Integrated Numerical Model to simulate the mass movements of the Mocoa event on March 31 (2017)

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Abstract

Mocoa, capital city of the department of Putumayo -Colombia-, was devastated the night of 31 March of 2017 after a series of landslides triggered a large debris flow along the Taruca, Taruquita creek basins. The emergency event was triggered by a 4-day rainfall accumulation and high rainfall intensities on the night of the event. These led to 629 mass movements, which transported solid material into the channel of the Taruquita and Taruca creeks and into Mulato and Sangoyaco river, deriving into debris flow and hyperconcentrated flows. Consequently, major damages were reported, including deaths, injuries, missing people, and the destruction of water and power supply system, roads and houses.

In order to analyze and simulate the Mocoa event, a numerical model which allows the slope stability evaluations considering pore water pressure changes due to infiltration of rainfall is necessary. The selected model –USGS TRIGRS (Transient Rainfall Infiltration and Grid-Based Regional Slope-Stability Model)- is a spatial model coupled with the infinity slope stability equilibrium method and subjected to the one-dimensional (vertical direction) infiltration of rain. This paper presents the application of TRIGRS focused to simulate the mass movements triggered on the night of 31 March in Mocoa.

After the extended review of information available and the studies previously done by the Colombian Geological Service (SGC), a geotechnical zonation in which geomaterials are grouped by similar geological, geomorphological, land cover and soil type classification, was done. These cover layers were complemented with the mass movements inventory reported by SGC, allowing to delimit 16 geotechnical zones. For each zone, shear strength and hydraulic parameters were assigned. Infiltration and slope stability analysis considered the temporal variation of rainfall of previous days to the event occurrence, recorded from two meteorological gauge stations.

TRIGRS model produced the spatial location and volume of landslides which matched very closely the landslide inventory done by the SGC. TRIGRS prove to be a useful tool to predict shallow landslides triggered by intense or cumulative rainfall and can serve to work with probabilistic rainfall scenarios to assess hazard levels in similar basins. Further recommendations due to limitations of the model are discussed.

1 INTRODUCTION

Four days of accumulated rainfall (214,8 mm) with high intensity precipitation triggered a series of mass movements on March 31, 2017 in the Mocoa Basin, in the Amazonian region of Colombia. These series of mass movements transported solid material into the channel of the Taruquita and Taruca creeks on the northern side of Mocoa and into the Mulato River on the southern side of the city (Figure 1). The transported mixture of solids with water and sediments derived in a debris flow along the Taruca Creek, transitioning to a hyperconcentrated flow along the Sangoyaco River, and a mudflow along the Mulato River. The debris flow in Taruca Creek produced most of the casualties and damages in the city. The event caused 332 deaths, 398 injuries, 77 people missing, and were 7794 families affected (Prada et al., 2019). More than 11 km of roads were destroyed, 1462 houses were damaged, and the city's water supply system and power station were completely devastated. A detailed description of the geology, geomorphology, hydrology and the sequence of events that took place during the event can be found in the works by Medina et al. (2017), Cheng et al. (2018), García-Delgado et al. (2019).

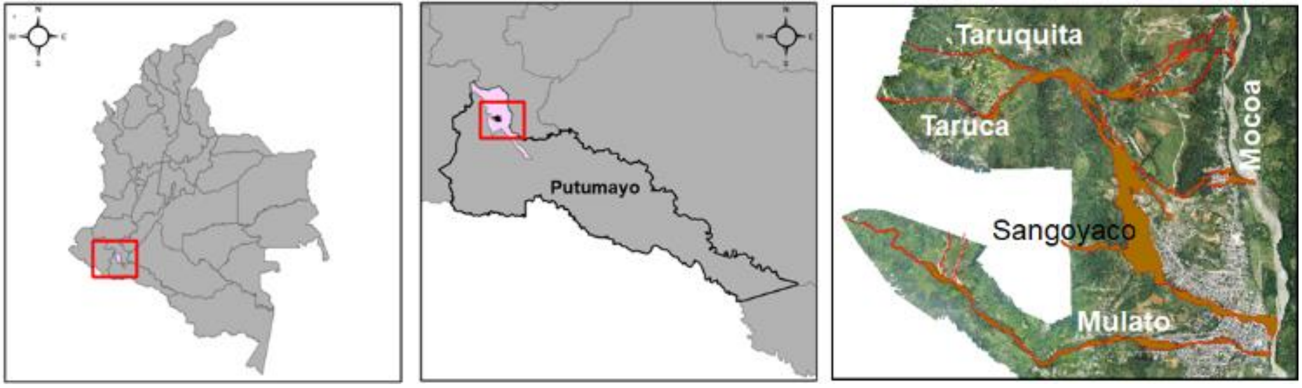

Figure 1. Location of Mocoa and description of natural river network.

The aim of this article is to present a spatial tool used to model the large number of shallow landslides observed in the Mocoa basin, prior to the occurrence of the devastating debris flow. This tool can be coupled with advanced 3D computational fluid dynamics codes to model the path, velocities, flow depths and pressures of the resulting debris / hyperconcentrated flow that were triggered by rainfall and landslides in Mocoa. The combination of different advanced spatial tools for the integrated modelling of these type of flows can prove extremely useful for urban planning and hazard zoning of cities that are located in the Andean-Amazonian piedmont of Colombia. This environment is particular, because the combination of intense rainfalls with abrupt changes of river slopes, tectonic faulting, extreme weathering of exposed rock outcrops produces the conditioning and triggering factors for the occurrence of debris and hyperconcentrated flows.

2 DESCRIPTION OF THE EVENT

During the 2017 event, the largest volume of debris was transported along the Taruca stream and deposited in the northwestern neighborhoods of Mocoa. Natural slopes with inclinations between 70° and 85° that define a V-shaped valley are typically observed in the Taruca and Taruquita sub-basins. In the upper part of those sub-basins, there are large granite blocks fallen from the high slopes on the creek margins. Downstream, there is an abrupt and sudden change of the main stream slope of the Taruca Creek and of the shape of the river valley in the area of Mocoa-La Tebaida thrust fault. In this area, outcrops of Monzogranite display evidence of physical weathering caused by the activity of the fault and chemical weathering induced by temperature, relative humidity and rainfall (mean annual rainfall between 3500 and 4500 mm) (Prada et. al, 2019). This is the zone where most of the landslides took place, previously to the event (Figure 2). Riverbanks in the topographic transition defined by the Mocoa-La Tebaida fault, between steep and flatter slopes, are matrix-supported, consisting of a mixture of materials ranging from sub-meter granite blocks to sand and silt sizes. Large blocks of granite are observed in the main stream of the creeks. These blocks have been transported from the upper part of the basin in previous events, and are mixed with finer size materials, forming large terrace deposits with thicknesses of close to 8 m (Prada et. al, 2019).

Figure 2. Natural slopes and landslides observed in the upper and middle part of Taruca creek basin.

Hydraulic capacity of the streams running along this watershed varies depending on the magnitude of rainfall and on the amount of effective runoff. Under extreme rainfall conditions, large water discharges attain higher velocities, so in a way that water can easily scour the alluvial banks (with measured changes of the level of the riverbed of between 4 and 7 m) and incorporate the blocks embedded in the granular matrix into the flow (Prada et. al, 2019). This mixture of water, mud and blocks is rapidly conveyed downstream causing huge damages along its way, as it happened in the event (Figure 3).

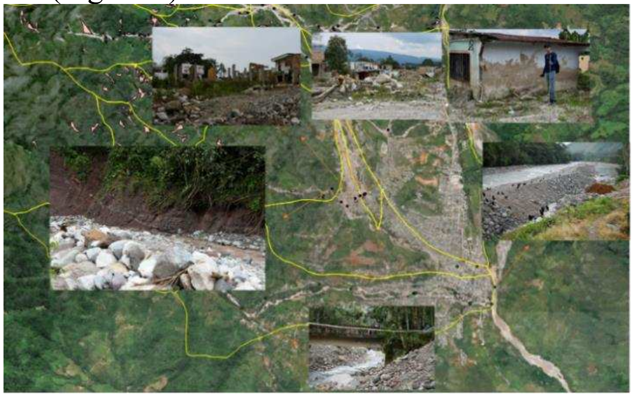

Figure 3. Evidence of destruction caused by the debris flow moving along Taruca creek valley, in Mocoa.

The hydraulic response of the Mocoa basin is strongly dependent on the amount of antecedent rainfall and saturation of the slopes in its upper part. Rainfall records between March 1 and March 31, 2017 show that during the first 16 days of the month, 408 mm of precipitation fell on the area. When the ground water level is close to the ground surface, intense rainfall events trigger landslides in the V-shaped valley. These landslides, depending on the amount of slid material, could dam the creeks or be incorporated into the flow, turning it into a viscous fluid. Colombian Geological Service produced an inventory of 629 mass movements registered in the event zone before and after the 2017 event (Medina et al. 2017). There were 420 mass movements linked to the event, of which ≈89% corresponds to flows, ≈10% corresponds to landslides, and ≈1% corresponds to rock falls (Prada et. al, 2019). Medina et al. (2017) estimated that mass movements produced 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 volumes were incorporated in the flow as suspended and transported solids and sediments. According to Medina et al. (2017), the estimated volume of transported and deposited material along the basin was 2.25×10^6 m^3 of solid material, which is more than 700% larger than the amount of material produced by the mass movements in the upper part of the basin. Great part of the mass movements was of flow-type, occurring predominantly over a wide range of slopes between 4° and 48°, while landslide-type movements occurred at gentler slopes. The 2017 event triggered mostly very small landslides (≈57% in a range of 500 to 5000 m^3), occurring predominantly at inclinations of between 30° and 32°. Most of the movements occurred on forested land (≈49%), then on grass and poorly covered land (≈20%), and finally on land with bush size vegetation (≈12%), with an uncertainty associated to approx. 19% of the movements without reported vegetation cover (Prada et. al, 2019).

Urban planning is supported by the estimation of hazard zones that may affect a town or city. As stated beforehand, towns located on the Andean-Amazonian piedmont of Colombia are prone to the occurrence of debris and hyperconcentrated flows. Therefore, adequate modelling tools are required to analyze these processes. In the specific case of Mocoa, a multiple tool approach was implemented to simulate the event of 2017 and other possible events based on historic rainfall records. One of the first steps in this approach is the modelling of landslides triggered by rain, conditioned by topography, geology and initial saturation of the soil profile. A tool that can take into account the spatial distribution of rainfall evolving with time, the spatial distribution of soil types and initial pore water conditions is desirable to produce raster files with the evolution of factor of safety with time. These raster files, with cells indicating the failure condition and the depth of the failure surface at a specific time, are fed to an advanced 3D hydrodynamic model. The hydraulic model transforms those cells with critical factors of safety into a runoff of water mixed with solids, taking into account the amount of rainfall in a specific time. Hydraulic routing of those mixed materials along the slopes and then along the main river channel can be complemented with scouring equations to produce a flow of water with solids. Flooding areas, with depths, velocities and hydraulic pressures can then be produced as final result of the hydrodynamic model. These maps are a fundamental input to assess hazard and risk produced by debris / hyperconcentrated flows.

3 NUMERICAL MODEL

A numerical and spatial model which allows to assess the slope stability analysis considering pore water pressure changes due to infiltration of rainfall and that is also capable of estimating the distribution in space-time and calculate volume of slides is desirable for the case of Mocoa. The landslides distribution is the result needed as an input for modeling the hydrodinamic routing of the flow (debris and hyperconcentrated flows) with robust 3D hydrodinamical computational codes.

As reported by SGC (2017), the most frequent failure mechanism observed in the basin corresponds to shallow translational landslides, triggered in weathered soil profiles near the transitional topographic and geomorphologic zone which is governed by the geological active thrust fault “Mocoa- La Tebaida”.

TRIGRS (Transient Rainfall Infiltration and Grid/Based Regional Slope Stability Model), a free open code developed by United States Geological Service (USGS), was the selected model due to its capability to represent the physical-nature of the problem and because satisfies the requirements described in the conceptual model

3.1 Features of the model

The Transient Rainfall Infiltration and Grid-Based Regional Slope-Stability Model (TRIGRS) is a Fortran program designed for modeling the timing and distribution of shallow, rainfall-induced landslides Below are presented the main features and advantages of the code (USGS, 2009):

- Computes transient pore-pressure changes, and attendant changes in the factor of safety, due to rainfall infiltration 1D.
- Models rainfall infiltration, resulting from storms that have durations ranging from hours to a few days, using analytical solutions for partial differential equations that represent one-dimensional, vertical flow in isotropic, homogeneous materials for either saturated or unsaturated conditions.
- Represents variable rainfall input using step-function series.
- A simple runoff routing model allows the user to divert excess water from impervious areas onto more permeable downslope areas.
- Uses a simple infinite-slope model to compute factor of safety on a cell-by-cell basis.
- An approximate formula for effective stress in unsaturated materials aids computation of the factor of safety in unsaturated soils.
- Horizontal heterogeneity is accounted for by allowing material properties, rainfall, and other input values to vary from cell to cell.
- This command-line program is used in conjunction with geographic information system (GIS) software to prepare input grids and visualize model results

TRIGRS has been applied previously in different geographic zones with a similar behavior to the basin studied in this paper, such as United States and Italy (Baum, W. Godt, & Savage, 2010) (Gioia, et al., 2015). There, the models have been calibrated with historical rainfall events that triggered landslides, producing reasonable results that matches closely with the data reported.

3.2 Limitations of the model

Based on the experiences reported in technical literature, where the TRIGRS model have been applied to simulate the shallow landslides triggered by rainfall, the main limitations and recommendations are summarized as:

- Model solutions are valid when the infiltration occurs just in vertical direction (1D)
- Unsaturated Gardner model is considered properly for granular soils. However, there is documented evidence that the model could provide reasonable results in fine-grained soils.
- Gardner model uses parameters that are not frequently determined in geotechnical characterization. Therefore, “pedotransfer functions” are required. As an example, Rosseta (developed by USDA) is a free code that allows to estimate the parameters of the soil-water characteristic curve, based on soil density and particle size distribution.
- USGS claims that the model is sensitive to mechanical properties. In the absence of

information, parameters collected from bibliographic references would be necessary.

- Results are highly sensitive to initial conditions: ground water level and infiltration rate.
- Model is 1D and there is no interaction considered between adjacent pixels (or columns), even though the major of shallow landslides occurs in areas that are bigger than pixel size. It means that the horizontal interaction occurs over real conditions.

Although limitations, TRIGRS model is capable to evaluate the slope stability based on changes in pore pressure and works with geographic information system (GIS), which allows to be coupled with hydrodynamic models.

3.3 Inputs and outputs

The procedure carried out by the program is presented schematically in Figure 4. From the inputs introduced in the model, the program executes transient pressure and factor of safety (FOS) calculation in each cell to obtain distributed space-time factors of safety, which allows to calculate the slid volume, considering those cells with FOS<1.0.

The input of the model are precipitation intensity, slope, soil depth, initial water-table depth, saturated vertical hydraulic conductivity, hydraulic diffusivity, a three-parameter soil-water characteristic curve, cohesion for effective stress, angle of internal friction for effective stress, and total unit weight of soil.

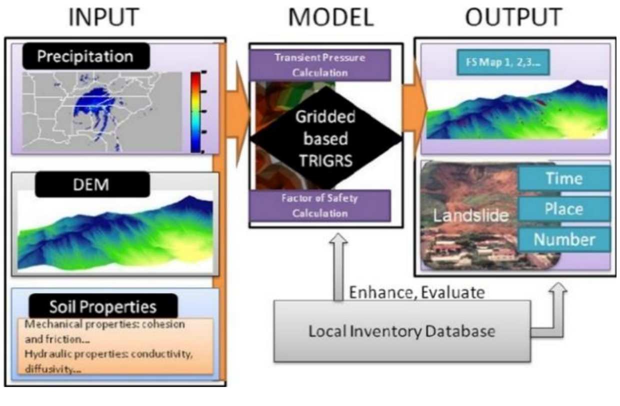

Figure 4.TRIGRS conceptual framework (Liao, et al., 2011)

As output, the program presents the pore pressure changes and factor of safety for each step of the rainfall introduced. The output is presented in the ASCII grid file (read by ArcGIS or Grass GIS), with a file that contains a listing of pore pressure and factor of safety at various depths for each grid cell. The TRIGRS program restricts the factor of safety to a maximum of 10 to facilitate plotting and eliminate division by zero in computing the factor of safety on flat slopes. To speed up computation time, the user can specify a minimum slope angle for computations; cells that are flatter than the minimum slope are assigned a factor of safety of 11 to distinguish them from the others. (USGS, 2009)

4 GEOTECHNICAL ZONATION AND PARAMETERS

As part of the implementation of the spatial slope stability model, a geotechnical zonation in which geomaterials are grouped by similar geological, geomorphological, land cover and soil type classification, was carried out.

From the previous works done by Colombian Geological Service (SGC, 2017), a geo-environment characterization which includes geological, geomorphological and land coverage studies were presented. These layers were generated for the landslide hazard zonation – scale 1:25,000- and were considered in this article.

Furthermore, the IGAC (Instituto Geográfico Agustín Codazzi) presented in 2014 a general soil zonation study for the State of Putumayo -scale 1:100,000-. The soil distribution and their characteristics described for the Mocoa basin, was also considered.

With those layers and further interpretation of the authors, complemented with the mass movements inventory reported by SGC (2017), 16 geotechnical zones were delimited in the zone of analysis (Figure 5). For each one, the model parameters were assigned based on the studies previously referenced (SGC, 2017) (IGAC, 2014), typical values reported in the technical literature (Bardet, 1997), and the specialist criteria after a field recognition visit carried out after the 2017 event. The procedure to adopt parameters is justified due to absence of geotechnical information as laboratory and field tests.

The parameters presented in Table 1 for each geotechnical zone, are discussed below:

- Soil depth: adopted from the geological description and complemented with field observations.
- Total unit weight, cohesion, friction angle and hydraulic conductivity: from the soil texture described by SGC and IGAC, the particle size distribution was estimated following the soil textural classification proposed by USDA (United States

Department of Agriculture). Therefore, bibliographic references were consulted (Bardet, 1997) to adopt the parameters values.

- Soil-water characteristic curve: includes water content at saturation, residual water content, saturated hydraulic conductivity, hydraulic diffusivity and steady infiltration rate. These parameters were determined through the MACRO 5.2 model, developed by SLU (Swedish University of Agriculture Sciences), where parameters values are selected from a database, in function of particle size distribution and soil texture.

As initial conditions, water table was determined from the rainfalls registered previous days of the event and an analysis carried out in HYDRUS 1D software. Topographic information was obtained from a 5 m Digital Elevation Model (DEM) uploaded to TRIGRS.

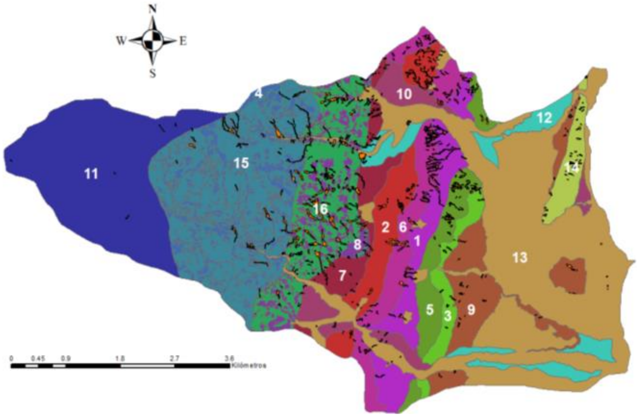

Figure 5. Geotechnical zonation and landslide inventory done by SGC (2017)

Table 1. Geotechnical and hydraulic parameters for each zone needed for the TRIGRS model

Zone number	Soil depth (m)	Total Unit Weight (kN/m^3)	Cohesion (kPa)	Friction Angle (°)	Water content at saturation (%)	Residual water content (%)	Saturated hydraulic conductivity (m/s)	Hydraulic diffusivity [m^2/s]	Steady infiltration rate Iz (m/s)
1	2	15	65	28	42.33	0.18	3.31E-07	2.50E-05	5.00E-09
2	1.5	15	65	28	42.33	0.18	3.31E-07	2.50E-05	5.00E-09
3	2.5	15	65	28	42.33	0.18	3.31E-07	2.50E-05	5.00E-09
4	1.7	13	10	20	42.33	0.18	3.31E-07	2.50E-05	5.00E-09
5	1	17	30	20	49.48	0.18	5.00E-07	2.50E-05	5.00E-09
6	1	16	7	14	42.33	0.18	3.31E-07	1.50E-05	3.00E-09
7	1	15	15	28	42.33	0.18	3.31E-07	1.50E-05	3.00E-09
8	2	13	12	19	49.48	0.18	5.00E-07	2.50E-05	5.00E-09
9	2.5	17	50	33	35.17	0.18	5.42E-07	5.00E-06	1.00E-09
10	2	16	60	30	42.33	0.18	3.31E-07	2.50E-05	5.00E-09
11	0.5	13	100	19	49.48	0.18	5.00E-07	2.50E-05	5.00E-09
12	0.5	18	45	33	35.17	0.18	5.42E-07	2.50E-05	5.00E-09
13	0.5	18	25	33	35.17	0.18	5.42E-07	1.50E-05	3.00E-09
14	1.5	15	10	10	35.17	0.18	5.42E-07	1.50E-05	3.00E-09
15	1.7	13	10	20	42.33	0.18	3.31E-07	2.50E-05	5.00E-09
16	2	13	12	19	49.48	0.18	5.00E-07	2.50E-05	5.00E-09

5 RESULTS

To simulate the Mocoa event on March 31, 2017, four days of antecedent rainfall were considered based on the analysis of historical rainfall series every 10 minutes. It was concluded that four days of accumulated rain period are statistically representative of the rainfall type that triggered the debris flow in the night of March 31.

An analysis with accumulated rainfall every 6 hours over four days was considered as the input. There are 16 results of volumes of solids from March 28 at 1:00 am to 1 April at 1:00 am, that shows the evolution of the landslides in each period analyzed, represented with the factor of safety (FOS) obtained in the pixels. FOS less or equal than 1 represents that the area of that pixel failed and slipped.

The estimated volume at each step analysis was calculated by multiplying pixels area with a FOS less or equal than 1 by the column soil depth where the failure is reported in one of the TRIGRS raster outputs. The calculated slid volumes are presented over the time in Figure 6. It is observed the landslides evolution with the rainfall -represented in time-. There are two significant increases in the slid volume: the first occurred in the afternoon on March 29, and the second (the major) occurred the

31 March day, reaching 738,095 m^3 of slid volume at 19:00.

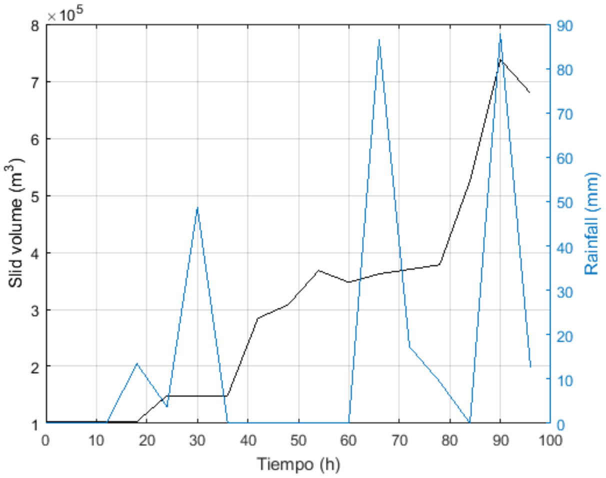

Figure 6. Simulated evolution of volume of landslides and recorded rainfall 96 hours before the event.

Because of the results obtained, it was evidenced that the TRIGRS model can increase FOS even in failed zones (that reaches FOS <1) at previous steps, because the DEM representing the terrain surface is not modified during the simulation. This is observed in the last period of analysis, where the slid volume decreases. Consequently, the representative volume considered for the event simulation corresponds to the maximum value obtained. It was presented in the penultimate analyzed period, it means at 19:00 of 31 March.

Figure 7 presents the FOS distribution in the basin at the moment of maximum slid volume, where red polygons (FOS less than 1) represents the landslides triggered by the accumulated rainfall.

The results obtained match very closely with the landslide inventory done by SGC. The spatial location distribution of the landslides (red polygons inFigure 7) is similar to mapped landslides in Figure 5. In both cases, the major affected zone corresponds to zone 16, were the landslide inventory reported the major of landslides triggered on the night of the event. This zone corresponds to a very poor and highly weathered and fractured monzogranite rock due to the activity of Mocoa-La Tebaida geologic fault; conditions that produce a high landslides susceptibility.

The slid volume reported in landslides inventory raster files done by SGC (2017), is approximately 690,000 m^3. This reference value was compared with the result obtained of 738,095 m^3 slipped, obtaining a relative error around 7%. It means that TRIGRS is in the capability to simulate shallow landslides triggered by rainfall obtaining results very closely to the event occurred.

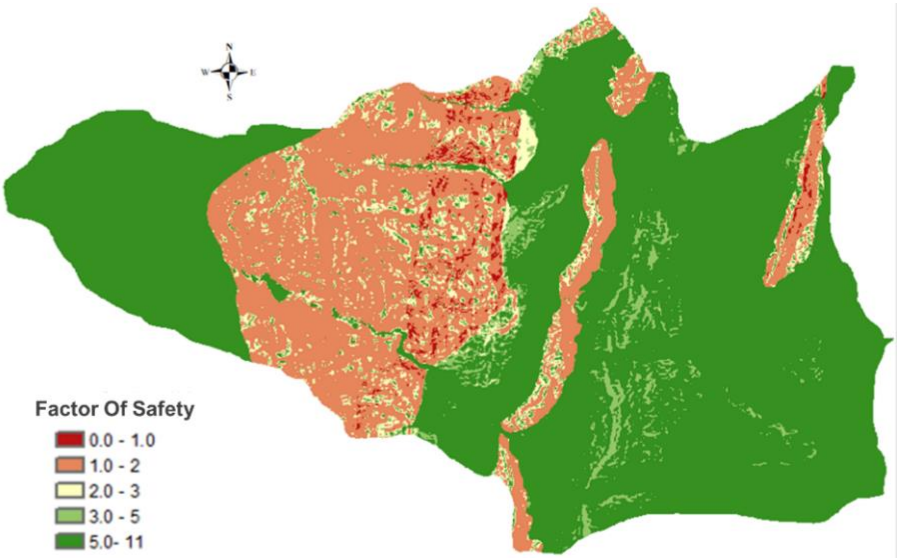

Figure 7. Spatial distribution of factors of safety obtained with TRIGRS in the Mocoa basin.

6 CONCLUSIONS AND RECOMMENDATIONS

As occurred in Mocoa, towns located on the Andean-Amazonian piedmont of Colombia are prone to the occurrence of debris and hyperconcentrated flows, triggered by landslides which are induced by rainfall. Therefore, advanced spatial tools for the integrated modelling of these type of flows can prove extremely useful for urban planning and hazard zoning.

This paper presented the application of TRIGRS to simulate the landslides in Mocoa event. Results obtained should be coupled with advanced 3D computational fluid dynamics codes to model the debris / hyperconcentrated flow.

TRIGRS is a code capable of modelling distribution of shallow rainfall-induced landslides and proved to be a useful tool to represent and evaluate events such as Mocoa. Features, including advantages and limitations were highlighted in Section 3.

In this type of events, it is common the absence of laboratory and field geotechnical tests due to the extensively areas of study and difficulties with topography access. Bibliographic information and previous studies carried out in the studied zone were analyzed, to assign some of the model parameters. Field recognition and back analysis with data measured are desirable to decrease uncertainty.

TRIGRS is highly sensitive to initial conditions as water table depth. It is further recommended to carry out boreholes that allows to set the location of water table. An analysis involving previous days rains with simple models for transportation and flow in the subsurface, as Hydrus 1D, could be used as a complement tool to set the water table depth. Hydrus 1D also incorporates pedotransfer functions to set soil-water parameters curve in function of particle size distribution and soil texture.

Four days accumulated rain period was considered as representatively to simulate the Mocoa event. The model presents as a result the spatial and time distribution of FOS in each raster cell. Cells with a FOS less than 1 represents a slipped area. With these results, the slid volume was estimated in function of the rain time-evolution. Finally, TRIGRS produced the spatial location and volume of landslides which matched very closely the landslide inventory done by the SGC.

After evidencing the TRIGRS capability to represent adequately the landslides triggered by rainfall, it is proved to be a useful tool to predict shallow landslides triggered by intense or cumulative rainfall and can serve to work with probabilistic rainfall scenarios to assess hazard levels in similar basins.

It is necessary the improvement of TIRGRS model regarding its discussed limitations. Specially, the authors emphasize the importance of consider removing from the DEM the areas and soil depths that in a step analysis reach values of FOS less than 1 -slid volume-. This will avoid decreases in temp of slid volume -as observed in last period analysis in Figure 6-, which are not plausible results. Besides, rock fall models and landslide runout calculation should be included in TRIGRS code, to represent a typical failure in the rock mass -different to shallow landslides- and to asses the quantity of slipped mass incorporated to streams.

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