

## Calculation of rainfall thresholds for debris flow prediction

### Cálculo de umbrales de precipitación de lluvia para la predicción de flujos de detritos.

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**Abstract:** Due to the fact that debris flow movements, commonly known as "huaycos," represent a potential threat worldwide, especially in Peru, it is necessary to analyze and study this hazard, as well as the ability to forecast these movements. Therefore, the objective of this research was to determine the precipitation thresholds that trigger debris flow movements in the Rosayoc/Batán ravine, in order to contribute to Disaster Risk Management (DRM). As a means of processing spatial data, this study used an approach that combines Geographic Information Systems (GIS), remote sensing, and satellite image analysis. Additionally, through the hierarchical analysis process, the most susceptible areas to debris flow in the Rosayoc/Batán ravine were evaluated and determined. In conclusion, the True Skill Statistic (TSS) of the thresholds was calculated through calibration and validation. This indicates that the model's ability to predict future outcomes was evaluated. Additionally, through the analysis and evaluation of hazard levels for debris flow movements using the hierarchical analysis process (CENEPRED 2014), it was established that the lower part has very high and high levels of hazard, the middle part has high and medium levels, and the upper part has a high level of hazard. Furthermore, these levels have the highest predominance of area in each part of the ravine. Moreover, hazard maps were also created for debris flow movements triggered by the maximum 24-hour precipitation and the critical threshold of accumulated rainfall (LA1) over 18 days, based on the maximum depths and velocities generated by the debris flow.

**Keywords:** landslides, debris flows, rainfall thresholds, hazard, forecast

**Resumen:** Debido a que los movimientos de flujo de detritos, comúnmente conocidos como huaycos, representan una amenaza potencial a nivel mundial, especialmente en Perú. Por lo que, es necesario analizar y estudiar este peligro, así como la capacidad de pronosticar estos movimientos. Por lo tanto, el objetivo de esta investigación fue determinar los umbrales de precipitación que desencadenan los movimientos de flujo de detritos en la quebrada Rosayoc/Batán, con el fin de contribuir a la Gestión del Riesgo de Desastres (GRD). Como medio de procesamiento de datos espaciales, este estudio utilizó un enfoque que combina Sistemas de Información Geográfica (SIG), teledetección y análisis de imágenes satelitales. Además, a través del proceso de análisis jerárquico, se evaluaron y determinaron las áreas más susceptibles a los movimientos de flujo de detritos en la quebrada Rosayoc/Batán. En conclusión, se calculó el Estadístico de Habilidad Verdadera (TSS, por sus siglas en inglés) de los umbrales mediante la calibración y validación. Esto indica que se evaluó la capacidad del modelo para predecir resultados futuros. Además, a través del análisis y evaluación de los niveles de peligro para los movimientos de flujo de detritos utilizando el proceso de análisis jerárquico (CENEPRED 2014), se estableció que la parte baja tiene niveles muy altos y altos de peligro, la parte media tiene niveles altos y medios, y la parte alta tiene un nivel alto de peligro. Además, estos niveles tienen la mayor predominancia de área en cada parte de la quebrada. Además, se crearon mapas de peligrosidad para los movimientos de flujo de detritos desencadenados por la precipitación máxima en 24 horas y el umbral crítico de lluvia acumulada (LA1) durante 18 días, basados en las máximas profundidades y velocidades generadas por el flujo de detritos.

**Palabras clave:** deslizamientos, flujo de detritos o escombros, umbrales de precipitación de lluvia, peligro, pronóstico

## 1. INTRODUCTION

The global danger posed by debris flow movements, or "huaycos" as they are called in Peru, necessitates the research and analysis of this hazard, as well as the development of methods for forecasting such movements. Therefore, it is necessary to establish what a debris flow is. Therefore, it is a rapid to very fast channelized flow down a steep slope. (Hung, 2005; Proyecto Multinacional Andino: Geociencias para las Comunidades Andinas, 2007; Varnes, 1978). Furthermore, debris flows may begin their journey by either surface landslides near the basin's headwaters or underground landslides (Iverson et al., 1997; cited in Yang et al., 2023) or when runoff mobilizes the debris that has collected on the slopes or channels due to erosion (Gregoretto et al., 2016; cited in Yang et al., 2023). Because of this, these flows carry a significant quantity of the coarse silt they encounter along their course as they travel down the channel and finally deposit it in debris fans (Hung et al., 2001; Ilinca, 2021; Proyecto Multinacional Andino: Geociencias para las Comunidades Andinas, 2007). Furthermore, numerous reasons, such as conditioning and triggering chemicals, contribute to debris flow motions. These factors may change from place to place, working with varying degrees of complexity and intensity in various contexts. Rainfall is considered to be the most common occurrence that causes these changes. Rainfall decreases effective tensions between particles, resulting in a drop in shear strength. This reduction in shear strength leads to decreased stability and, ultimately, debris flow movements (Aristizábal et al., 2010). This highlights the need of researching the connection between precipitation and the prevalence of debris flow movements. The danger may be accurately described in terms of occurrence probabilities over time and space when physical models are combined with empirical models. The goal of this method is to improve the accuracy with which debris flow motions can be predicted under these critical situations (Crosta 1998, cited in Aristizábal et al., 2010; Salinas Jasso, 2016).

The neighborhood of San Rafael was selected as the research region because it contains the most documented instances of Huayco-Aluvi3n (debris flow-flood), an external geodynamics phenomenon. When it comes to climatic events like rainfall and flash floods, Ambo ranks fourth overall and is the second province with the most number of records of occurrences of these phenomena (huaycos). Finally, when looking at the total number of reported incidences of dangers induced by natural phenomena, broken down by kind, the department of Huánuco ranks among the top 10 departments (Instituto Nacional de Defensa Civil [INDECI], 2016 and DesInventar.org, 2022). Located on the right side of San Rafael (the district capital), the Rosayoc/Batán ravine is particularly at risk from debris flow movements, which are often driven by rains. Due to its location so close to critical infrastructure like the Central Highway, the Huallaga River, and the 07 de Junio Human Settlement (Pomabamba ravine), this problem has the potential to have far-reaching effects. Lastly, the objective of this research was to determine the precipitation thresholds that trigger debris flow movements in order to contribute to disaster risk management (DRM). In addition, it is intended to provide technical information on the dynamics that these movements could present in order to develop mechanisms to design control, prevention, and disaster reduction measures for the likely

occurrence of this event. This event could cause various problems, such as loss of human and economic life, obstruction of traffic, leaving several cities cut off, and damage to road infrastructure.

## **2. RELATIONSHIP OF THE MAIN VARIABLES ASSESSED**

### **2.1. Rainfall Thresholds That Trigger Debris Flow Movements**

Rainfall thresholds may be determined empirically or by the use of physical concepts. The identification of regions that have or have not seen a mass migration in relation to a precipitation event is the first step in the process of establishing empirical thresholds. On the other hand, physical thresholds are derived using numerical models that include both hydrological and geotechnical evaluations. These models integrate the two types of analysis. These models consider the connections that exist between precipitation (rainfall), infiltration, pore pressures, and the stability of slopes. Knowledge on hydrological, lithological, morphological, and soil characteristics is needed in order to produce a better forecast of mass movements for these thresholds. This is because these elements govern the activation of these movements, and so knowledge on these characteristics is necessary (Crosta, 1998; Montgomery & Dietrich, 1994; Wilson & Wieczorek, 1995). As these models can foretell the quantity of precipitation needed to cause slope failure surfaces, as well as the position and date at which a movement may occur, they are of tremendous value as a foundation for the creation of Early Warning Systems (EWS). However, there are constraints on their use due to the necessity for data across broad regions and the utilization of specialist equipment (rain gauges, tensiometers, piezometers) (Aleotti, 2004; Crosta, 1998, cited in Aristizábal et al. 2010).

## **3. MATERIALS AND METHODS**

As a means of geoprocessing spatial data, this study used an approach that combines Geographic Information Systems (GIS), remote sensing, and satellite image analysis. Using a hierarchical analytic approach, the researchers examined and evaluated vulnerable regions where debris flow movements take place (CENEPRED, 2014). Conditions were taken into account from variables including slope, geological and geomorphological units (relief), plant cover, and land use. Curve numbers (CN), critical in estimating peak runoff rates, were calculated using information on land use. It was also possible to calculate flood areas, maximum depths, and flow velocities across probable deposition zones for both the AMC and TR scenarios by simulating debris flows using the FLO-2D mathematical model. Using the simulation findings as a starting point, a danger map was constructed with the debris flow's depth and speed as primary factors.

## **4. RESULTS DISCUSSION**

### **4.1. Minimum Accumulated Rainfall Thresholds (AR)**

An accumulated rainfall series represents a threshold that begins on the day of the debris flow movement and continues until the day when there is no rainfall, potentially being activated by another precipitation event (new series), so the thresholds that are similar to statistical equations vary from one

potential curve family to the next. Moreover, the data population changes when additional rainfall events linked with debris flow movements are recorded in the research region, necessitating a recalculation of the threshold. Since AR1 has an intercept coefficient and AR2 does not, we analyzed the two minimum thresholds independently. The data above shows that the minimum threshold AR1 of 18 days receives more rain than the minimum threshold AR1 of 5 days. Additionally, the precipitation at the AR2 minimum threshold of 5 days is greater than that at the AR2 minimum thresholds of 6 and 7 days. It is also well-known that the minimal thresholds signify the quantity of rainfall over which the likelihood of debris flow movements dramatically rises. This is why we compared the daily maximum rainfall to the minimal AR1 and AR2 standards. Once the return time (TR) reaches 20 years, it is clear that the maximum rainfall exceeds the minimal threshold AR1 of 5 days. Also, the maximum rainfall is much over the AR2 minima for 5, 6, and 7 days. However, the maximum rainfall is lower than the AR1 requirement of 18 days. Finally, we conclude that debris flow movements may be triggered by the highest daily rainfall under the circumstances of the minimum thresholds AR1 (TR=20) of 5 days and AR2 of 5, 6, and 7 days.

**Table 1**

*Comparative table between minimum thresholds (AR) and maximum rainfall in 24 hours*

| Return<br>Period<br>(TR) | AR1 MIN 5DÍAS                      | AR1 MIN 18DÍAS                         | AR2 MIN 5DÍAS             | AR2 MIN 6DÍAS             | AR2 MIN 7DÍAS             |
|--------------------------|------------------------------------|--|---------------------------|---------------------------|---------------------------|
|                          | (mm)                               | (mm)                                   | (mm)                      | (mm)                      | (mm)                      |
|                          | $E = (6.6 + 0.7)D^{(0.43 - 0.03)}$ | $E = (0.57 + 0.06)D^{(0.784 - 0.021)}$ | $E = D^{(0.870 - 0.065)}$ | $E = D^{(0.670 - 0.033)}$ | $E = D^{(0.568 - 0.034)}$ |
|                          | $24 \leq D \leq 120$               | $24 \leq D \leq 432$                   | $24 \leq D \leq 120$      | $24 \leq D \leq 144$      | $24 \leq D \leq 168$      |
| 10                       |                                    | 61.06                                  |                           |                           |                           |
| 15                       | 53.02                              | 64.94                                  |                           | 25.29                     |                           |
| 20                       | 54.36                              | 67.48                                  |                           | 26.15                     | 16.85                     |
| 25                       | 55.34                              | 69.35                                  | 54.33                     | 26.79                     | 17.23                     |
| 50                       | 58.14                              | 74.71                                  | 58.43                     | 28.60                     | 18.30                     |
| 100                      | 60.67                              | 79.53                                  | 62.11                     | 30.24                     | 19.27                     |
| 200                      | 62.98                              | 83.94                                  | 65.48                     | 31.73                     | 20.15                     |
| 500                      | 65.78                              | 89.28                                  | 69.57                     | 33.55                     | 21.22                     |

#### 4.2. Minimum Antecedent Accumulated Rainfall Thresholds (AAR)

The antecedent accumulated rainfall (LAA) is just as important as the triggering accumulated rainfall (AR) in setting off debris flow movements. The latter is associated with the Rosayoc/Batán ravine's original soil moisture conditions and water table level. The water table rises in the Rosayoc/Batán ravine as a result of increasing groundwater saturating the soil, causing both surface erosion (runoff) and subsurface erosion (infiltration). All the water that falls into the ravine adds to the bulk and makes debris flows more likely to happen. These cutoffs were established using standard statistical inference procedures and probability theory in traditional hydrology. At last, the following minimal AAR criteria were established reliably for various return periods:

**Table 2**

*Minimum Antecedent Accumulated Rainfall Thresholds (AAR) for different return periods*

| Return Period<br>(TR) | AAR2 MIN 3                | AAR 2 MIN 4             | AAR 2 MIN 5           | AAR 2 MIN 8           | AAR 2 MIN 12          |
|-----------------------|---------------------------|-------------------------|-----------------------|-----------------------|-----------------------|
|                       | DÍAS (mm)                 | DÍAS (mm)               | DÍAS (mm)             | DÍAS (mm)             | DÍAS (mm)             |
|                       | $E = D^{(0.521 - 0.021)}$ | $E=D^{(0.653 - 0.073)}$ | $D^{(0.572 - 0.020)}$ | $D^{(0.573 - 0.010)}$ | $D^{(0.796 - 0.004)}$ |
|                       | $24 \leq D \leq 72$       | $24 \leq D \leq 96$     | $24 \leq D \leq 120$  | $24 \leq D \leq 192$  | $24 \leq D \leq 288$  |
| 10                    | 9.08                      | 14.76                   | 14.44                 | 19.31                 |                       |
| 15                    | 9.48                      | 15.50                   | 15.15                 | 20.31                 |                       |
| 20                    | 9.73                      | 15.98                   | 15.62                 | 20.97                 | 93.72                 |
| 25                    | 9.93                      | 16.33                   | 15.97                 | 21.46                 | 96.34                 |
| 50                    | 10.47                     | 17.35                   | 16.95                 | 22.85                 | 103.82                |
| 100                   | 10.96                     | 18.27                   | 17.84                 | 24.10                 | 110.56                |
| 200                   | 11.41                     | 19.10                   | 18.65                 | 25.24                 | 116.72                |
| 500                   | 11.95                     | 20.12                   | 19.64                 | 26.63                 | 124.18                |

**Table 3**

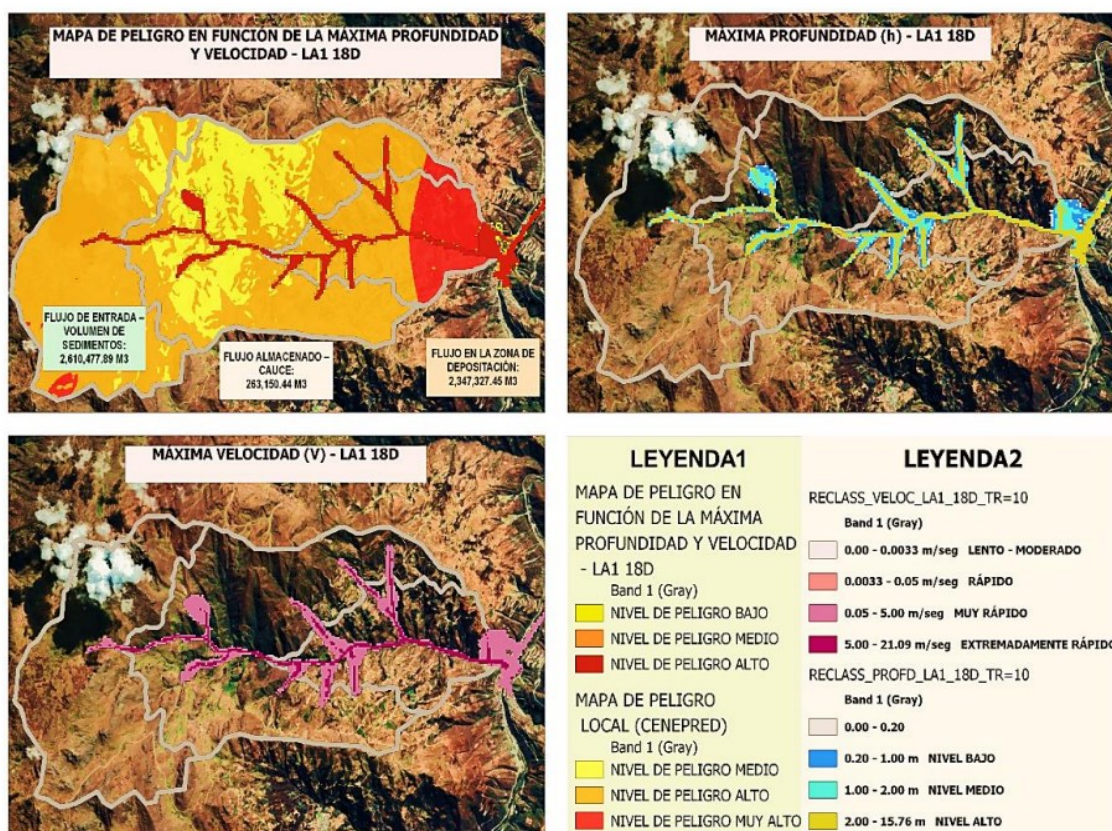
*Debris flow volumes triggered by minimum AR thresholds in the Rosayoc/Batán stream*

| DEBRIS FLOW VOLUMES TRIGGERED BY THE 5-DAY MINIMUM ARI THRESHOLD OF THE ROSAYOC/BATÁN STREAM  |              |                                     |                |   |              |                                     |                |
|---|--------------|-------------------------------------|----------------|---|--------------|-------------------------------------|----------------|
| AMCH (PREVIOUS MOISTURE: WET CONDITION)<br>DEBRIS FLOW - ARI 5D - TR = 15 YEARS               |              |                                     |                | AMCH (PREVIOUS MOISTURE: WET CONDITION)<br>DEBRIS FLOW - ARI 5D - TR = 20 YEARS       |              |                                     |                |
| FLOW (m3)   | WATER (m3)   | WATER + SEDIMENTS (m3) = BF*(WATER) | SEDIMENTS (m3) | FLOW (m3)   | WATER (m3)   | WATER + SEDIMENTS (m3) = BF*(WATER) | SEDIMENTS (m3) |
| INFLOW (m3)   | 2,995,428.69 | 4,974,400.16                        | 1,978,971.47   | INFLOW (m3)   | 3,148,750.51 | 5,229,052.49                        | 2,080,301.98   |
| STORAGE FLOW WITHIN THE ANALYSIS AREA OR CHANNEL (m3)   | 407,721.40   | 677,088.20                          | 269,366.79     | STORAGE FLOW WITHIN THE ANALYSIS AREA OR CHANNEL (m3)                                 | 406,060.49   | 674,334.66                          | 268,274.17     |
| OUTFLOW OUTSIDE THE ANALYSIS AREA OR DEPOSITION ZONE (m3)                                     | 2,587,707.29 | 4,297,311.96                        | 1,709,604.68   | OUTFLOW OUTSIDE THE ANALYSIS AREA OR DEPOSITION ZONE (m3)                             | 2,742,690.02 | 4,554,717.83                        | 1,812,027.80   |
| CV =  |              |                                     | 0.4            | CV =  |              |                                     | 0.4            |
| BF =  |              |                                     | 1.66           | BF =  |              |                                     | 1.66           |
| DEBRIS FLOW VOLUMES TRIGGERED BY THE 18-DAY MINIMUM ARI THRESHOLD OF THE ROSAYOC/BATÁN STREAM |              |                                     |                |   |              |                                     |                |
| AMCH (PREVIOUS MOISTURE: WET CONDITION)<br>DEBRIS FLOW - ARI 18D - TR = 10 YEARS (m3)         |              |                                     |                | AMCH (PREVIOUS MOISTURE: WET CONDITION)<br>DEBRIS FLOW - ARI 18D - TR = 15 YEARS (m3) |              |                                     |                |
| FLOW (m3)   | WATER (m3)   | WATER + SEDIMENTS (m3) = BF*(WATER) | SEDIMENTS (m3) | FLOW (m3)   | WATER (m3)   | WATER + SEDIMENTS (m3) = BF*(WATER) | SEDIMENTS (m3) |
| INFLOW (m3)   | 3,951,105.99 | 6,561,583.88                        | 2,610,477.89   | INFLOW (m3)   | 4,441,647.13 | 7,376,148.96                        | 2,934,501.84   |
| STORAGE FLOW WITHIN THE ANALYSIS AREA OR CHANNEL (m3)   | 398,293.09   | 661,443.53                          | 263,150.44     | STORAGE FLOW WITHIN THE ANALYSIS AREA OR CHANNEL (m3)                                 | 398,018.40   | 660,980.70                          | 262,962.30     |
| OUTFLOW OUTSIDE THE ANALYSIS AREA OR DEPOSITION ZONE (m3)                                     | 3,552,812.90 | 5,900,140.35                        | 2,347,327.45   | OUTFLOW OUTSIDE THE ANALYSIS AREA OR DEPOSITION ZONE (m3)                             | 4,043,628.72 | 6,715,168.26                        | 2,671,539.54   |
| CV =  |              |                                     | 0.4            | CV =  |              |                                     | 0.4            |
| BF =  |              |                                     | 1.66           | BF =  |              |                                     | 1.66           |
| DEBRIS FLOW VOLUMES TRIGGERED BY THE 5-DAY MINIMUM AR2 THRESHOLD OF THE ROSAYOC/BATÁN STREAM  |              |                                     |                |   |              |                                     |                |
| AMCH (PREVIOUS MOISTURE: WET CONDITION)<br>DEBRIS FLOW - AR2 5D - TR = 25 YEARS               |              |                                     |                | AMCH (PREVIOUS MOISTURE: WET CONDITION)<br>DEBRIS FLOW - AR2 5D - TR = 50 YEARS       |              |                                     |                |
| FLOW (m3)   | WATER (m3)   | WATER + SEDIMENTS (m3) = BF*(WATER) | SEDIMENTS (m3) | FLOW (m3)   | WATER (m3)   | WATER + SEDIMENTS (m3) = BF*(WATER) | SEDIMENTS (m3) |
| INFLOW (m3)   | 3,146,184.08 | 5,224,806.05                        | 2,078,621.97   | INFLOW (m3)   | 3,626,638.65 | 6,022,714.75                        | 2,396,076.10   |
| STORAGE FLOW WITHIN THE ANALYSIS AREA OR CHANNEL (m3)   | 404,715.22   | 672,102.61                          | 267,387.39     | STORAGE FLOW WITHIN THE ANALYSIS AREA OR CHANNEL (m3)                                 | 401,123.96   | 666,141.69                          | 265,017.73     |
| OUTFLOW OUTSIDE THE ANALYSIS AREA OR DEPOSITION ZONE (m3)                                     | 2,741,468.86 | 4,552,703.43                        | 1,811,234.58   | OUTFLOW OUTSIDE THE ANALYSIS AREA OR DEPOSITION ZONE (m3)                             | 3,225,514.69 | 5,356,573.06                        | 2,131,058.38   |
| CV =  |              |                                     | 0.4            | CV =  |              |                                     | 0.4            |
| BF =  |              |                                     | 1.66           | BF =  |              |                                     | 1.66           |
| DEBRIS FLOW VOLUMES TRIGGERED BY THE 7-DAY MINIMUM LA2 THRESHOLD OF THE ROSAYOC/BATÁN STREAM  |              |                                     |                |   |              |                                     |                |
| AMCH (PREVIOUS MOISTURE: WET CONDITION)<br>DEBRIS FLOW - AR2 7D - TR = 20 YEARS               |              |                                     |                | AMCH (PREVIOUS MOISTURE: WET CONDITION)<br>DEBRIS FLOW - AR2 7D - TR = 25 YEARS       |              |                                     |                |

| FLOW (m3)   | WATER (m3) | WATER + SEDIMENTS (m3) = BF*(WATER) | SEDIMENTS (m3) | FLOW (m3)   | WATER (m3) | WATER + SEDIMENTS (m3) = BF*(WATER) | SEDIMENTS (m3) |
|---|------------|-------------------------------------|----------------|---|------------|-------------------------------------|----------------|
| INFLOW (m3)   | 181,032.15 | 300,627.09                          | 119,594.94     | INFLOW (m3)   | 193,629.29 | 321,532.79                          | 127,903.49     |
| STORAGE FLOW WITHIN THE ANALYSIS AREA OR CHANNEL (m3)     | 181,032.15 | 300,627.09                          | 119,594.94     | STORAGE FLOW WITHIN THE ANALYSIS AREA OR CHANNEL (m3)     | 193,607.33 | 321,496.32                          | 127,888.99     |
| OUTFLOW OUTSIDE THE ANALYSIS AREA OR DEPOSITION ZONE (m3) | 0          | 0                                   | 0              | OUTFLOW OUTSIDE THE ANALYSIS AREA OR DEPOSITION ZONE (m3) | 21.96      | 36.47                               | 14.51          |
| CV =  |            |                                     | 0.4            | CV =  |            |                                     | 0.4            |
| BF =  |            |                                     | 1.66           | BF =  |            |                                     | 1.66           |

**Figure 1**

*Hazard map based on the maximum depth and velocity of debris flow using the 18-day minimum threshold (LA1) under wet conditions (AMCIII) for a return period (TR) of 10 years.*



**5. CONCLUSIONS**

After extensive testing and analysis, we were able to determine the thresholds' True Skill Statistic (TSS). As a consequence of testing the model's prognostic capabilities, we came at the following conclusions: The prediction rate for the 18-day AR1 threshold is higher than the 5-day threshold (49% vs. 48%), and the uncertainty for that threshold is lower, at about 10%. The 7-day AR2 threshold had the greatest prediction rate (62%) while the 5-day, 6-day, and 10-day AR2 thresholds all had uncertainties below 10%.

Uncertainties are less than or near to 10% for the AAR2 3-day, 4-day, 5-day, 8-day, and 12-day thresholds, with the 3-day AAR2 threshold having the greatest prediction percentage (41%), while being unlikely to cause runoff. To be clear, the projection rate for the 12-day AAR threshold is 6%, but the uncertainty is just 0.5%, and it is quite likely to cause substantial runoff.

Additionally, through the analysis and evaluation of hazard levels for debris flow movements using the Analytic Hierarchy Process (CENEPRED 2014), it was established that in the lower part, there are very high levels (red color) and high levels (orange color); in the middle part, high levels (orange color) and medium levels (yellow color) were found; and in the upper part, a high level of hazard (orange color) was identified. Furthermore, these levels have the greatest predominance of area in each part of the ravine.

On the other hand, hazard maps were also created for debris flow movements triggered by the maximum 24-hour rainfall and the critical accumulated rainfall threshold (LA1) for 18 days, based on the maximum depths and velocities generated by the debris flow in the computational simulation using the FLO-2D program. This model presented three levels, namely low, medium and high, with the predominant hazard levels being medium (orange) and high (red) along the channel paths.

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### CONFLICT OF INTERESTS

The author declares that there are no conflicts of interest.

### AUTHORSHIP CONTRIBUTION

In accordance with the internationally established taxonomy for the assignment of credits to authors of scientific articles (<https://credit.niso.org/>). The authors declare their contributions in the following matrix:

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| <b>PARTICIPAR ACTIVAMENTE EN:</b>                      |             |
| CONCEPTUALIZACIÓN                                      | X           |
| ANÁLISIS FORMAL  | X           |
| ADQUISICIÓN DE FONDOS                                  | X           |
| INVESTIGACIÓN  | X           |
| METODOLOGÍA  | X           |
| ADMINISTRACIÓN DEL PROYECTO                            | X           |
| RECURSOS   | X           |
| REDACCIÓN –BORRADOR ORIGINAL                           | X           |
| REDACCIÓN –REVISIÓN Y EDICIÓN                          | X           |
| LA DISCUSIÓN DE LOS RESULTADOS                         | X           |
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