Reduction of the Hazard Level Due to Hyperconcentrated Flows in a Dry Creek Applying FLO-2D Modeling

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***Abstract*—In the face of an event of mud or debris flow in a dry creek, a reduction of the hazard level was sought through hyperconcentrated flow modeling in FLO-2D. Among the software requirements, the characterization of the hydrology, topography, geology and geotechnics of the stream was required. In addition, it was necessary to establish the Manning "n" roughness for the zone within the simulation and the rheological parameters that represented the behavior of the fluid. Three methodologies were used for calibration, which validated the contribution of the research. The FLO-2D model showed values of flow depths and flow velocities, which were necessary for the elaboration of the hazard map. As a mitigation measure, the placement of dykes in the stream bed was considered to analyze flow depths, velocities, and the hazard level. Among the results obtained, it was observed that, in the urban zone, the area corresponding to a medium and high level of hazard was reduced by 59.8% and 96.1%, respectively. In conclusion, the placement of dykes in the creek significantly reduced the level of hazard generated by a hyperconcentrated flow.**

***Index Terms*— FLO-2D, hyperconcentrated flow, hazard map, mitigation measure and dry creek**

I. Introduction

In the last decades, several institutions, such as the World Meteorological Organization and the Servicio Nacional de Meteorología e Hidrología del Perú (SENAMHI), affirm that there is technical evidence of a temperature increase of 1.1 °C. The “niño costero” phenomenon is a consequence of this temperature raise, causing an increase in the intensity of the precipitations and adverse effects such as floods and debris flow. These climate-related factors are associated with trigger factors of a hyperconcentrated flow, since they generate a greater load on the natural basin. A clear example of this type of factor was what happened on February 21st, 2020 in the city of Tacna, since reports from the Instituto Geológico, Minero y Metalúrgico (INGEMMET) indicate that the detonating factor that caused the event was a rainfall that lasted 3 days.

Among the conditioning factors, the Diablo’s creek characteristics such as the plant cover, soil type and pronounced slope can trigger a hyperconcentrated flow. This event affected 2,001 people, and caused 221 homes to become uninhabitable, according to the report of the National Emergency Operations Center in 2020. Considering these problems, information was sought from various authors on possible solutions to mitigate the impact of the debris flow.

According to Zhang et. al (2019) [1] they carried out an investigation of the spatial-temporal properties, in order to generate an impact model of a landslide associated with the amount, duration and intensity of rainfall; and conditioning factors specific to the zone such as the slope of the terrain, the type of soil cover and the type of soil. The simulated event was projected in different locations, to be able to quantify the relations between occurrence rate and influence factors. According to Eder et al. (2017) [2] through an analysis of a quadratic rheological model, the shear stress can be defined with the FLO-2D software. Deterministic models were also used in order to imitate the physical processes and minimize the errors, thus generating a standardization of the return period for future hydraulic works in the town of Sijan. According to the study by Sepulveda et al. (2016) [3], a standardized criterion was developed to evaluate the hazard level and vulnerability according to the return period and the level of depth that would generate the debris flow to be simulated. The Centro Nacional de Estimación, Prevención y Reducción del Riesgo de Desastres (CENEPRED) proposes the use of Saalty's empirical model to determine the hazard level and since it is based on the researcher's perception, which generates a high degree of imprecision. According to Ref. [4] a more practical way of studying streams was created in Peru, where a hazard map and a valid procedure was obtained to simulate hyperconcentrated flows in FLO-2D with high precision. The various sources reviewed conclude that the use of structural and non-structural mitigation measures help reduce damage caused by debris flows.

The present work proposes an analysis of possible scenarios in the Diablo's creek, which depending on the return period, and through a hydrological and hydraulic study, will be able to generate a greater perception of the level of hazard to which the inhabitants of the Alto Alianza district urban zone are exposed to. This research will be relevant for future reological studies about

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hyperconcentrated flows in the city of Tacna, since the study of these events is scarce in that region of Peru.

II. Study Area

The Diablo's creek is located in the province of Tacna, in the south of Peru. This area is characterized by an arid climate with low intensity of rainfall throughout the year; however, hyperconcentrated flows that have affected the district of Alto Alianza were witnessed, causing material and economic damage to inhabitants who were close to the creek. These events were generated due to extraordinary rainfall and the intrinsic characteristics of the basin, such as the elongated shape, the steep slope, the scarce vegetation cover and the high capacity to drag sediments when there is a water flow.

The study area is delimited by the basin of the creek and the alluvial fan, where the urban area of La Florida, Alto de la Alianza district, is located. Tacna is geographically located, according to the WGS84 coordinate system, at 18°0'52.74" south latitude and 70°15'13.03" west longitude.

III. Methodology

In Fig. 1 the flow chart of the proposed methodology for the simulation in FLO-2D can be seen.

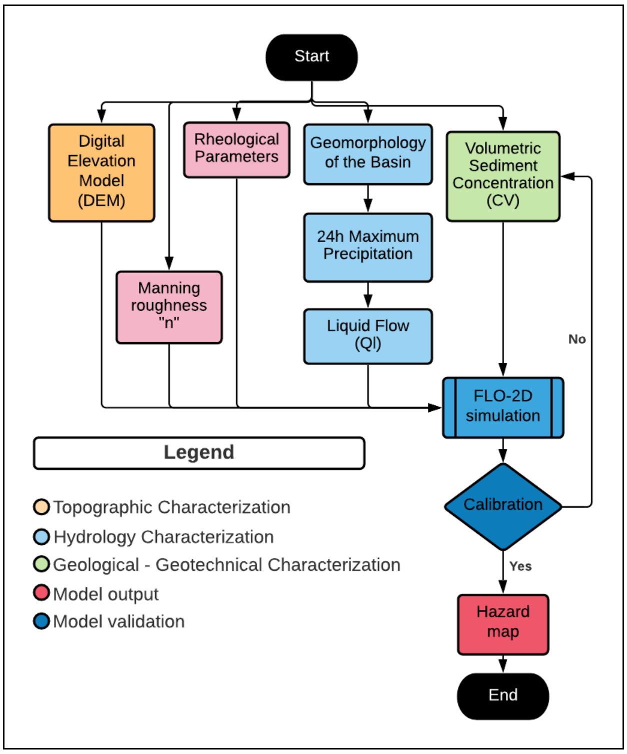

Figure 1. Flowchart of Methodology for the FLO-2D mode

In order to obtain the topographic information of the study area, a Digital Elevation Model (DEM) was used, which was processed by the ArcMap software to export the simulation area to FLO-2D and obtain the geomorphological characteristics of the basin.

With the compilation of different geological and geotechnical studies in the area, the physical properties of the soil were described in order to propose different values of volumetric concentration of sediments (Cv) and thus calibrate and validate the FLO-2D model. In addition, the rheological parameters of the stream were established, and a Manning "n" roughness was proposed for the stream bed and the urban area.

The HEC-HMS software was used to model the hydrology in the study area, which required the analysis of the maximum precipitation in 24 hours and the different geomorphological factors of the Diablo's Basin in order to obtain the liquid hydrograph for the simulated scenarios.

With the mentioned data, the simulation was carried out in FLO-2D to replicate the event that occurred on February 21st, 2020. Then, the model was calibrated through 3 different methodologies and the results were validated. Finally, the hazard maps were obtained, and structural mitigation measures were proposed to reduce the hazard level that would be generated by a hyper concentrated flow.

IV. Hydrological Analysis

In Fig. 2, we can see a delimitation plane of the Diablo's creek basin. Among the geomorphological factors of the basin we have an area of 52.0 km^2, a perimeter of 55.1 km, an average slope of 11.0 %, a length of the main channel of 25.6 km, and a concentration-time of 2.37 hours.

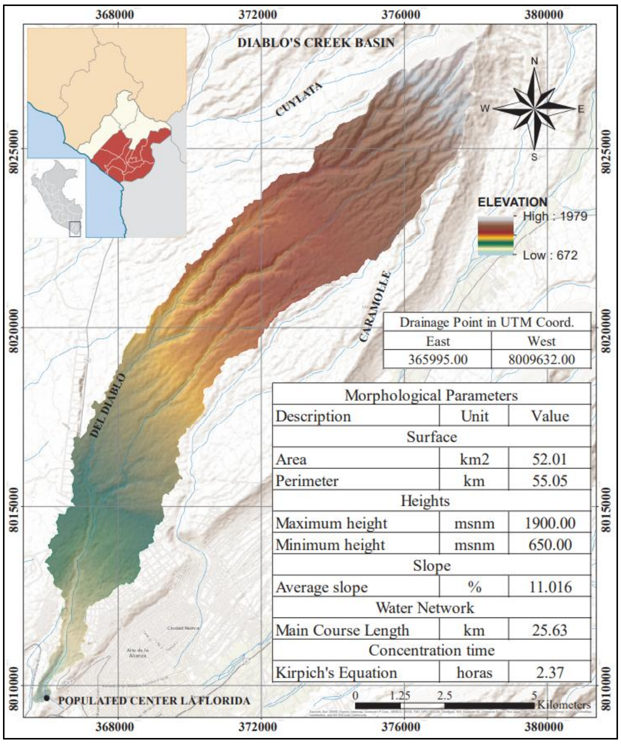

Figure 2. Diablo's creek basin delimitation map.

To obtain the value of maximum precipitation in 24 hours, a statistical analysis of the data recorded by the Talabaya, Sitajara, and Susapaya stations was carried out. The criteria by which these stations were chosen was their proximity and the fact that they were located in the highest part of the Diablo's creek basin. In Table I, the coordinates and altitude values of the stations are shown.

TABLE I. LOCATION OF STATIONS FOR HYDROLOGICAL ANALYSIS

Station	Basin	Latitude	Length	Altitude
Talabaya	Sama	17°33'33" S	69°59'59" W	3420
Susapaya	Sama	17°20'51.8" S	70°08'05" W	3468
Sitajara	Sama	17°22'21" S	70°08'08" W	3132

Two scenarios were analyzed: The first simulating the event that occurred on February 21, 2020, and the second corresponding to a hyper concentrated flow for a return period of TR=100 years. In order to obtain the liquid hydrographs, the simulation was carried out in HEC-HMS, and a maximum flow of 27.7 m^3/s was obtained for scenario 1 and 35.80 m^3/s for scenario 2, as shown in Fig. 3.

The methodology proposed by Soil Conservation Service (SCS) was used with a type II storm choice to obtain the results of both scenarios in HEC-HMS. It is worth mentioning that for scenario 1 a curve number (CN) [5] was chosen in the wet condition, due to the presence of rain before the event, while for scenario 2 a normal condition was chosen.

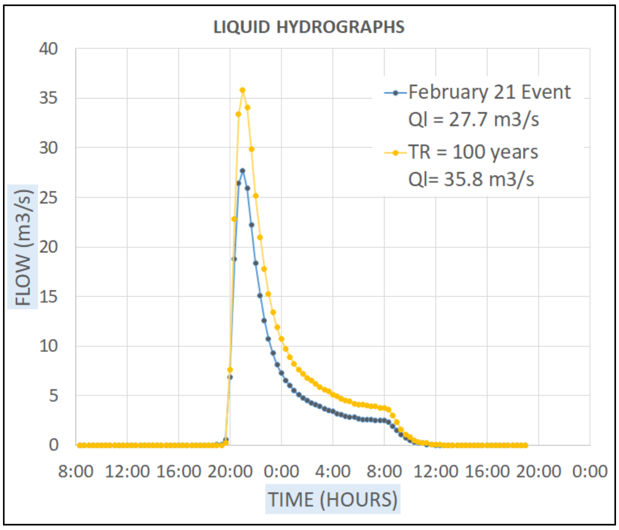

Figure 3. Liquid hydrographs of scenarios 1 and 2.

V. HYDRAULIC ANALYSIS

The simulation in FLO-2D was achieved by dividing the input data into 2 categories. The first corresponds to the stage before performing the calibration of the model, where 6 different hydrographs were considered, in which the volumetric concentration ranges of sediments vary as follows: 0.22 to 0.35, 0.22 to 0.40, 0.22 to 0.45, 0.35 constant, 0.35 to 0.40 and 0.40 to 0.45. The second one corresponds to the parameters that were kept constant both before and after validating the model: laminar flow resistance (K) equal to 2285, specific gravity of sediments (Gs) of 2.65, Manning's roughness "n" of 0.05 for the basin bed and 0.02 for the urban area, and the selection of a sample of soil type Glenwood sample 2. [6]

Using the rheological parameters, the liquid hydrographs and the different ranges of volumetric concentration of sediments (Cv), the simulation was carried out with a digitized topography (curves every 2m) of the Diablo's creek stream bed, with a delimitation of the area of study covering a length of 2.50 km upstream of the stream bed, a grid size of 8x8m for each cell and a simulation time of 20 hours.

VI. FLO-2D MODEL CALIBRATION AND RESULTS

A. *Calibration and Validation*

To validate the results of the research, 3 calibration methodologies were used.

1) Photographic and video evidence

According to the information gathered from the event that took place on February 21, 2020, it was possible to define which of the Cv ranges is the right one based on how similar the maximum flow depth obtained in FLO-2D is to the flow depth of the photographic evidence of the event. For this purpose, 4 control zones were chosen to compare the previously mentioned flow depth, as shown in Table II and Fig. 4.

TABLE II. CONTROL ZONES UTM19S COORDINATES

Zone	Latitude	Length	Depth
1	366046.78	8009618.30	0.90 - 1.00
2	367025.39	8008667.72	0.15 - 0.20
3	367040.89	8008568.23	0.10 - 0.20
4	366395.00	8009224.00	0.30 - 0.45

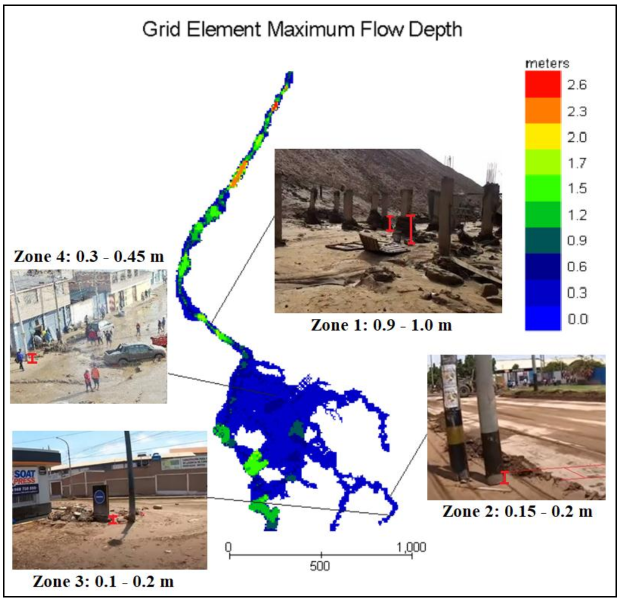

Figure 4. The contrast between photographic evidence and the FLO-2D results.

By establishing a Cv of 0.22 to 0.35 for the FLO-2D modeling, the values of flow depths with the highest degree of similarity to the photographic evidence of the event that occurred on February 21, 2020, were obtained. In addition, according to different videos, it could be observed that the flow was characterized by the presence of small sized sediments.

2) Maximum hydraulic capacity

In order to verify if the FLO-2D results respect the maximum hydraulic capacity, 6 cross-sections were analyzed in the bed of the stream, which are represented by the following progressive distances: 0+650, 0+660, 0+720, 0+800, 0+825m, as shown in Fig. 5.

Considering these control points, Manning's formulas and the Bulking Factor formula were applied to find the liquid and mixing flows, and the maximum depths of the cross-sections. As a result, it was observed that for a maximum value of Cv equal to 0.35, the flow heights obtained in FLO-2D respected the maximum hydraulic capacity of the section. Furthermore, it was concluded that the results through simulation, photographic evidence and hydraulic capacity were similar to each other when the Cv value was established from 0.22 to 0.35.

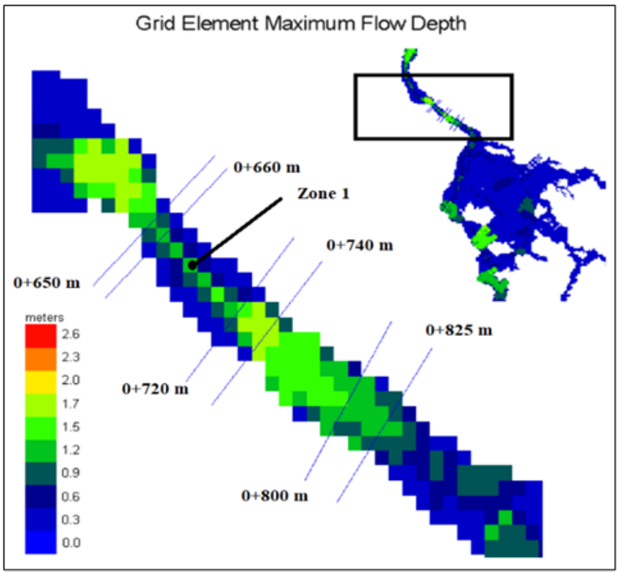

Figure 5. Cross-sections to find the maximum hydraulic capacity

3) Sediment production volume

Finally, a sediment volume value was calculated for the event that occurred on February 21, 2020, in the Diablo's creek, using the Erosion Potential Method (EPM) formula proposed by Milanesi et al. (2016) [7] and then compared with the result obtained from the FLO-2D software, as shown in Table III.

TABLE III. SEDIMENT PRODUCTION IN DIABLO'S CREEK

Description	Symbol	Value	Unit
Annual accumulated precipitation	P	19.8	mm
Average annual temperature	t	17.8	℃
Protection by vegetal or artificial cover	X	0.6	-
Soil resistance against the erosive capacity of water	Y	1.4	-
Intensity of active erosion processes	φ	0.3	-
Average slope of the creek	i	0.11	m/m
Average annual sediment production	Wsp	1,714.9	m^3
Annual production accumulated until the event	Wsp acum	159,493.1	m^3
Total volume of sediments in FLO-2D with Cv from 0.22 to 0.35	Wsp acum	148, 636.1	m^3

When comparing the results, it was observed that application of the EPM formula had a variation of 6.58% with respect to the result in FLO-2D, which indicates that the simulation with the Cv value of 0.22 to 0.35 presents a great similarity with the event that occurred on February 21, 2020.

4) Validation of results

According to the 3 previously mentioned methodologies, it was determined that the simulation of the event that occurred on February 21, 2020, could be carried out quite accurately using FLO-2D software and its results validated by the comparison of evidence of hyperconcentrated flow and the applying of empirical formulas.

The mixing hydrographs and the Cv value of both scenarios are presented in Fig. 6.

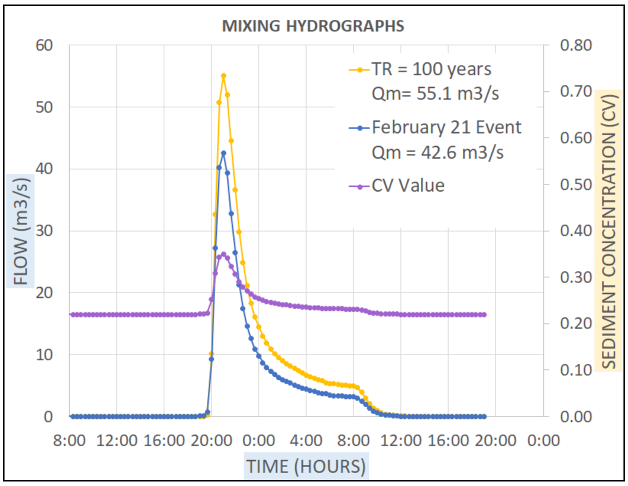

Figure 6. Mixing hydrographs for scenarios 1 and 2.

B. Interpretation and Analysis of Results

1) Scenario 1 (21 Feb. Event)

According to the results in FLO-2D, scenario 1 presented a volume of flow bulked with sediment of 514,677 m3, from which the water volume is 366,041 m^3, while the sediment volume is 148,636 m^3, as shown in Table IV.

TABLE IV. SCENARIO 1 VOLUME DATA

Flow	Water (m^3)	Bulked with sediment (m^3)	Sediment (m^3)
Input hydrograph (INFLOW)	366,041	514,677	148,636
Storage within the analysis area	27,235	36,098	8,863
Flow outside the simulation area (OUTFLOW)	345,038	478,579	133,541

Within the area of the model, the maximum flood area was 478,912 m^2 and the maximum flood area with depths greater than 15 cm was 301,824 m^2.

Among the results of maximum depths and maximum velocity within the urban zone, the maximum and average depths were 1.58 m and 0.28 m, respectively; while the average velocity in the city was 0.78m/s.

A hazard map was made based on the BASABE methodology, which describes that a high hazard level is reached when the flow velocity is greater than 1.00 m/s and the depth is greater than 1.00 m; while for a medium hazard level the velocity is between 0.20 and 1.00 m/s and the depth is between 0.20 and 1.00 m. A low hazard level is not considered for a hyperconcentrated flow.

With the previously mentioned data, the hazard map for scenario 1 was created, as shown in Fig. 7.

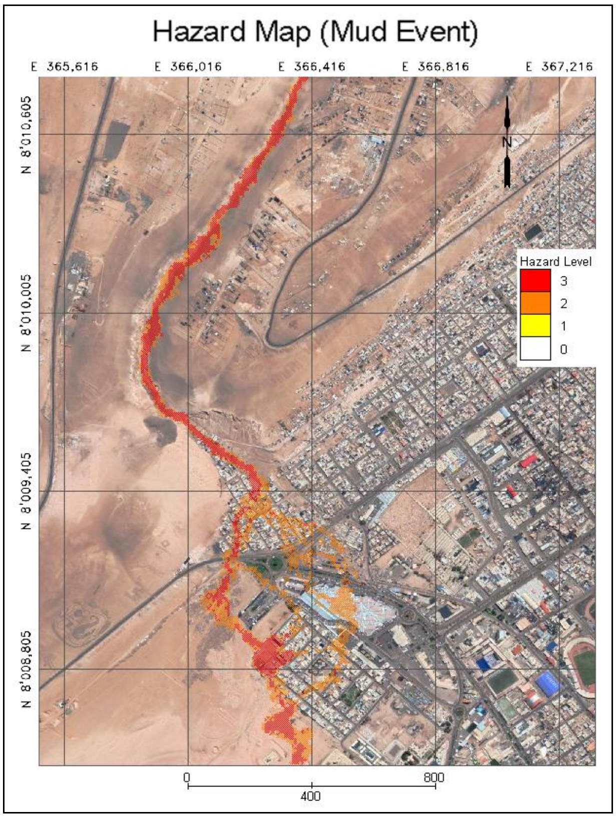

Figure 7. Hazard map of scenario 1.

Within the urban zone, it was determined that the areas corresponding to a high and medium hazard levels are 40,896 m2 and 80,384, respectively.

2) Scenario 2 (TR=100 years)

According to the results in FLO-2D, scenario 2 presented a volume of flow bulked with sediment of 713,773.78 m^3, from which the volume of water is 507,649 m^3, while the volume of sediment is 206,125 m^3, as shown in Table V.

TABLE V. SCENARIO 2 VOLUME DATA

Flow	Water (m^3)	Bulked with sediment (m^3)	Sediment (m^3)
Input hydrograph (INFLOW)	507,649	713,774	206,125
Storage within the analysis area	30,064	41,684	11,620
Flow outside the simulation area (OUTFLOW)	466,651	672,090	205,439

Within the model area, it was obtained that the maximum flood area was 520,576 m^2 and the maximum flood area with depths greater than 15 cm was 330,048 m^2.

Among the results of maximum depths and maximum velocity within the urban zone, the maximum and average depths were 1.74 m and 0.29 m, respectively, while the average velocity in the city was 0.82 m/s.

With the previously mentioned data, the hazard map for scenario 2 was elaborated, as shown in Fig. 8.

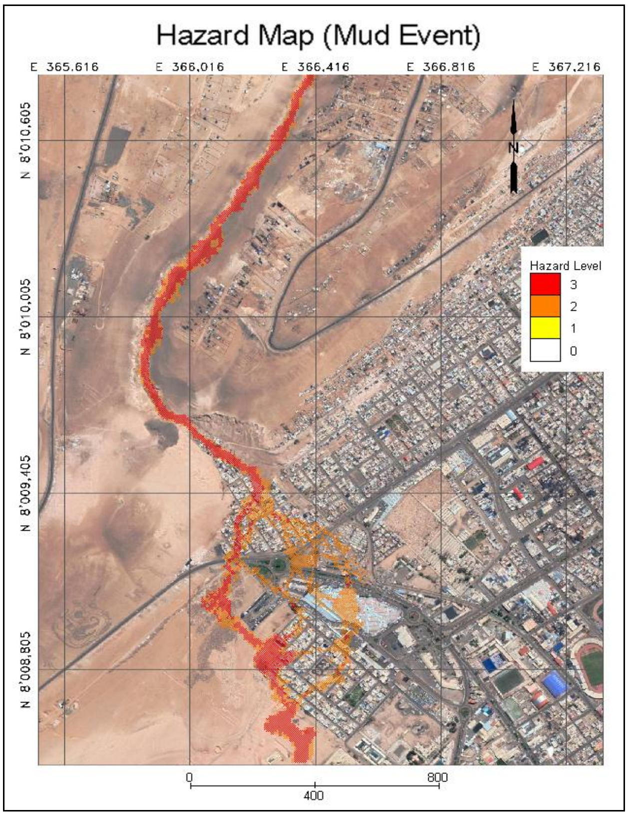

Figure 8. Hazard map for scenario 2.

Within the urban zone, it was determined that the areas that correspond to a high and medium hazard levels are 52,608 m2 and 81,024, respectively.

VII. HAZARD REDUCTION PROPOSAL

In order to propose mitigation measures, we worked with the simulation of a hyperconcentrated flow of TR=100 years, since most of the designs of hydraulic works in Peru work with this return period.

A. Location of Mitigation Measures

Eleven dykes with heights of 2, 6 and 8 meters were located along the course of the Diablo's creek so that the energy released by the hyperconcentrated flow is reduced and, likewise, the level of hazard in the city is diminished.

B. Reducing the Hazard Level

Among the results, it was observed that, for the 2, 6 and 8 meter high dykes, the high hazard level area decreased to 45,312 m^2, 19,392 m^2 and 2048 m^2, respectively. While the medium hazard level area increased to 92,096 m2 for the 2-meter dyke, it decreased to 57,792 m^2 for the 6-meter dyke and to 32,576 m^2 for the 8-meter dyke. Fig. 9 shows the hazard maps for the different heights of dykes.

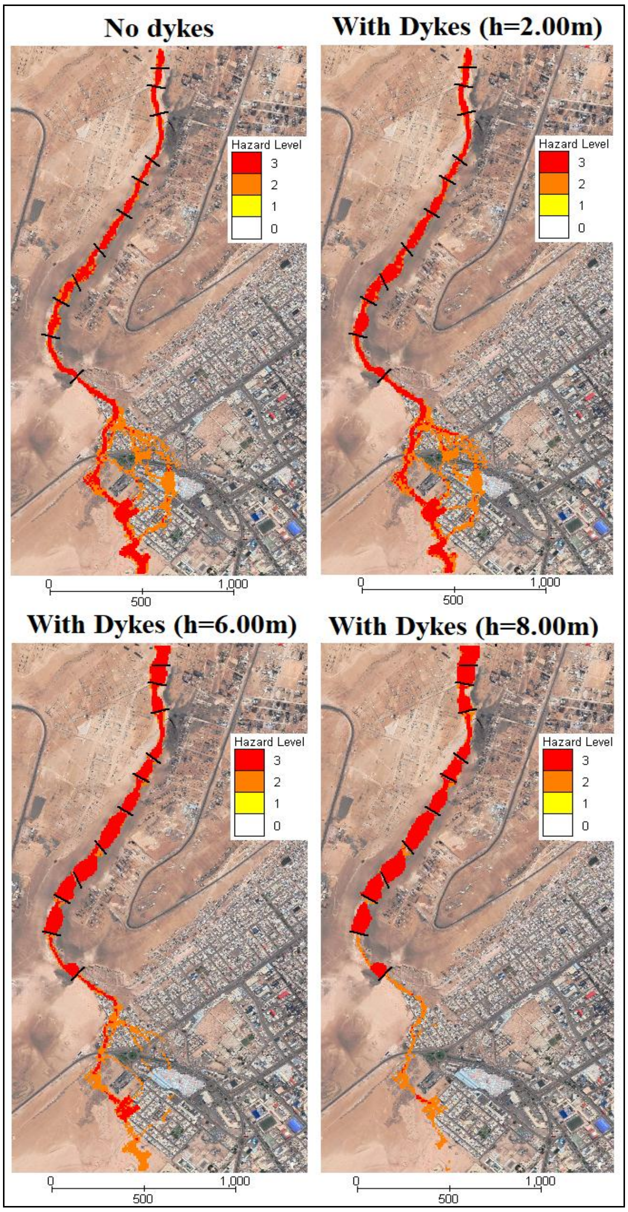

Figure 9. Hazard map with different height of dykes.

VIII. Conclusions

After performing the calibration of the FLO-2D model by means of the comparison of the maximum flow depths, the verification of the maximum hydraulic capacity, and the contrast of the total volume of sediments; it was determined that the Cv value with better results was 0.22 to 0.35.

It was possible to simulate, with high precision, the hyperconcentrated flow that occurred on February 21, 2020, in the Diablo's creek. Among its results, an average flow depth of 1.58 m and an average flow velocity of 0.78 m/s were obtained within the urban area; while for an event of TR=100 years the flow depth and average velocity increased by 10.1% and 5.13%, respectively.

A hazard map was drawn up for hyperconcentrated flows in the urban area of La Florida, which allows the identification of high and medium hazard level zones in the study zone. With this, it was determined that for scenarios 1 and 2, the size of the areas of the city that correspond to a high hazard level are 40,896 m2 and 52,608 m2, for scenarios 1 and 2, respectively.

By proposing structural measures along the course of the Diablo's creek, the hazard level generated by a hyperconcentrated flow of TR=100 years was significantly reduced. For dyke heights of 2, 6 and 8 m, the high hazard level area size was reduced by 13.9%, 63.1% and 96.1%, respectively.

Conflict of Interest

The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

Author Contributions

Sissi Santos and Leonardo Castillo conceptualized the idea, Sissi Santos managed the project, Roberto Talledo, Sergio Cardoso and Leonardo Castillo contributed to the analyses and writing the manuscript; Roberto Talledo edited the final draft. All authors have read and agreed to the published version of the manuscript.

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The author has a strong interest in conducting research on the study of natural events and their impact on the population.