulation to reproduce the transport and deposition processes of the sludge flow on March 15, 2017, strongly impacting the town of Pampapacta in Punta Hermosa-Peru.
The debris flow initiation process in the basin was represented by hydrographs obtained from the estimated volumes of stormwater runoff and solid materials. The sludge flow was modeled in Flo2D to calculate hazard maps with the discharge event and others with different return periods.
The numerical simulation results show acceptable results in relation to what happened. The model used to assess the hazard due to debris flow can predict and delineate, with acceptable precision, potentially hazardous areas for a landslide. The application of the proposed methodology to assess the hazard of disasters due to debris flows in basins and streams is useful to understand the extent of the impact of the mud flow during extreme weather events, as well as to develop emergency plans and formulate disaster policies.

Keywords— Mud flow, gully, hydrological model, hydraulic model, FLO-2D model.

I. INTRODUCTION

Global interest in the environment and its rapid deterioration has intensified in recent decades. Peru is not alien to this reality, since, being in Latin America, it has geographical, topographic, geological and hydrometeorological characteristics; that make it a country exposed to various natural phenomena. According to a study carried out by the Tyndall Climate Center in England in 2003, Peru is among the 10 countries most vulnerable to the effects of climate change in the world, which allows the various phenomena to intensify its effects [1].

One of these great phenomena that alter the climatic conditions of the country, and start the rainy season, causing seasons of heavy rainfall, and various natural disasters such as landslides, floods, mud flows and debris, is the El Niño Phenomenon (FEN).

Indeed, mud and debris flows are disasters that eventually occur generating loss of human life, cultivation areas, homes, civil works and everything in their path, damages that are intensified thanks to the nature of a rugged geography, such as that presented by Peru, becoming another problem in the design of civil works, such as bridges, roads, hydraulic structures, among others, being a challenge for all engineers.

For this reason, it is essential for our context to understand the operation of these fluids, since the evaluation of the flood discharge and the deposition process is very important for the risk assessment, management and design of possible support works for mitigation of these geological threats [2].

In Peru and in the world, various studies have been carried out focused on studying the behavior of hyper-concentrated flows, since the geographical location of many countries and the external factors that increase their occurrence, make an ideal setting for the study of these. natural disasters.

Zhang, Ma, Shu, Han, & Zhang (2014) conducted an investigation based on the process of movement and deposition of a debris flow gully in Gansu, China, this was simulated using the curve number approach of the Conservation Service of Soils (SCS-CN) and a finite two-dimensional model (PRO FLO-2D model). The results obtained were consistent with the measured results of the waste stream documented on the day of the event [3].

Quispe, Pino, & Avendaño (2018) seek to explain the criteria for modeling mud and debris flows, using the FLO-2D software. As input data, they used the digital topography of the terrain, the geometry of the channel, values of the roughness of the channel and the floodplain, input hydrographs (liquids and solids), precipitation and rheological properties of the water-sediment mixture and the Rheological parameters were obtained with samples from the stream and with samples of the "literature" type. With the afore mentioned data, they modeled a possible mud flow with the FLO2D model, developing a threat map [4].

Verification on most of these demonstrated that the model results could be used to help predict disaster-causing mud and / or debris flows, thus helping to protect the lives, property and the economy of local people.

On March 15, 2017, the heavy rains caused by the FEN activated the Malanche ravine, generating mud flows in the area, where the dragging of various solid wastes, animals, vehicles and people in the Pampapacta sector, located in the district of Punta Hermosa, province of Lima. Faced with this situation and need in the district of Punta Hermosa, this research seeks to model said event with the FLO 2D PRO software, in order to understand and visualize the behavior of the sludge flow and develop a threat map, which will create an environment awareness of this natural phenomenon and inform the population about the consequences of these disasters.

II. FLO-2D MODEL

Mud flows generally consist of high concentrations of fine particles (silts and clays). According to experiments by Wan and Chien (1989), a fluid becomes a milky mixture at a

978-1-7281-9466-0/20/$31.00 ©2020 IEEE

concentration of fine particles of only 90 kg / m3. As the concentration of fines increases, the structure of the sediments flocculates, forming a kind of cohesion of soil-water mixture. According to Vames (1958), mud flows are distinguished by the presence of at least 50% · sand, sediment, and clay-sized particles [5].

Thus, for its modeling, the use of adequate software is necessary, since being such a complex flow it cannot be represented as Newtonian Fluid.

The FLO-2D software is a finite difference model that integrates two-dimensional equations using a geometric scheme with cells of constant dimension and finished in the cell-by-cell calculation in 8 directions of the hydraulic variables (depth, velocity and flow), allowing the adequate simulation of this type of fluids.

A. FLO-2D Numeric model

The equations on which this program is based are the continuity and momentum equations.

$$i = \frac{\partial h}{\partial t} + \frac{\partial h V_x}{\partial x} + \frac{\partial h V_y}{\partial y} \quad (1)$$

$$S_{fx} = S_{ox} - \frac{\partial h}{\partial x} - \frac{V_x}{g} * \frac{\partial V_x}{\partial x} - \frac{V_y}{g} * \frac{\partial V_x}{\partial y} - \frac{1}{g}\frac{\partial V_x}{\partial t} \quad (2)$$

$$S_{fx} = S_{oy} - \frac{\partial h}{\partial y} - \frac{V_y}{g} * \frac{\partial V_y}{\partial y} - \frac{V_x}{g} * \frac{\partial V_y}{\partial x} - \frac{1}{g}\frac{\partial V_y}{\partial t} \quad (3)$$

Where: Vx and Vy are the components of the average velocity for the different heights along the x and y coordinates; h is the depth of flow; t is time; g is the acceleration of gravity; Sf is the friction slope; So is the slope of the bed and i is the intensity of the rain.

Shear stresses for hyper concentrated flows, such as mud flows, can be calculated from the sum of five components of shear stresses.

$$\tau = \tau_c + \tau_{mc} + \tau_v + \tau_t + \tau_d \quad (4)$$

Where τ_c is the yield shear stress; τ_{mc} is the Mohr-Coulomb shear stress; τ_v is the viscous shear stress; τ_t is the turbulent shear stress and τ_d is the dispersive shear stress

Likewise, when we write in terms of strain rates (dv/dy) the following rheological quadratic model can be developed in the following way [6].

$$\tau = \tau_y + \eta\left(\frac{d_v}{d_y}\right) + C\left(\frac{d_v}{d_y}\right)^2 \quad (5)$$

Where $\tau_y = \tau_c + \tau_{mc}$ and $C = \rho_m l^2 + a_i \rho_s \lambda^2 {d_s}^2$. In these equations η is the dynamic viscosity; τ_c is the cohesive yield stress; the Mohr Coulomb stresses $\tau_{mc} = p_s \tan\Phi$ depend on the "intergranular pressure, p_s" and the "angle of repose of the material, Φ"; "C" denotes the coefficient of inertial shear forces, which depends on the "mass density of the mixture, ρ_m"; of "Prandtl length, l", of "sediment size, d_s" and of a function of "sediment concentration, C_v".

On the other hand, the shear forces analyzed in the FLO-2D model can be rewritten as follows:

$$S_f = S_y + S_v + S_{td}$$

S_f is the total friction slope, S_y is the yield slope, S_v the viscous slope and S_{td} the turbulent-dispersive slope. S_v is written as:

$$S_v = \frac{K_n V}{8\gamma_m h^2} \quad (6)$$

"γm, is the specific weight of the sediment mixture, K_n is the resistance parameter for laminar flows.

TABLE I. RESISTANCE PARAMETERS FOR LAMINAR FLOW

Laminar Flow resistance parameters	
Surface	Range of K
Concrete / Asphalt	24-108
Scarce sand	30-120
Gradual surface	90-400
Sparse clay-eroded marl soil	100-500
Low vegetation	1000-4000
Short meadow grass	3000-10000
Indigo Grass Lawn	7000-50000
Woolhiser (1975)	

Source: O'Brien and Julien (1988)

III. RHEOLOGICAL MODEL

Rheology is the study of the physical principles that regulate the movement and deformation of matter when it is subjected to external stress, it studies the relationship between stress and deformation in materials that are capable of flowing. The properties that depend on this relationship are called rheological parameters and the way they are related is called the rheological model [7].

The rheological parameters with which we work in this investigation are the viscosity (η) and the yield stress (τy) of the mixture, given between the combination of the sediments with the water. O'Brien and Julien (1988) performed a laboratory analysis of samples collected from natural deposits from mudflows in Colorado Rocky Mountain near the cities of Aspen and Glenwood Springs. The properties of the mud flow samples can be observed in Table II, these are found in terms of sediment size distribution and its clay content.

TABLE II. PROPERTIES OF MUD FLOW MATRICES

Sample Types	Sediment size distribution				Liquid limit	Plastic index
	Clay (%)	D_{16} (mm)	D_{50} (mm)	D_{84} (mm)		
Glenwood original	4,8	0,010	0,034	0,062	-	-
Glenwood sample 1	6,8	0,009	0,023	0,050	-	-
Glenwood sample 2	3,0	0,016	0,035	0,061	-	-
Glenwood sample 3	4,8	0,011	0,025	0,053	-	-
Glenwood sample 4	7,6	0,001	0,018	0,032	-	-
Aspen Pit 1	31,3	0,001	0,011	0,032	0,32	0,11
Aspen natural soil	27,0	0,001	0,012	0,028	0,25	0,06
Aspen mine fill	27,8	0,001	0,013	0,030	0,24	0,06
Aspen natural soil source	31,6	0,001	0,016	0,039	-	-
Aspen mine fill source	25,2	0,001	0,018	0,061	-	-

Source: O'Brien and Julien (1988)

O'Brien and Julien determined that viscosity and yield stress potentially increase with sediment concentration (C_v):

$$\eta = \alpha_1 e^{\beta_1 Cv} \qquad (7)$$

$$\tau_y = \alpha_2 e^{\beta_2 Cv} \qquad (8)$$

Where α and β are empirical coefficients defined by these mentioned laboratory experiments and C_v is the volumetric concentration of sediments.

TABLE III. YIELD STRESS AND AS A FUNCTION OF C_V

Yield Stress and Viscosity as a Function of Sediment Concentration				
Source	$\tau_y = \alpha e^{\beta Cv}$		$\eta = \alpha e^{\beta Cv}$	
	α	β	α	β
Field Data				
Aspen Pit 1	0.181	25.7	0.036	22.1
Aspen Pit 2	2.72	10.4	0.0538	14.5
Aspen Natural Soil	0.152	18.7	0.00136	28.4
Aspen Mine Fill	0.0473	21.1	0.128	12
Aspen Watershed	0.0383	19.6	0.000495	27.1
Aspend Mine Source Area	0.231	14.3	0.000201	33.1
Glenwood 1	0.0345	20.1	0.00283	23
Glenwood 2	0.0765	16.9	0.0648	6.2
Glenwood 3	0.000707	29.8	0.00632	19.9
Glenwood 4	0.00172	29.5	0.000602	33.1
Relationships Available from the Literature				
Iida (1938)	-	-	0.0000373	36.6
Dai et al. (1980)	2.6	17.48	0.0075	14.39
Kang and Zhang (1980)	1.75	7.82	0.0405	8.29
Qian et al. (1980)	0.00136	21.2	-	-
	0.05	15.48	-	-
Chien and Ma (1958)	0.0588	19.1-32.7	-	-
Fei (1981)	0.166	25.6	-	-
	0.0047	22.2	-	-

Source: O'Brien and Julien (1988)

In the case of volumetric concentration, it must be borne in mind that hyper concentrated flows have a different behavior than an avenue and a landslide, since initially, clean water flows from the rain-runoff basin until it reaches the apex of the fan, this can be accompanied by frontal waves of mud and debris, it is thus that for these fluids a distribution of Cv in time is estimated starting from a value close to 0.2 and gradually increasing to 0.35 or 0.45 depending on the type of sediment of Basin.

TABLE IV FLOW BEHAVIOR AS A FUNCTION OF C_V

Description of the Type of Flow	Sediment Concentration (Cv)		Flow Characteristics
	By Volume	By Weight	
Slides	0,65 – 0,80	0,83 – 0,91	There is no flow; block slip failure
	0,55 – 0,65	0,76 – 0,83	Collapse of blocks with internal deformation during sliding, gradual movement of the ground before failing.
Mud Slides *(Mudflow)*	0,48 – 0,55	0,72 – 0,76	Obvious flow; slow sliding sustained by mud flow; plastic deformation under its own weight; cohesive; it does not expand on the surface.
	0,45 – 0,48	0,69 – 0,72	Flow spreads over the surface; cohesive flow; some mixing.
Mud Avenue *(Mud Flood)*	0,40 – 0,45	0,65 – 0,69	The flow mixes easily; shows fluid properties in deformation; distributed on the horizontal surface but maintains an inclined flowing surface; deposit of large particles (rocks); waves appear but dissipate quickly.
	0,35 – 0,40	0,59 – 0,65	Marked deposition of gravels and boulders; expands almost completely on the horizontal surface; the liquid surface appears with two phases of the fluid; waves travel on the surface.
	0,30 – 0,35	0,54 – 0,59	Separation of water on the surface; waves travel easily; most of the sand and gravel has settled and moves as bottom drag
	0,20 – 0,30	0,41 – 0,54	Waves and ripples are clearly distinguishable; all the particles resting on the bottom in an immobile condition.
Water Flood	< 0,20	< 0,41	Water flooding with conventional suspended load and bottom drag.

Source: O'Brien and Julien (1988)

IV. THREAT MAP

FLO-2D Mapper PRO is a post-processor program that creates maps and other graphs from the results of the FLO-2D model. The resulting map allows to represent the potential threat that exists in each area [8].

The areas have different threats, these are differentiated into high, medium or low, each type of threat corresponds to a series of damages to people and buildings.

TABLE V. DEFINITION OF FLOW INTENSITY AND RISK OF FLOODING

Intensity	*h(m)*	*V(m/s) *h(m)*	*Threat*
HIGH	h>1	v*h>1	People are in danger both inside and outside of homes or buildings.
MEDIUM	0.2<h<1	0.2<v*h<1	People are in danger outside of homes or buildings. Buildings can suffer damage, but not sudden destruction, if their structure is adapted to the conditions of the place.
LOW	0.2<h<1	v*h<0.2	The danger to people is weak or non-existent. (Does not exist for this phenomenon (mud / debris flow)

V. ZONING, SIMULATION AND VALIDATION

The Malanche ravine is in the district of Punta Hermosa, province of Lima-Peru. The stream basin has an area of 173.46 km2, a perimeter of 102 km and an average slope of 32.15%.

Fig. 1. Location map of the Punta Hermosa district (study area)

To generate the runoff flows, we worked with the maximum 24-hour rainfall from 5 nearby weather stations. With the help of Hyfran software the return periods (TR) of 25, 50, 100 and 200 years were calculated. Due to the size of the basin it has been subdivided into three parts, in order to obtain more precise rainfall values for each sub-basin in the HEC-HMS simulation.

TABLE VI. FLOWS FOR EACH SCENARIO

Scenarios	*Q water(m^3/s)*	*Q solids(m^3/s)*
Scenario 1 (2017 Storm)	7.3	13.3
Scenario 2 (TR 25)	21.5	39.1
Scenario 3 (TR 50)	28.2	51.3
Scenario 4 (TR 100)	35.5	64.5
Scenario 5 (TR 200)	43.3	78.7

Source: Self-prepared

Table Nº 6 shows the flow rates obtained from the simulation process in the HEC-HMS and the flow solids. Once the liquid flow rates were obtained, the Bulking Factor (BF) formula proposed by O'Brien (2000) was used to estimate the solid hydrographs, these are estimated from the water flow hydrograph multiplied by a factor that is a function of the volumetric concentration of sediments (Cv).

According to the O'Brien reference, the value of Cv varies between 0.20 (for low flows) and 0.45 (for high flows). In the case of the present investigation, the maximum value was used $\boldsymbol{C_V = 0.45}$

$$\boldsymbol{BF = \frac{1}{1-C_V}} \quad (9)$$

In Fig. 2. the liquid and solid hydrographs are displayed, colored blue and red, respectively.

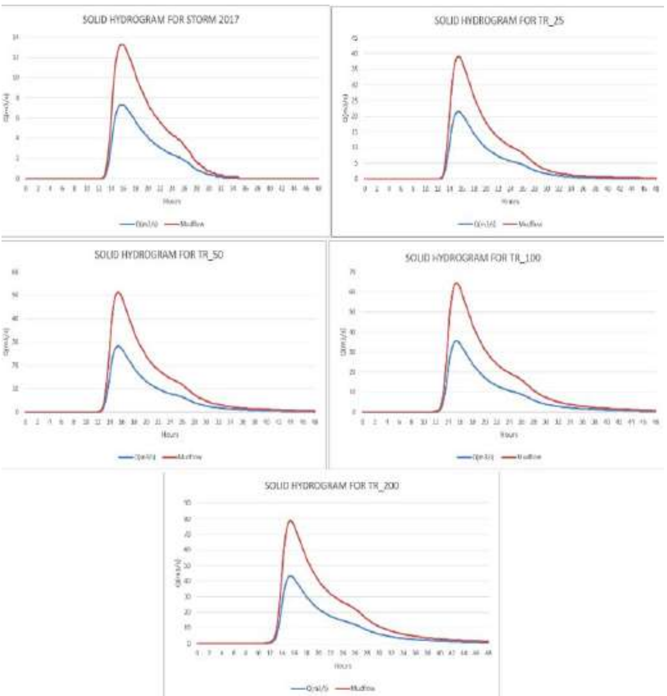

Fig. 2. Liquid and solid hydrographs for the storm that generated the phenomenon of 2017, and their respective return periods TR 25, TR 50, TR 100 and TR 200 years.

The topography of the surface to be analyzed must be as detailed as possible, since, when introduced to the software, it is discretized in a mesh formed by cells of uniform size and each of these is assigned a position in the mesh, an elevation or ground level, a roughness coefficient (Manning's n) and factors for reducing the flow through the cell to simulate blockage by buildings. For a cell and a given time, the net flow that enters and leaves on each side of said element is calculated.

In the present study, the spatial representation of the data of the area under study was obtained directly from the National Center for Estimation, Prevention and Reduction of Disaster Risk (CENEPRED) in its online platform "Information System for Risk Management of Disasters" (SIGRID), said Peruvian platform gives us the contour curves of the Malanche creek with a resolution of 4.17 cm and an interval of 0.5 m.

To calculate the roughness coefficient, the Cowan criterion was used, obtaining a value of 0.05 for the channel and the upper-middle part of the basin. Likewise, the tables prepared by Ven Te Chow in the book “Hidráulica De Canales Abiertos 1994” were used, obtaining a value of 0.015 for the urbanized part.

The rheological parameters of the fluid were set with the report published by INGEMMET, a public entity of the Peruvian state, research entitled "Evaluation of geological threats in the district of Punta Hermosa", which provides geological information on the area, as it is a composite area by gravels with a silty-sandy matrix interspersed with silts, sands, a low proportion of clay and a large contribution of loose material (blocks, gravel), it is concluded that the sample used for modeling resembles a material from the Gleenwood Sample. 2, defined in table Nº 3.

Once the characteristic parameters of the stream were known, the model was simulated for scenario 1, corresponding to the day of the event, with a volumetric concentration of sediments of Cv = 0.45, in this way the following result was obtained:

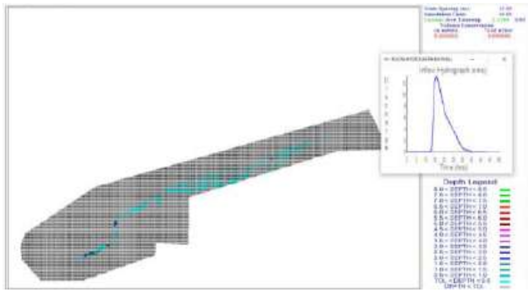

Fig. 3. FLO 2D output (Program simulation)

Once the model is obtained, it must be calibrated, which was elaborated with the methodology based on the search for similarity between the maximum ties obtained by the software, with the flow marks observed in the field, through the analysis of the surveying with Civil3D software. For this, control points must be established, Fig. 4 shows the 6 control points defined and listed vertically for the afore mentioned validation.

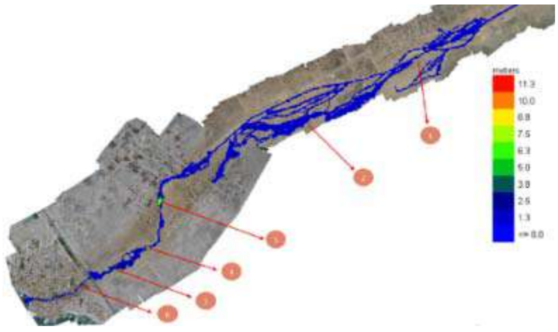

Fig. 4. Control points for the validation of the modeling in FLO 2D

Points No. 1, 3, 4, 5:

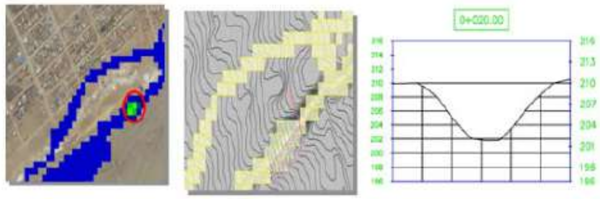

Fig. 5. Control point No. 1

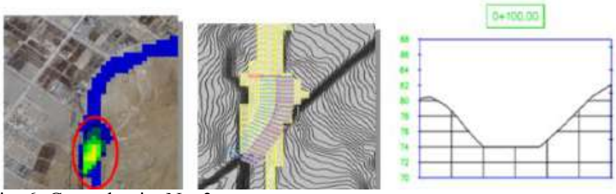

Fig. 6. Control point No. 3

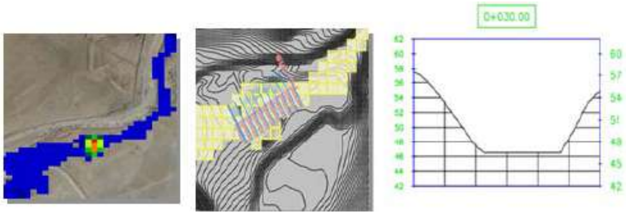

Fig. 7. Control point No. 4

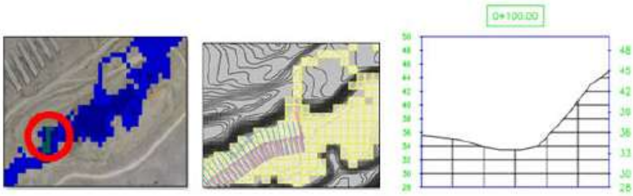

Fig. 8. Control point No. 5

In these areas, ties between 3.8 and 11.8m were modeled, considering the excessive ties compared to the 1.3m found in most of the model, but it was verified in the cross sections that there are depressions that allow these heights to exist. as well as it was validated.

In Fig. 9, the marks left by the mud flow in the various structures of the population can be seen. These areas were in the plan and it was verified that the pull in that area was 1.00 m to 1.50 m.

Points No. 2 and 6:

Fig. 9. Marks left by the mud flow in Pampapacta (Punta Hermosa)

This way the model was validated, obtaining similar straps on the day of the event.

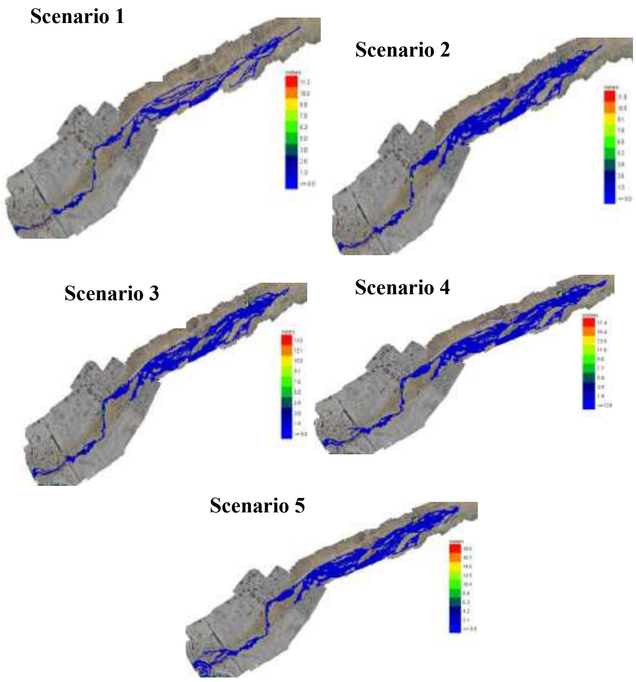

Fig. 10. Flo-2D simulations for all developed scenarios (Storm 2017, TR 25, TR 50, TR 100 and TR 200 years)

VI. Results

The floods were studied for each flow obtained, with their respective return periods, and with a volumetric concentration of sediments (Cv) of 45%.

TABLE VII Results of the volume modeled for each scenario

Scenarios	**Results**		
	Flow (m3)	***Water (m3)***	***Bulked with Sediment (m3)***
Nº 1	Inlet hydrograph (inflow)	210782.98	383241.79
	Storage within the analysis area	117924.91	214408.93
	Flow outside the analysis area (outflow)	92858.07	168832.86
Nº 2	Inlet hydrograph (inflow)	588835.48	1070609.98
	Storage within the analysis area	184440.96	288545.49
	Flow outside the analysis area (outflow)	474693.477	782064.50
Nº 3	Inlet hydrograph (inflow)	812447.24	1477176.85
	Storage within the analysis area	204166.46	342082.31
	Flow outside the analysis area (outflow)	653527.916	1135094.54
Nº 4	Inlet hydrograph (inflow)	1078767.03	1961394.65
	Storage within the analysis area	248302.07	410139.61
	Flow outside the analysis area (outflow)	907338.496	1551255.04
Nº 5	Inlet hydrograph (inflow)	1407187.16	2558522.18
	Storage within the analysis area	298441.39	500901.68
	Flow outside the analysis area (outflow)	1207777.94	2057620.50

Table VII represents the total volumes of the floods, made up of water and sediment (volume stored + volume outside the simulation area) for all scenarios. In the same way, in Table VIII, the speeds and depths obtained for each developed scenario are presented.

TABLE VIII Results of speeds and depths

Scenarios	Results	
	Speeds (m/s)	*Depths (m)*
Nº 1	0.5<V<4.9	1.3<h<11.30
Nº 2	0.5<V<4.6	1.3<h<11.80
Nº 3	0.7<V<6.3	1.5<h<13.60
Nº 4	0.8<V<7.20	1.9<h<17.40
Nº 5	0.7<V<6.3	2.1<h<18.80

Threat maps were obtained for each return period.

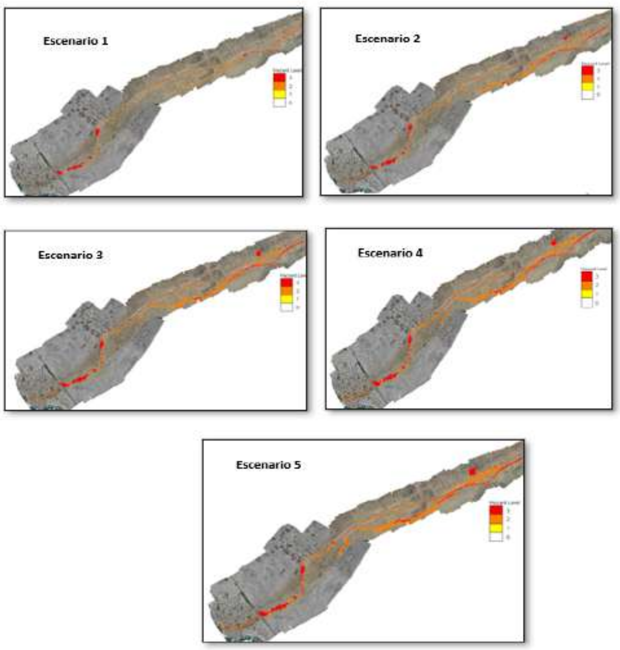

Fig. 11. Threat map

Analyzing the maps obtained, it can be seen that the town of Pampapacta is in constant danger due to future mudflows in the Malanche ravine, presenting the most critical scenario (TR 200 years), and high-level threats are observed in this town. This suggests that subsequent mudflows will develop high critical pulls along with high velocities, compared to the 2017 mudflow, which will be more destructive.

Due to the complexity of relocation of the populated centers that are affected by this phenomenon, one way to mitigate the damage is the construction of a retaining wall based on the height of the maximum pull obtained from the riverbed in the simulations. In Flo-2D, this structure must prevent flow overflow.

Another point to be analyzed is the Panamericana Sur bridge since the channel of the stream and future mud flows pass below it. As observed in the different threat maps, this point is critical because the span of the bridge is not wide enough to allow the passage of the mud flow and possibly, as happened in the 2017 event, material accumulates underneath. it and generate that the sediments, and any material that carries the mud flow, obstructs the passage causing the mud flow rate to increase and overflow the sides of the bridge, this would interrupt the traffic of a high traffic density road and it would divert the flow of mud from its natural channel, which could cause the flow to flood areas that are not registered in this investigation.

VII. CONCLUSIONS

The physical process of initiation of sludge flows can be represented in sludge flow hydrographs for different return periods calculated from the corresponding liquid flow hydrographs, which are congruent with geomorphological conditions, the availability of detrital materials and the almost non-existent vegetative cover of the Malanche micro basin.

The results of the numerical simulations of the sludge flow transport and deposition processes corresponding to the sludge flow hydrographs for the day of the event under study show acceptable results in terms of the similarity of the affected extension and solid deposition areas. of the sludge flow that occurred in 2017. The model developed in the FLO-2D software was able to predict and delimit, with acceptable precision, the affected areas of the 2017 sludge flow and from there to other determined return periods.

The methodology proposed and validated in this paper for assessing the risk of mudflow disasters in basins and streams can be used to understand the extent of mudflow floods in extreme weather events, as well as to develop emergency plans and for the formulation of disaster management policies in Peru.

REFERENCES

[1] Vargas, P. (14 de Junio de 2009). El Cambio Climático y Sus Efectos en el Perú. Banco Central de Reserva del Perú

[2] Zhang, P., Ma, J., Heping, S., Han, T., & Yali, Z. (2015). *Simulating debris flow deposition using a two-dimensional finite model and Soil.* Gansu: Environmental Earth Sciences.

[3] Zhang, P., Ma, J., Shu, H., Han, T., & Zhang, Y. (2014). Simulating debris flow deposition using a two-dimensional finite model and Soil Conservation Service-curve number approach for Hanlin gully of southern Gansu (China). Environ Earth Sci, 6417-6426.

[4] Quispe, R., Pino, E., & Avendaño, C. (2018). Nivel de riesgo por desborde e inundación aplicando un modelo de flujo de escombros en la quebrada lluta para la mina Karla en Tacna. Ciencia y Desarrollo, 11-20.

[5] Castillo Navarro, Leonardo Franco. (2006). Aplicación de un modelo numérico de flujo de escombros y lodo en una quebrada en el Perú. (Tesis de titulación). Lima: Universidad Nacional de Ingeniería.

[6] O'Brien, J. S., and Julien, P. Y. (1985). "Physical properties and mechanics of hyperconcentrated sediment flows." Proc. of the Specialty Conference on Delineation of Landslides, Flash Flood and Debris Flow Threats in Utah, Utah Water Research Laboratory, 260-279.

[7] Oc, Miranda. (s. f.). Parámetros reólogicos. Recuperado de https://www.academia.edu/15326356/Par%C3%A1metros_re%C3%B3logicos

[8] FLO 2D (2017). Mapper manual versión manual 2017.