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Design and validation of an early warning system for debris flows in Colombia

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ABSTRACT: In 2017, the city of Mocoa in Colombia suffered partial destruction due to a series of mass movements that evolved into debris flows, triggered by four days of intense rainfall. These events were localised in an active zone marked by a thrust fault between highly fractured monzogranite and alluvial deposits. The flows, mobilised by increased velocities caused by abrupt changes in V-shaped valleys, resulted in significant scouring of the riverbed. The transported mixture of soil, boulders, and water led to debris flows, hyper-concentrated flows, and mudflows along the two main rivers crossing Mocoa. The debris flow was the primary cause of casualties and damage, and it was not accounted for in the pre-event local hazard map. In response, an early warning system was developed to prevent further catastrophic loss of life. This article presents the modelling strategy used to determine thresholds associated with debris flows in Mocoa, Putumayo, Colombia. Thresholds were proposed based on precipitation, water level elevation, and flow rate. Results were obtained through physics-based debris flow modelling and assessing damage to homes near the riverbed. Rainfall-landslide thresholds were also determined using a probabilistic analysis of reported curves and a comparison with two previous events in Mocoa. The early warning system was successfully validated after the occurrence of another debris flow. Details of the performance of the system regarding the effectiveness of the different proposed thresholds are discussed.

KEYWORDS: Debris flows, Rainfall thresholds, Early warning system, TRIGRS, R.AVAFLOW.

1 INTRODUCTION

Mocoa, the capital of Putumayo Department in southwestern Colombia, lies at elevations between 1,100 and 2,500 m above sea level, is located in the Andean-Amazonian piedmont of Colombia (Figure 1) and has an urban population of roughly 35,000 (DANE, 2016). Its economy is primarily based on agriculture and commerce, with additional growth driven by oil-related exploration and exploitation.

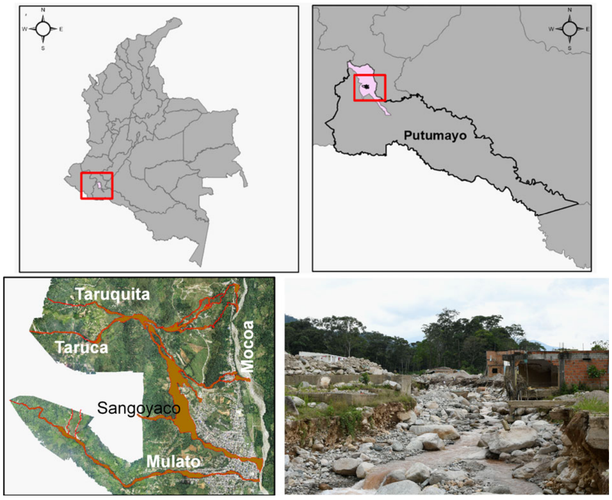

Figure 1. Location of Mocoa, main rivers draining the basin and damages inflicted by the debris flow on the northern part of Mocoa.

On March 31, 2017, four days of intense rainfall triggered widespread mass movements in the Mocoa Basin, devastating the western sector of the city. Landslides in the Taruquita, Taruca, and Mulato catchments transformed into debris flows, hyperconcentrated flows, and mudflows, with the debris flow along Taruca Creek causing most casualties and damage. The disaster resulted in 332 fatalities, 398 injuries, 77 missing persons, and over 7,700 affected families (Pontificia Universidad Javeriana, 2018). Infrastructure losses included 11 km of roads, 1,462 homes, and the complete collapse of water and power systems. Field evidence showed transport of boulders up to 5 m in diameter, extensive scouring, and deposition on alluvial fans shaped by previous debris flow events (Prada-Sarmiento et al., 2019).

The event revealed critical gaps in local hazard preparedness, particularly the absence of any early warning mechanism for debris flows. In response, a multidisciplinary effort led to the design and implementation of an Early Warning System (EWS) aimed at predicting and preventing similar future disasters. This paper presents the modelling strategy, threshold development, and validation of this EWS.

2 GEOGRAPHICAL AND GEOLOGICAL CONTEXT

Mocoa is situated in a region characterised by steep slopes, high rainfall (mean annual precipitation between 3500 and 4500 mm), tropical humid conditions, high temperatures and complex geological structures, including the Mocoa-La Tebaida thrust fault that favour the physical and chemical weathering of igneous and metamorphic rocks. This fault marks the boundary between highly fractured monzogranite and unconsolidated alluvial deposits (Pontificia Universidad Javeriana, 2018). The area exhibits sharp transitions in valley morphology from steep V-shaped upper basins with slopes between 50° and 75°, to flatter depositional zones mainly composed of alluvial fans, which facilitate rapid flow acceleration and scouring.

Mocoa is drained upstream by a series of creeks and rivers that run in a west-east direction as shown in Figure 1. Taruquita Creek merges with Taruca Creek northwest of Mocoa's outskirts. Downstream of this confluence, the presence of large igneous boulders indicates high-energy transport potential along that reach. Here, an abrupt change in channel slope has formed alluvial terraces, many shaped by past debris and mudflow events larger than those of 2017. Taruca Creek continues through the city's northwestern sector before joining the Sangoyaco River. The creek demonstrated considerable hydraulic power, capable of transporting boulders up to 5 m in diameter despite its longitudinal slope decreasing to less than 8%. Further downstream, debris flow deposition impacted a substantial portion of the municipality (Prada-Sarmiento et al., 2019).

These geological and geomorphological conditions render Mocoa highly susceptible to debris flows, particularly during high-intensity rainfalls.

3 THE 2017 DEBRIS FLOW EVENT

The 2017 disaster was initiated by 214.8 mm of rainfall accumulated over four days, with especially intense precipitation on the night of March 31 (Prada-Sarmiento et al., 2019). Figure 2 illustrates the daily and cumulative rainfall during the year preceding the 2017 event. Rainfall data from March 1 to March 31, 2017, indicate that 408 mm of precipitation fell during the first 16 days of the month. Rainfall intensity was particularly high on the day before and the day after the disaster. Notably, the day prior to the event recorded nearly 130 mm of precipitation, 10.3 times the annual daily average and 7.5 times the average for the April–June rainy season.

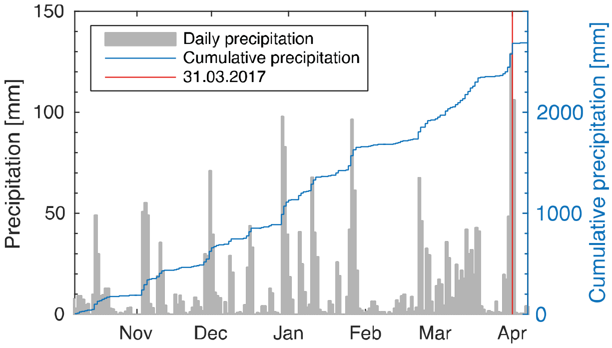

Figure 2. Daily and cumulative rainfall in the Mocoa drainage basin during the last year before the 2017 event (Prada-Sarmiento et al., 2019).

When groundwater levels are near the surface, intense rainfall can trigger landslides within the steep V-shaped valleys. Depending on the volume of displaced material, these mass movements may either block the creeks or merge with the water, transforming the flow into a dense, viscous mixture. The excessive rainfall triggered 629 mass movements as reported in the inventory collected by the Colombian Geological Service (Ruiz et al., 2017). Those mass movements were primarily shallow translational landslides, which deposited large volumes of debris into the Taruca and Taruquita creeks. These materials rapidly transformed into debris and hyperconcentrated flows as they descended toward the urban centre.

Both rainfall intensity and the volume of effective runoff influence the hydraulic capacity of streams within the Taruca and Sangoyaco watersheds. During extreme precipitation events, large discharges generate high flow velocities, enabling the water to erode alluvial banks (documented by riverbed level changes of 4 to 7 meters) and entrain boulders embedded in the granular matrix (Prada-Sarmiento et al., 2019). This resulting mixture of water, mud, and coarse debris is swiftly transported downstream, inflicting severe damage along its path, as observed during the event (Prieto et al., 2020).

Ruiz et al. (2017) estimated that mass movements generated approximately 190,000 m^3 of solid material in the Taruca Basin, 34,000 m^3 in the Mulato Basin, and 77,000 m^3 in the Sangoyaco Basin. These materials were incorporated into the flow as suspended and bedload sediments. Across the entire watershed, the volume of transported and deposited solids was estimated at 2.25×10^6 m^3, more than seven times the amount produced by the initial mass movements in the upper basin. Most failures were flow-type movements, occurring over a broad slope range from 4° to 48°, while landslide-type failures were concentrated on gentler slopes. The 2017 event was dominated by very small landslides (about 57% ranging from 500 to 5,000 m^3) primarily occurring on slopes between 30° and 32° (Prada-Sarmiento et al., 2019). The spatial distribution and volume of landslides were successfully modelled using the USGS TRIGRS software, achieving a 7% error margin when compared to the official landslide inventory.

4 METHODOLOGY FOR EWS DESIGN

The EWS was built upon an integrated conceptual model that simulates hydrological, geotechnical, and hydraulic processes (Munévar et al., 2020; Ramos-Cañón et al., 2023). Hydrological modelling was conducted using GR4J, HBV, and Sacramento models, optimised through DDS and SCE algorithms (Pontificia Universidad Javeriana, 2018). Geotechnical stability was assessed using TRIGRS, which calculates transient pore pressures and Factors of Safety (FoS) based on rainfall infiltration. Flow dynamics were simulated with tools such as FLO2D, RAMMS, and OpenTelemac, enabling prediction of flood extent and debris flow behavior in the urban area.

The multi-tool modelling approach used to develop the EWS for Mocoa was employed to replicate the 2017 event and simulate other potential scenarios using historical rainfall records. The process began with modelling rainfall-induced landslides, considering the influence of topography, geology, and initial soil saturation. A suitable tool for this task accounts for the spatial and temporal variability of rainfall, soil type distribution, and initial pore-water pressure conditions, producing raster outputs that depict the temporal evolution of the FoS. These raster layers, identifying cells at failure and indicating the depth of the slip surface (assuming an infinite slope failure mechanism) at specific time steps, are then integrated into an advanced 3D hydrodynamic model. The hydraulic component converts raster cells with critical stability conditions into a viscous runoff containing both water and sediment, factoring in the rainfall volume for each time interval. Routing of this mixed flow along slopes and through the main river channels is enhanced by incorporating scouring equations, thereby simulating the progressive entrainment of additional material. The hydrodynamic model ultimately generates flood maps that display water depth, velocity, and hydraulic pressure distributions. These outputs are essential for evaluating the hazard posed by debris and hyperconcentrated flows (Prieto et al., 2020).

4.1 *Spatial slope stability*

According to Ruiz et al. (2017), the predominant slope failure mechanism in the Taruca Basin is shallow translational landslides, typically occurring in weathered soil profiles near the transitional topographic and geomorphologic zone influenced by the active Mocoa-La Tebaida thrust fault.

The TRIGRS model (Transient Rainfall Infiltration and Grid-Based Regional Slope Stability), developed by the USGS, was selected as the numerical modelling tool for its ability to physically represent the problem and meet the requirements outlined in the conceptual model. TRIGRS is a Fortran-based tool developed to simulate the timing and spatial distribution of shallow, rainfall-induced landslides. Key features include:

- Calculation of transient pore-pressure and factor of safety changes due to 1D rainfall infiltration.
- Analytical modelling of vertical flow in isotropic, homogeneous materials under saturated or unsaturated conditions.
- Step-function series for variable rainfall input.
- A runoff routing module that redirects excess water from impervious to permeable downslope areas.

- Cell-by-cell factor of safety computation using an infinite-slope model.
- An approximate formula for effective stress in unsaturated soils.
- Support for horizontal heterogeneity via spatially variable input parameters.
- Integration with GIS software for input preparation and result visualisation.

The model requires as input parameters raster files with precipitation intensity, slope inclination, soil depth, initial water-table depth, saturated vertical hydraulic conductivity, hydraulic diffusivity, a three-parameter soil-water characteristic curve, cohesion and internal friction angle (for effective stress), and total soil unit weight. TRIGRS calculates transient pore-pressure changes and factor of safety values for each rainfall time step. Results are provided as ASCII grid files compatible with GIS platforms, along with detailed listings of pore pressure and factor of safety at various depths for each grid cell.

To implement the spatial slope stability model, a geotechnical zonation was established by grouping geomaterials with similar geological, geomorphological, land cover, and soil characteristics. Based on these layers and further interpretation by the authors, complemented by the landslide inventory from Ruiz et al. (2017), 16 geotechnical zones were delineated within the study area (Figure 3).

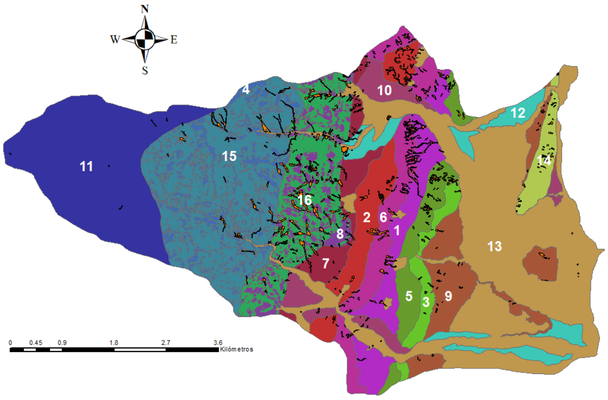

Figure 3. Geotechnical zonation proposed for TRIGRS model and landslide inventory (orange polygons) published by Ruiz et al., (2017).

Model parameters for each zone were assigned using data from previous studies (Ruiz et al., 2017; IGAC, 2014), standard values from technical literature, and expert judgment following a post-event field survey. Initial water table conditions were estimated using rainfall data from the days preceding the event and simulations in HYDRUS 1D. Topographic input was derived from a 5 m Digital Elevation Model (DEM) uploaded to TRIGRS.

The geological, geomorphological, and land cover layers used were originally developed by Ruiz et al., (2017) for landslide hazard zonation at a 1:25,000 scale and were incorporated into this study.

For the simulation of the Mocoa event on March 31, 2017, four days of antecedent rainfall were analyzed using historical 10-minute interval data. This period was found to be statistically representative of the rainfall conditions that triggered the debris flow. Rainfall input was structured in 6-hour intervals over four days, resulting in 16 simulation steps from March 28 at 01:00 to April 1 at 01:00. Each step produced slope stability results represented by the Factor of Safety (FoS) across grid cells, where FoS ≤ 1 indicates slope failure.

The estimated landslide volume at each time step was calculated by multiplying the area of failed pixels (FoS ≤ 1) by the corresponding depth of failure within the soil colum, calculated from TRIGRS outputs.

Figure 4 shows the spatial distribution of FoS at the time of maximum landslide volume, where red polygons (FoS ≤ 1) indicate areas of failure triggered by accumulated rainfall. The simulation results closely match the landslide inventory compiled by Ruiz et al. (2017), with a similar spatial distribution of failures. The most affected area (Zone 16) corresponds to highly weathered and fractured monzogranite, influenced by the Mocoa-La Tebaida fault, which contributes to its high susceptibility to landslides.

The landslide inventory estimates a slide volume of approximately 690,000 m^3, while the TRIGRS simulation produced a volume of 738,095 m^3, yielding a relative error of about 7%. This confirms TRIGRS's capability to simulate shallow, rainfall-induced landslides consistently.

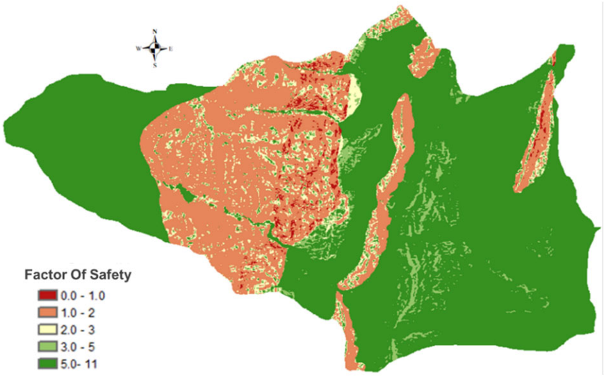

Figure 4. Spatial distribution of factors of safety obtained with TRIGRS in the Mocoa basin in the penultimate simulation increment corresponding to March 31st at 19:00.

4.2 *Fluid dynamic hydraulic model*

The simulation of the March 31, 2017 debris flow event in Mocoa integrated both hydrological and geotechnical components, enabling the estimation of rainfall intensity, discharge, and mobilised volume during the event. Flow dynamic modelling was conducted using four different shallow-water theory hydraulic programs, namely FLO2D (finite differences), R.AVAFLOW (finite differences), RAMMS (finite differences), and OPEN TELEMAC (finite volume/element).

To assess the quality of the simulations, the modelled flow depths were compared with field measurements reported by the Colombian Geological Service (SGC). This comparison helped evaluate how well each computational platform replicated the actual debris flow event. The analysis revealed that only models capable of simulating material entrainment could approximate the deposited volume estimated by SGC. The simulations also identified areas with unrealistically high mass accumulation, inconsistent with observed conditions. As a result, modifications to the Digital Elevation Model (DEM) were necessary to improve the representation of debris flow dynamics and to correct elevation errors in the original dataset. Each fluid dynamic modelling platform was evaluated in terms of its strengths and limitations, including computational efficiency, ability to reproduce physical processes, and the interaction between solid and liquid phases. Based on this analysis, the R.AVAFLOW model was identified as the most suitable for representing this type of event.

Following the simulation of the March 31, 2017 debris flow event, 19 geotechnically-based rainfall scenarios were developed. These scenarios span a four-day period, with the first nine featuring rainfall equal to or greater than that of the actual event (producing solid volumes between 290,000-2'200,00 m^3), and the remaining ten (scenarios 10-19) featuring rainfall equal to or less than the observed event (producing solid volumes between 150,000-1'100,00 m^3).

To estimate the volume and temporal distribution of sediments produced from the failure of slopes for each scenario, preliminary simulations were conducted using two models: TRIGRS, to assess slope stability in response to rainfall infiltration, and R.AVAFLOW, to simulate the fluid dynamic routing downstream of sediment material originated from the slope failures, incorporating hydraulic and scouring processes along the river reaches. Those combined simulations using TRIGRS and R.AVAFLOW also enabled the estimation of clear water hydrographs and solid volumes. Scenario 1 resulted in the highest mobilisation of both water and sediment, with peak liquid discharges exceeding 110,000 m^3/s and peak solid volumes reaching 50,000 m^3. The outputs from these simulations were used to construct solid and liquid hydrographs, which served as input for FLO-2D, RAMMS, and Open TELEMAC.

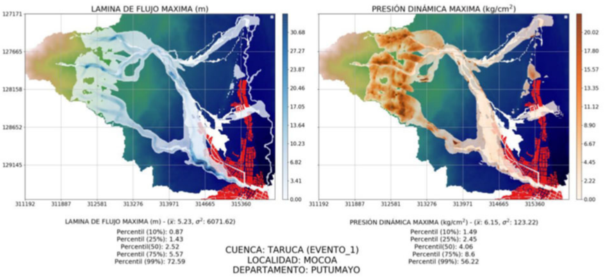

Figure 5. Maximum flow depth (left) and dynamic pressure (right) obtained from simulation of scenario 1 with R.AVAFLOW for the Taruca basin

Once the solid and liquid hydrographs were established, they were used as input for the FLO-2D, RAMMS, and Open TELEMAC models to simulate the 19 proposed scenarios. Each model produced results for fluid depth, flow velocity, and dynamic pressure across the study area.

Notably, Open TELEMAC was used to perform a detailed simulation of Mocoa's urban area. This included the integration of city infrastructure, allowing for a more realistic assessment of flow behaviour upon entering the city centre. This level of detail was made possible by the software's ability to handle unstructured meshes.

Critical cross-sections along each river channel were identified based on the lowest-elevation buildings located nearest to the watercourse. These areas were confirmed through detailed field topography surveys and simulation results, specifically for the Taruca, Sangoyaco, and Mulato rivers. For each critical section, a topographic profile was generated, indicating the elevation of nearby buildings relative to the channel bed.

Based on the fluid dynamic simulations and the selected critical sections, Q-H curves (discharge-elevation relationships) were generated for each critical location and for the level sensor sites previously installed by the Colombian Government. These curves were used to define flow level thresholds for issuing flood warnings and alerts.

Finally, flow-level thresholds corresponding to specific water depths and discharge rates were calculated for each sensor installed within the basin. Each threshold was linked to its respective calibration curve to support the EWS implementation.

4.3 *Threshold determination*

A set of four primary thresholds was established to trigger alerts in the EWS based on 11 water-level sensors and rain gauges distributed across diverse locations in the catchment. Rainfall thresholds were developed using Flash Flood Guidance and rainfall-runoff models, calibrated for various soil moisture conditions. These thresholds indicate when rainfall exceeds the soil's infiltration and storage capacity (Munévar et al., 2020). The maximum stream discharge under each condition (dry, medium, fully saturated soil) was used to calibrate the GR4J rainfall-runoff model. Runoff-rainfall curves were developed for critical channel sections across various volumetric concentrations using the calibrated model. Rainfall thresholds were then determined by analysing the inverse rainfall-runoff relationship, identifying the point at which stream discharge exceeds the hydraulic capacity of critical sections. Thresholds corresponding to different warning levels (yellow, orange, and red) are presented in Figure 6.

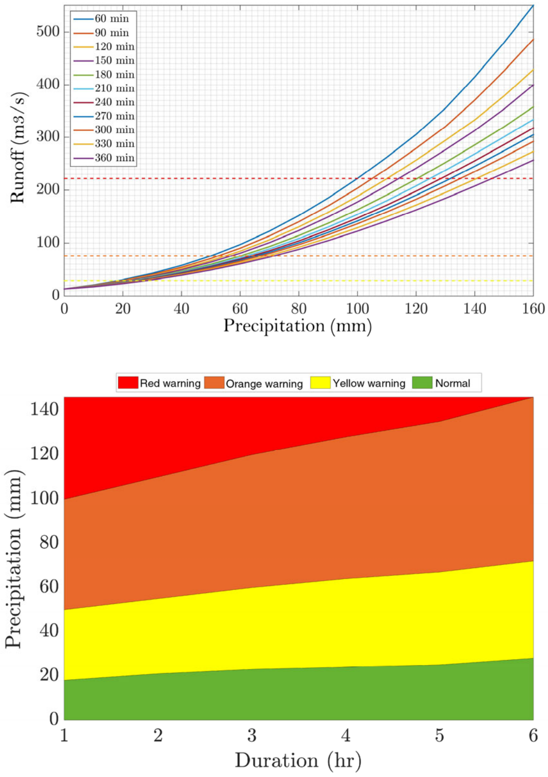

Figure 6. Runoff vs rainfall for saturated antecedent condition (top), defined rainfall thresholds (bottom)

Flow level thresholds were defined as the water depths that exceed stream capacity at the critical sections. These thresholds enable the issuance of flood warnings. Eleven monitoring sections were identified based on debris-flow modelling results, focusing on urban areas near the stream that are most vulnerable to flooding. Using the debris-flow simulation outputs, rating curves were developed for each section, allowing identification of the flow levels and corresponding discharges at which each section is overtopped. The level thresholds for critical section No. 3 are illustrated in Figure 7.

Rainfall intensity–duration thresholds were derived from approximately 87 intensity–duration curves compiled by Ramos et al. (2014) and based on landslide-triggering conditions reported in the literature. These curves were compared with the characteristic intensity–duration profiles of two rainfall events in Mocoa: one on March 31 and another on August 31, 2017. The March 31 event curve aligned with several literature-based thresholds across different durations. Using this data, the probability of landslide occurrence was estimated as the likelihood of exceeding the event's characteristic curve. Figure 8 shows that the March 31 curve falls within the 70% to 100% probability range for landslide occurrence, supporting the definition of intensity–duration thresholds. These thresholds, categorised by warning levels (yellow, orange, and red), are presented in Figure 9 for the Sangoyaco River watershed.

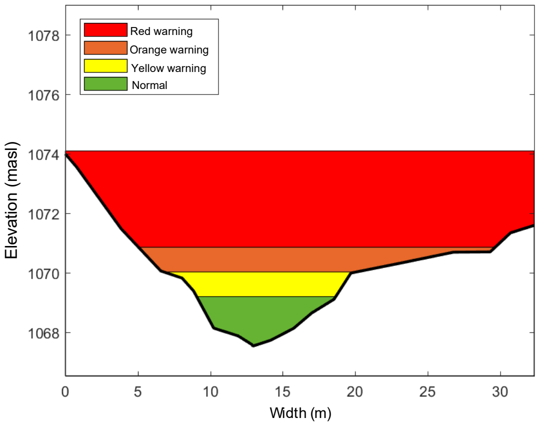

Figure 7. Runoff vs rainfall for saturated antecedent condition (top), defined rainfall thresholds (bottom)

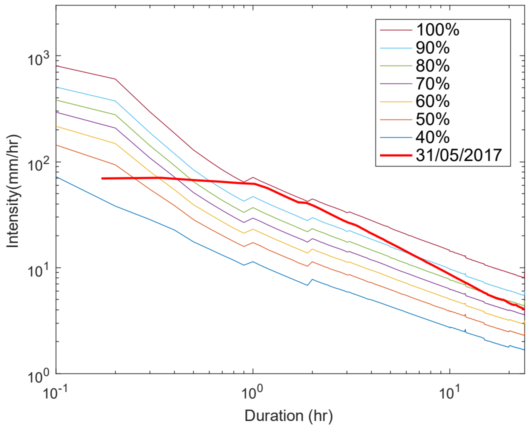

Figure 8. Landslide occurrence probability for intensity-duration of rainfall

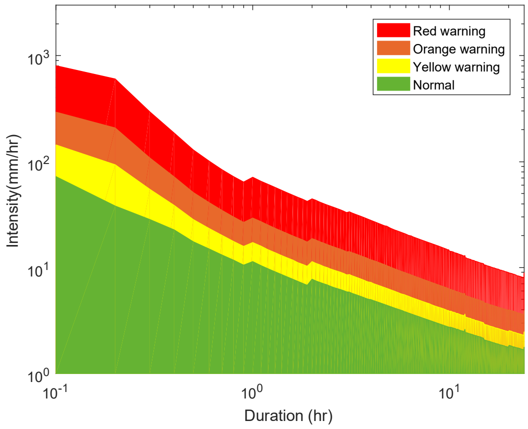

Figure 9. Intensity-duration thresholds, Sangoyaco River.

During the four days of antecedent rainfall leading up to the March 31 event, the probability of exceeding the observed rainfall accumulation was nearly zero, indicating that this event represented an extreme condition for the region. Consequently, the accumulated rainfall over this period was adopted as a threshold for landslide generation.

Based on this threshold, warning levels were defined to support early detection and response. Figure 10 presents the rainfall accumulation thresholds and their corresponding warning levels for landslide occurrence in the study area. This threshold helps identify conditions where slope saturation poses a high risk of mass movement.

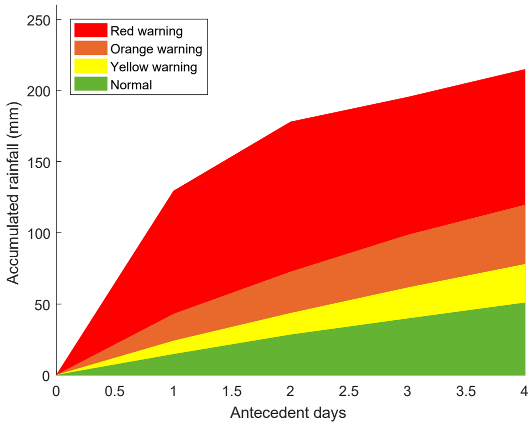

Figure 10. Antecedent rainfall thresholds.

The intensity-duration characteristic curves of the March 31 and August 31, 2017 events were compared with a set of curves reported in the literature, allowing the conclusion that both events (particularly the March 31 event, which triggered 276 landslides) exhibited rainfall magnitudes significantly higher than those typically observed in the region.

A filtering process was applied to the literature-based intensity–duration thresholds, selecting five curves corresponding to watersheds with climatic and geomorphologic conditions similar to those of Mocoa. The March 31 event curve aligned closely with the upper range of these filtered thresholds, showing a similar slope from the 1-hour duration mark onward. In contrast, the August 31 event curve was closer to the lower threshold, with a noticeable increase in slope after 4 hours. These differences may reflect the distinct flow types-debris flow versus mudflow-associated with each event.

Using the March 31 event as a reference, the probability of landslide occurrence was found to be near 1 for rainfall intensities of 50-60 mm/h over durations of 1-2 hours. This probability decreases with longer durations and lower intensities. Conversely, for the August 31 event, the highest probability of landslide occurrence was associated with durations of 4–6 hours and intensities around 10 mm/h.

Antecedent rainfall was identified as a key triggering factor for landslides in the Mocoa watershed. The events analysed were strongly correlated with rainfall accumulated over the four days preceding each event, as confirmed by the calculated landslide occurrence probabilities.

5 VALIDATION OF THE EARLY WARNING SYSTEM

The EWS was tested during a subsequent debris flow on August 12, 2018. Despite similar rainfall conditions (120 mm on the day of the new event), no casualties were reported, and over 20,000 residents were evacuated promptly and safely thanks to the EWS-triggered alarms (Ramos-Cañón et al., 2023).

Figure 11 shows the evolution of the accumulated precipitation thresholds for the basin, along with the rainfall recorded during the night of August 12, 2018, at the San Antonio, Campucana, Cristalina, and Palmeras rain gauge stations. Notably, only the San Antonio station reached the red alert level at 04:08:42 AM (GMT-5), approximately 24 minutes after the debris flow entered the urban area of Mocoa. The other three stations did not reach the critical red warning condition.

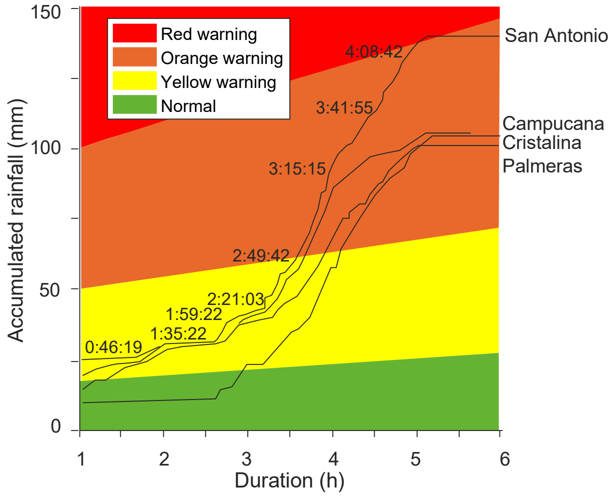

Figure 11. Time evolution of accumulated rainfall thresholds on August 12, 2018 for the monitoring sections San Antonio, Campucana, Cristalina, and Palmeras.

The timeline of the August 12, 2018, event was reconstructed using data from level sensors installed at critical monitoring points for the Early Warning System (EWS). Considering the arrival of the debris flow to Mocoa's urban area at 03:44:00 AM, the following observations were made:

- For the variable of four-day accumulated rainfall, the red alert threshold was reached 74 minutes prior to the event.
- For the intensity-duration variable, which indicates rainfall capable of triggering mass movements, the red alert was reached 37 minutes earlier at the San Antonio station and 68 minutes earlier at the other stations.
- For the discharge-level variable, the red alert threshold at the confluence of the Taruca and Taruquita streams was reached 9 minutes before the event.
- For the rainfall-runoff variable, the red alert was reached 24 minutes after the event began. Notably, this was the only variable that did not reach the red alert threshold in advance.

Rainfall-runoff models commonly used in early warning systems assume clear water flow, which does not accurately represent debris or hyperconcentrated flows. In such events, the solid material load poses the greatest threat to human life. Therefore, rainfall-runoff models alone are insufficient for designing effective early warning systems for debris flows.

The varying lead times at which red alert thresholds were reached across different variables highlight the importance of accounting for uncertainty in system design. On one hand, the availability of data related to triggering factors (e.g., rainfall or seismic events) and subsequent physical processes (e.g., mass movements) is limited both spatially and temporally. On the other hand, numerical models capable of simulating debris flows are still under development and rely on simplifications that approximate reality, making it difficult to predict the spatial and temporal evolution of such events with precision. This validation underscored the importance of redundancy, using multiple, independent variables to improve system robustness.

6 CONCLUSIONS

The EWS designed for Mocoa represents a significant advancement in hazard management for debris flows in Colombia. Through the integration of physics-based modelling and empirical data, reliable thresholds were developed and successfully validated. Redundancy in alert variables improves warning accuracy and lead time. Intensity-Duration and antecedent rainfall thresholds are particularly effective predictors for the tropical Andean conditions of that Basin. Rainfall-runoff thresholds require adaptation for solid-laden flows. Continuous recalibration and community training are essential for sustained effectiveness.

The EWS demonstrated that combining different thresholds provides earlier and more reliable alerts. Nonetheless, results emphasised that rainfall-runoff models alone are insufficient for debris flows due to the high solid content and unique flow mechanics. Validation also stressed the need to recalibrate thresholds after significant morphological changes and maintain community engagement for effective response (Ramos-Cañón et al., 2023).

This approach offers a replicable framework for other regions in the tropical Andean-Amazonian piedmont in the northern part of South America.

7 ACKNOWLEDGEMENTS

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