Assessing torrential flow susceptibility using triggering and propagation models for tropical mountainous regions, a case study of the northern Andes, Colombia

Author(s) name: Maria Isabel Arango Carmona[1], Edier Aristizábal[2], Michel Jaboyedoff[3], Brian McArdell[4]

Author(s) affiliation: [1]Faculty of Geo-Information Science and Earth Observation (ITC), University of Twente, [2]Escuela de Geociencias y Medio Ambiente, Universidad Nacional de Colombia Sede Medellin, [3]ISTE - Institute of Earth Sciences, University of Lausanne, [4] Swiss Federal Research Institute for Forest, Snow and Landscape Research

m.i.arangocarmona@student.utwente.nl

Abstract

The Colombian Andean region characterizes for its tropical climate and mountainous topography, where torrential flow events have affected 1,246,705 people and caused 3,318 deaths between 1920 and 2018. Although this scenario shows the importance of torrential flow susceptibility assessment and mapping in tropical areas, there is not a clear methodology to evaluate susceptibility on a local scale. The approach presented in this work is the coupling of three models: TRIGRS for slope stability, FLOW-R for the propagation of debris flows along slopes, and IBER for the propagation of floods along stream channels. The methodology is calibrated using the data of the major torrential flow of the 21st September 1990 in the Arenosa Basin, located in the Antioquia region of Colombia. The performance of the model was measured with Receiver Operating Characteristic Curve (ROC) indexes by comparing its results with the mapped extent of landslides, debris flows and debris floods of the real event. The TRIGRS model was calibrated using several pre-storm water table depth scenarios, with the best scenario yielding an accuracy of 60%, a True Positive Rate of 70%, and a False Positive Rate of 40% when compared to the unstable cells of the real event. These cells were used as the input for the debris flow propagation model Flow-R, which was calibrated using different variables of the routing and persistence algorithms. Best debris flow run-out modeling yielded an Area under the Curve of 0.87 when comparing to the debris flow propagation of the real event. Finally, the propagation of the flow resulting from the rainstorm on the main river of La Arenosa, combined with the volume of debris flows reaching the main streams, is used as the input for the hydraulic modeling with the IBER software. The results yielded a True Positive Rate of 69% and a false positive rate of 2% when comparing the modeled flood extent with the real event.

1 INTRODUCTION

Rainfall-induced landslides represent one of the most common and damaging phenomena in the world (Sidle & Ochiai, 2006). Under certain conditions, these shallow rainfall-induced landslides become debris flows. Although debris flows initiate in steep areas, generally associated with small catchments, they can channelize into bigger watersheds, where processes of remobilization and deposition affect large areas downstream with high velocities and impact forces, making this hazard a very destructive one (Borga et al.,2014).

Although the differences between clear stream flows and gravitational slope processes are physically established (Iverson, 1997; Nettleton et al., 2005), there is not a consensus about the classification of flows involving a mixture of water and sediments in different proportions. Typically, the debris flows definition criteria vary according to several authors. They include sediment concentration, grain size distribution, number of phases or type of transport, causing a general confusion of terminologies for events composed of mixtures of water and sediments like debris torrents, mudflows, mudslides, flash floods, hyperconcentrated flows or lahars (Hungr et al., 2001; Iverson, 1997).

The lack of consensus in definitions of debris flow phenomena gives place to a broad diversity of approaches to debris flow characterization and analysis of damages, given that its impact information is often reported as landslide or flooding phenomena (Borga et al., 2014). As a consequence, the subject is treated from different approaches, sometimes contradictory and without reaching an agreement on the analysis, diagnosis, and risk reduction measures.

The northern Andean region characterizes for its tropical climate and mountainous topography, where short and intense rainfall events are commonly orographically anchored and enhanced. These extreme rainfall events often generate debris floods caused by the rapid accumulation of rainfall in small and steep watersheds; and generate significant clusters of hillslope debris flows in the sheds of the valleys. This phenomenon is defined by Crozier (2005) as multiple occurrence regional landslide events (MORLE). When the debris flows reach the flooded channels, they increase the sediment concentration of the flow, altering its fluid properties (Hungr et al., 2014; J. O'Brien & Julien, 1985). These continuous process changes clean water floods into viscous mass surges of water and sediments that range from hyperconcentrated flows to channelized debris flows as the solid concentration of flow increases. As the surge moves downstream, erosion power increases, and sediments of the stream-bed and the conjunction of small-scale bank slides or collapses are added to the debris flow (Jakob & Hungr, 2005). In Colombia, the general term for these events is "Avenida Torrencial", or torrential avenue, but in the present work will be called torrential flows, understanding the term as an entire phenomena in the catchment, where several types of lows are presented, following the descriptions of Hungr et al., (2014) and Jakob & Hungr, (2005).

According to the Desinventar database (http://www.desinventar.org/), in Colombia, there have been a total of 1,358 reports of channelized debris flows, debris floods, and flash floods between 1921 and February of 2018. These events caused the death of 3,318 people and left 1,246,705 people affected. Nevertheless, these events are often misregistered or confused with other phenomena like floods or landslides.

This critical scenario shows the importance of regional channelized debris flow susceptibility assessment and mapping in tropical areas and its incorporation into land-use planning. Given the high affectations by the occurrence of the last events of this type in Colombia, disaster risk management policies have been modified to include floods, landslides, and channelized debris flows hazard maps into land-use plans. Although these policies have suggested methodologies for assessing floods and landslides hazard maps (IDEAM & CNM, 2018; SGC, 2015; SGC, 2017), there is not a clear methodology to evaluate torrential flows hazard on a local scale, which results in studies made with different approaches, some of them using modified slope stability models and others using flooding propagation models. There is currently a lack of knowledge about methodologies to assess the hazard of this type of combined processes.

This work proposes a framework for determining torrential flow susceptibility combining the slope stability model TRIGRS, the debris flows propagation models Flow-R and the flood propagating model IBER. The models will be calibrated with a well-documented case study of the past event of the La Arenosa torrential flow in the Antioquia region in Colombia, and the results of the application of the models will be compared to the event observations.

2 STUDY AREA

La Arenosa basin is in the Department of Antioquia, on the Colombian Andean region (Figure 1).

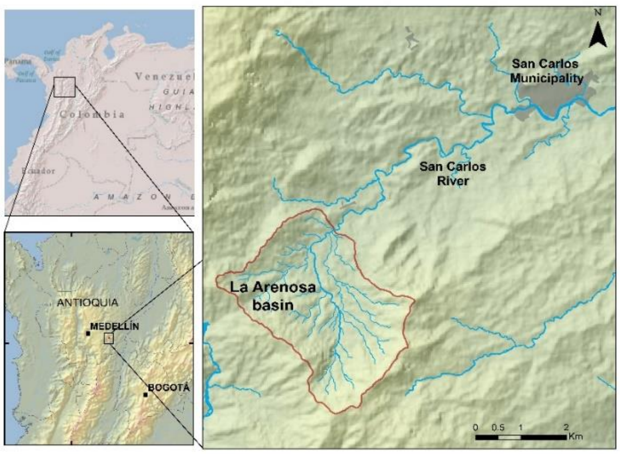

Figure 1. Location of the Arenosa basin

On the 21st of September of 1990, a 208 mm rainstorm fell within three hours, causing hundreds of mudflows on the slopes of the Arenosa Basin, with a calculated volume of 1.5 Mm^3. The mudflows reached the San Carlos River, which along with the intense rainfall, initiated a debris flood. The incorporation of significant volumes of the flows into the streams increased its erosional power, causing a significant widening and deepening of river channels and the erosion of materials with boulders up to 8 m in diameter and the deposition of about 300.000m^3 of deposits including boulders and sand. The event caused the death of 20 people, the destruction of 27 houses and affectations to 30 more in the municipality of San Carlos, located approximately 5 Km east of the basin. It also caused severe damages to the Calderas Hydroelectric Plant (Hermelin, Mejia, & Velasquez, 1992). Prolonged low-intensity precipitation of approximately 621 mm characterized the two preceding months of the event.

3 METHODOLOGY

The methodology proposed in this work for torrential flow susceptibility analysis combines slope stability, debris flow propagation, and flood extent physically based models.

The slope stability analysis is carried out using the TRIGRS model, developed by Baum et al., (2008). TRIGRS is a slope stability coupled with an infiltration model that simulates the temporal and spatial distribution of shallow landslides triggered by rainfall. It is based on the analysis of pore pressure transitory changes and its incidence on the factor of safety, using the method outlined by Iverson (2000) (Baum et al., 2008).

The final output of the slope stability analysis is the location of unstable cells, which is combined with the depth of soil of the study area to assess the volume of unstable soil that will potentially be transported in a debris flows.

Then, the unstable cells are used as the input for the Flow-R debris flow propagation model. This model relies on the simple but accurate run-out model proposed by Perla, Cheng, & McClung, (1980), that considers the distance traveled by a debris flow as a function of the topography and the rheology parameters of the flow such as the coefficient of friction and a ratio of mass–to–drag (Perla et al., 1980); and uses different routing algorithms to assess the most likely path of the debris flow based on the digital elevation model.

The purpose of using debris flow propagation models is to determine direct exposure to this type of phenomena, but also to determine how many of the hillslope debris flow will eventually propagate until reaching main streams and assessing the volume of sediments that will finally get incorporated into the debris flood. Using the time variation of the Factor of Safety resulting from the slope stability analysis and Precipitation-Runoff models, the volume of water and sediments exiting the basin can be calculated, creating a hydrograph. This hydrograph will be finally used as input for modeling the flood extent.

For this, the IBER (Bladé et al., 2014) two-dimensional software is used. IBER is a numerical tool for 2D simulation of turbulent free-surface unsteady flow in watercourses using non-structured meshes.

The performance of the models for source areas, propagation of debris flows, and flood extent are be compared to the extent of the real event using Receiver Operating Characteristics (ROC) such as False prediction rate (FPR), True Prediction Rate (TPR), Accuracy and Precision.

3.1 Landslide Inventory

The analysis carried out by INTEGRAL (1990) and Mejía & Velásquez (1991) allowed a reconstruction of the pattern and characteristics of the landslides in La Arenosa catchment after the event. They offered a coarse landslide inventory and a comprehensive description of the landslides that occurred (Figure 2). Mejía & Velásquez (1991) reported at least 699 landslides in the La Arenosa catchment.

After the event, ISAGEN took aerial photographs of the basin. The available photographs that had no cloudy coverage were georeferenced using ArcMap, delineating the scars and runout extent of the landslides, together with the flooding extent of the event. The south-eastern and central part of the basin was not visible due to cloudy conditions, so there is no information about landslides on the zone. This area was removed from the study area for the calibration of the models.

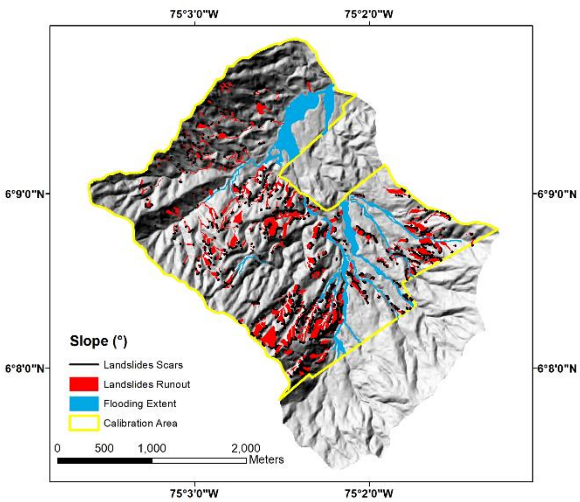

Figure 2. Landslide inventory of the Arenosa channelized debris flow event.

3.2 Slope stability analysis

The mechanical and hydraulic properties of the soils are required for the use of the TRIGRS model. Given the rather homogeneous geology of the study zone, characterized by sandy soils with high permeability, they are classified into mainly two types identified by IGAC (2007), as the Yarumal soil association, derived from the granitic rocks of the Antioquenian batholith (YAE1 and YAF2), and the Polanco (POc1) soil association, derived from the alluvial deposits of the Arenosa and San Carlos River. For each geological unit, Aristizábal et al., (2016) constructed a stratigraphic profile for the definition of geotechnical parameters using soil descriptions, field tests and laboratory analyses on soil samples from the La Arenosa catchment provided by INTEGRAL (1990) and Mejía & Velásquez (1991). The hydraulic parameters of these soils were taken from Aristizabal & García, (in preparation), who estimated them from soil type descriptions found in the literature and based on Gardner's model (Gardner, 1958), that describes the characteristic curves of water retention in soils.

Table 1 shows the soil parameters obtained in the mentioned study.

Table 1. Geotechnical and hydraulic parameters of the soils present in the study zone

Soil parameter	POc1	YAE1-YAF2
Cohesion (kPa)	1	5
Friction angle (°)	34	24
Saturated unit soil weight (kN/m^3)	20	18
Soil thickness (m)	2.5-2.8	1.2-2.8
Steady, pre-storm infiltration rate (I_{ZLT}) (m/s)	2.59×10^{-7}	2.59×10^{-7}
Hydraulic conductivity of saturated soil (K_s) (m/s)	5.33×10^{-6}	2.18×10^{-5}
Hydraulic diffusivity (D_0) (m^2/s)	5.33×10^{-4}	2.18×10^{-3}
Soil saturated volumetric water content (q_s)	0.48	0.46
Soil residual volumetric water content (q_r)	0.18	0.18
Fitting parameter for soil size distribution (α) (1/m)	2.3	2.3

The soil depth, another required parameter, was calculated using the methodology proposed by Catani, Segoni, & Falorni (2010). This model assumes that the soil depth development depends on the slope of the terrain and requires restraining values for soil thickness. These values were assessed by Mejía & Velásquez, (1991) based on field observations.

Given the uncertainty on the pre-storm saturation conditions of the study area, several pre-storm depths of water table were used when running the model to evaluate its performance.

The results of the simulations and the real event conditions are compared to evaluate the performance of the model using the False Positive and True Positive Rate, with the best fitting results achieved by those with the lowest FP rate and the highest TP rate (Figure 3). The scenario with the water table 0.5 meters above the soil depth was chosen as the best scenario with a TP of 70.2%, a FP of 39.6%, and an accuracy of 60.7%. The final factor of Safety map is shown in Figure 4.

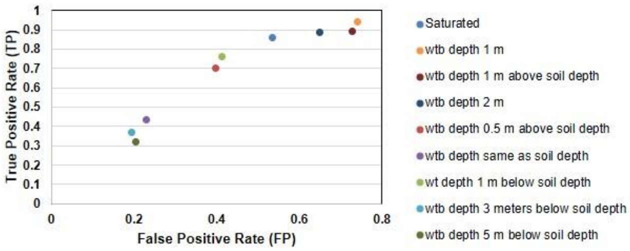

Figure 3. Results of the model performance using different depths of the water table. The purple dot (water table depth 0.5 m above soil depth) corresponds to the water depth scenario with the best fitting results.

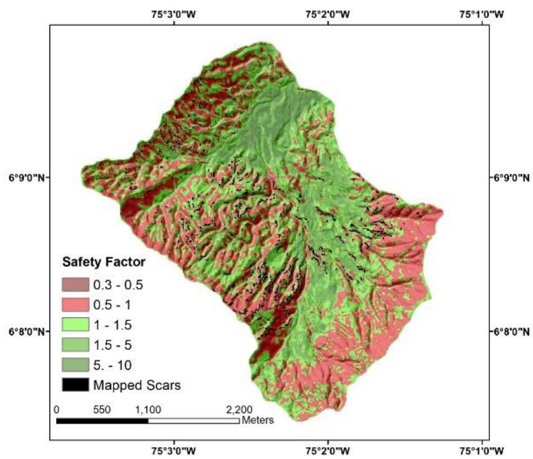

Figure 4. The factor of Safety map for the Arenosa Basin

3.3 Debris flow propagation

Calibration of the parameters of the routing and energy algorithms of Flow-R was done considering the landslide inventory as the source areas.

For the routing method, the Holmgren (1994) modified algorithm was used to define the direction of the flow. This algorithm includes an exponent x that increases as the flow becomes more divergent. The algorithm also changes the height of the central cell by a factor of dh.

The energy calculations were made based on the Perla et al. (1980) algorithm, which runs with two variables: μ, as the friction, and the Mass to Drag ratio (Perla et al., 1980).

A sensitivity analysis was carried out with more than 50 calculations of the debris flow propagation, changing the routing and energy algorithms variables. For the evaluation of the performance of the model, they were compared to the real runout of the event using the Area under de Curve (AUC). The best-fitting parameters yielded and AUC of 0.867.

After assessing the variables of the modeling algorithms that best fit the conditions of the study area, the model Flow-R was used to model the propagation of all the source areas that resulted as unstable in the TRIGRS slope stability model. The sources were defined as all the cells with FS<1 on the TRIGRS model results by the end of the storm.

Figure 5 shows the results of the propagation modeling.

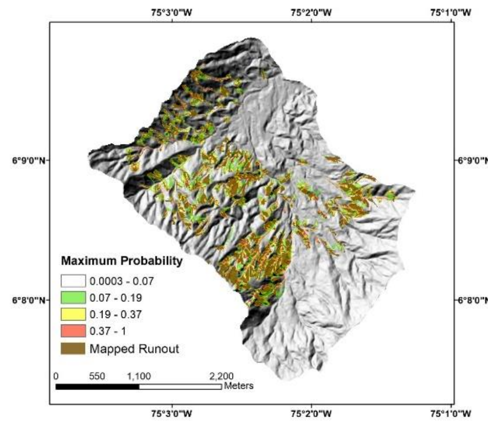

Figure 5. Debris flow propagation map result from modeling in Flow-R

3.4 Flood propagation model

IBER hydraulic modeling software was used to simulate the extent of the flooding resulting from the incorporation of debris flow sediments into the main streams. For this, a rainfall-runout model was used to calculate a hydrograph of streamflow, and the results of the slope stability model were used to add up the volume of sediments on the hydrograph. In the end, the hydrograph was used as the input for the hydraulic model.

The transformation of the rainstorm of 21 of September 1990 in La Arenosa basin into runoff was done with the HEC-HMS 4.2 software using Clark's synthetic unit hydrograph method. The input variables of the HEC-HMS are the concentration-time and the Curve Number of the basin, defined by the Soil Conservation Service (SCS) as its degree of impermeability. The concentration-time depends on the morphometric characteristics of the basin, and different empirical equations have been used for its estimation. Table 2 shows the methodologies, and the selected concentration-time was the mean of the different formulas.

Table 2. Expressions used to calculate the concentration-time of the Arenosa basin.

Methodology	**Formula**	**Concentration Time (Min)**
(Témez, 1991)	$T_c = 0.3 * (\frac{L}{S^{0.25}})^{0.76}$	66.9
(Kirpich, 1940)	$t_c = 0.0078 L_p^{0.77} * S^{0.385}$	18.4
California Culvert Practice	$t_c = 60 * \left(\frac{0.87075 * L^3}{H}\right)^{0.385}$	22.8
Passini	$T_c = \frac{0.108 * (A * L)^{1/3}}{S^{0.5}}$	38.3
Giandotti	$T_c = \frac{4 * \sqrt{A} + 1.5 * L}{25.3 * \sqrt{S * L}}$	36.8
(Clark, 1945)	$T_c = 0.335 * \left(\frac{A}{S^{0.5}}\right)^{0.593}$	107.1
	Mean	58
	Lag Time	32.4

tc= Concentration time (min), Tc= Concentration time (hrs),Lp=Length of the main stream (ft), L=Length of the main stream (Km), S=Slope of the main stream (m/m), A= Area of the basin (km2), Basin Relief (m)

The results of the slope stability model were used to estimate the rate of volume of sediments being transported by the Arenosa river from the apex of the basin. Since the Factor of Safety results is given on an hourly scale, the volume of material that failed during each hour of the storm was calculated using the soil depth map and the TRIGRS model results. It is assumed, however, that the moment when each cell fails, is the same moment when the sediment associated with the cell is added to the hydrograph, being the travel time of the sediments between their failing locations to the apex of the basin out of the scope of this study.

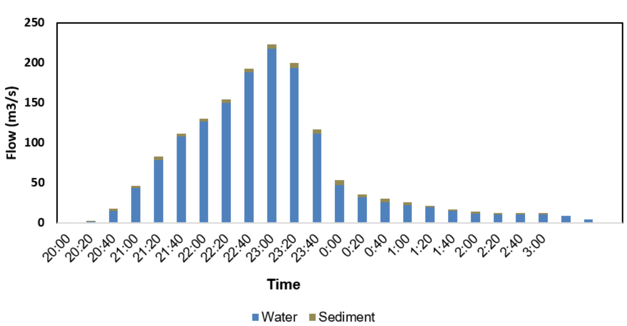

Figure 6. Obtained hydrograph of water and sediments exiting the apex of the basin during the rainstorm event

Finally, the hydrograph of the mixture of water and sediments going through the Arenosa basin mouth is shown in Figure 6. The highest discharges occurred around three hours after the beginning of the storm, with a flow rate of 215 m^3/s. According to the model, 89.400 m^3 of sediments fell on the streams during the event in 8 hours, with the highest rate of material falling on the 4th hour of the rainstorm.

4 RESULTS

Figures 7 and 8 show the results of the modeled flood path and the real extent of the flood on the event. The results yielded a True Positive Rate of 68.9% and a False Positive Rate of 1.8%, showing in general good results, although there is a general underestimation of the flooding extent.

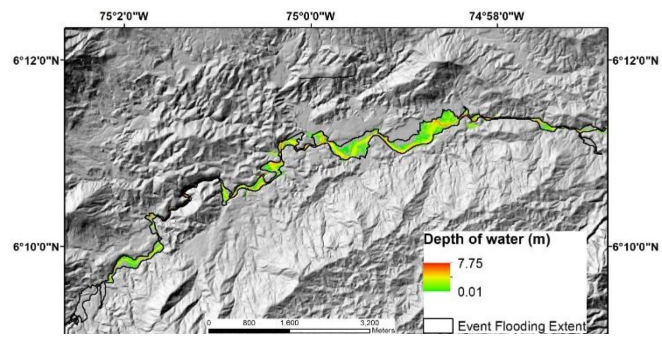

Figure 7. Map showing the results of the hydraulic model applied to the Arenosa basin event of 21st of September, 1990.

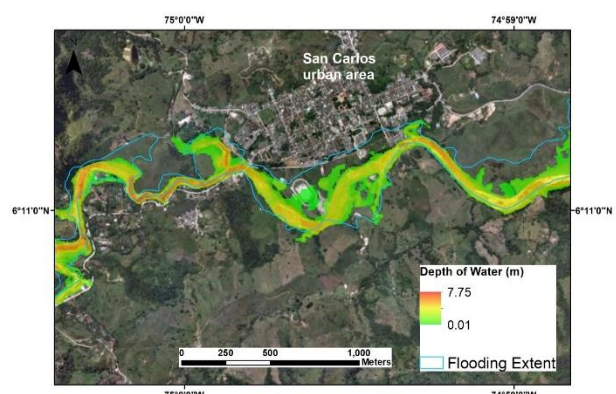

Figure 8. Detailed view of the flooding map modeled and the real event's flooding extent on the San Carlos urban area.

These differences between reality and the results of models may be due to some uncertainties of the methodology. For instance, the flow coming from other tributary streams that discharge on the Arenosa river were not taken into account for the flood runout. Also, according to Hermelin et al. (1992), the event caused a significant widening and deepening of river channels, mobilizing a large volume of sediments from channel banks that was not accounted on the model. Also, the hydraulic model did not account for rugosity variation inside the channel during the storm, which probably increased as the sediments were deposited.

The most important limitation for the runout analysis, is that there is an uncertainty linked with the travel time of sediments from its source to the apex of the basin. These travel times can vary with the velocity, volume, and sediment concentration of the flow. Finally, the hydrograph was calculated based on the rainfall records of the Calderas power plant rain gauge that was in the lower part of the basin. Differences on the final flooding map may be due to a more intense rainstorm that the one registered by the rain gauge.

5 CONCLUSIONS

Modeling torrential flow susceptibility using slope stability and propagation models for debris flows and floods provide a useful tool for hazard zonation. It results crucial for risk mitigation strategies in places like Colombia where concatenated debris flow-debris flood processes generate a very high hazard on populations located in lowlands of mountain torrents. In this study, a methodology is proposed to account the susceptibility hazard of concatenated hydrologic and hillslope events. This methodology couples a spatially distributed map of potentially unstable areas, the propagation and deposition of the triggered masses into the hillslope and main streams, and the subsequent deposition of the flooding event. To achieve this, a simple framework for combining these models is proposed as an attempt to improve channelized debris flood hazard maps, that commonly only account for one type of hazard, and does not take into account the multi-hazard of this type of phenomena.

Even though the calibration of the model on a well-studied event in Colombia yielded good results, the model still have some drawbacks and uncertainties, mainly related to the volume of sediments from debris flows effectively contributing to the channelized debris flow, the time when the sediment will be added to the flow hydrograph, and the sediments coming from the river bed and banks that get eroded and also contributes to the flow. Normally, information about the debris flow volume contributing to the flow is constructed on a study zone based on historical records and field observations of events of this type. In Colombia is urgent, therefore, the detailed observation of this type of factors when this type of disasters occurs.

6 BIBLIOGRAPHY

Aristizabal, E., & García, E. F. (Paper in preparation). *Modelling landslides triggered by rainfall using the model TRIGRS in a tropical catchment of the Andean Mountains*. Medellin.

Aristizábal, E., Vélez, J. I., Martínez, H. E., & Jaboyedoff, M. (2016). SHIA_Landslide: a distributed conceptual and physically based model to forecast the temporal and spatial occurrence of shallow landslides triggered by rainfall in tropical and mountainous basins. *Landslides*, *13*(3), 497–517. https://doi.org/10.1007/s10346-015-0580-7

Baum, R. L., Savage, W. Z., & Godt, J. W. (2008). TRIGRS—A Fortran Program for Transient Rainfall Infiltration and Grid-Based Regional Slope-Stability Analysis, Version 2.0. In *U.S. Department of the Interior U.S. Geological Survey*. https://doi.org/Open-File Report 2008–1159

Bladé, E., Cea, L., Corestein, G., Escolano, E., Puertas, J., Vázquez-Cendón, E., … Coll, A. (2014). Iber: herramienta de simulación numérica del flujo en ríos. *Revista Internacional de Metodos Numericos Para Calculo y Diseno En Ingenieria*, *30*(1), 1–10. https://doi.org/10.1016/j.rimni.2012.07.004

Borga, M., Stoffel, M., Marra, F., Marchi, L., Marra, F., & Jakob, M. (2014). Hydrogeomorphic response to extreme rainfall in headwater systems: Flash floods and debris flows. *Journal of Hydrology*, *518*(PB), 194–205. https://doi.org/10.1016/j.jhydrol.2014.05.022

Catani, F., Segoni, S., & Falorni, G. (2010). An empirical geomorphology-based approach to the spatial prediction of soil thickness at catchment scale. *Water Resources Research*, *46*(5), 1–15. https://doi.org/10.1029/2008WR007450

Clark, C. (1945). Storage and the unit hydrograph. *Proceedings of the American Society of Civil Engineers*. Retrieved from https://cedb.asce.org/CEDBsearch/record.jsp?dockey=0355680

Crozier, M. J. (2005). Multiple-occurrence regional landslide events in New Zealand: Hazard management issues. *Landslides*, *2*(4), 247–256. https://doi.org/10.1007/s10346-005-0019-7

Gardner, W. R. (1958). Some steady-state solutions of the unsaturated moisture flow equation with application to evaporation from a water table. *Soil Science*, *85*(4), 228–232. https://doi.org/10.1097/00010694-195804000-00006

Hermelin, M., Mejia, O., & Velasquez, R. E. (1992).

Erosional and depositional features produced by a convulsive event, San Carlos, Colombia, September 21, 1990. *Bulletin of the International Association of Engineering Geology*, *45*(1), 89–95.

Hungr, O., Evans, S. G., Bovis, M. J., & Hutchinson, J. N. (2001). A review of the classification of landslides of the flow type. *Environmental and Engineering Geoscience*, *7*(3), 221–238. https://doi.org/10.2113/gseegeosci.7.3.221

Hungr, O., Leroueil, S., & Picarelli, L. (2014). The Varnes classification of landslide types, an update. *Landslides, 11*(2), 167–194.

IDEAM, & CNM. (2018). *Guia metodologica para la elaboración de mapas de inundación*. Retrieved from http://documentacion.ideam.gov.co/openbiblio/bvirtual/023774/GUIA_METODOLOGICA_MAPAS_INUNDACION_MARZO_2018.pdf

IGAC – Instituto Geográfico Agustín Codazzi. (2007). Estudio general de suelos y zonificación de tierras del departamento de Antioquia. *Bogotá*, 207.

INTEGRAL, S. A. (1990). Informe sobre daños en la central de calderas por la avalancha ocurrida en l quebrada LA Arenosa el 21 de septiembre de 1990 y su reparación. *Report Interconexión Eléctrica SA ISA*, 45.

Iverson, R. M. (1997). The physics of debris flows. *Reviews of Geophysics*, *35*(3), 245. https://doi.org/10.1029/97RG00426

Jakob, D., & Hungr, O. (2005). *Debris-flow hazards and related phenomena*. Retrieved from http://link.springer.com/content/pdf/10.1007/b138657.pdf

Kirpich, Z. (1940). Time of concentration of small agricultural watersheds. *Civil Engineering*, *10*(6), 362.

Mejía, R., & Velásquez, M. E. (1991). Procesos y depósitos asociados al aguacero de septiembre 21 de 1990 en el Área de San Carlos (Antioquia). *Undergraduate Thesis, Universidad Nacional de Colombia, Medellín*.

Nettleton, I., Martin, S., Hencher, S., & Moore, R. (2005). Debris flow types and mechanisms. *Scottish Road Network*. Retrieved from http://www.geoffice.it/files/download/0015327.pdf

O'Brien, J., & Julien, P. (1985). Physical properties and mechanics of hyperconcentrated sediment flows. *HD Delineation of Landslides, Flash Flood and Debris Flow Hazards.*

Perla, R., Cheng, T. T., & McClung, D. M. (1980). A Two–Parameter Model of Snow–Avalanche Motion. *Journal of Glaciology*, *26*(94), 197–207. https://doi.org/10.3189/S002214300001073X

Servicio Geológico Colombiano (SGC). (2015). Guía metodológica para estudios de amenaza, vulnerabilidad y riesgo por movimientos en masa. *Bogotá, DC, Colombia*.

SGC. (2017). *GUÍA METODOLÓGICA PARA LA ZONIFICACIÓN DE AMENAZA POR MOVIMIENTOS EN MASA ESCALA 1: 25 000*. 1–160.

Sidle, R. C., & Ochiai, H. (2006). Landslides: Processes, Prediction, and Land Use. In *Water Resources Monograph Series* (Vol. 18). https://doi.org/10.1029/WM018

Témez, J. (1991). Extended and improved rational method. Version of the highways administration of Spain. *XXIV Congress Madrid*.