Definition of Rainfall Thresholds for Shallow Landslides in Colombian Tropical Mountainous Catchments as Debris Flow Triggering Mechanism

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Abstract. As a cascade precursor of the Debris Flow phenomenon, landslides generate economic losses and human fatalities worldwide, especially in mountainous and tropical countries like Colombia. This work proposes two different methodologies of defining rainfall thresholds as a tool for Early Warning Systems for Debris Flow occurrence in Colombian urban and mountainous catchments: Empirical-Statistical and Physically based. Empirical-Statistical rainfall thresholds are defined using several data sources such as rain gauges (pluviometers), radar, and satellite data allowing a different timing and spatial resolution in the definition. The definition of physically based rainfall thresholds the TRIGRS software is used in mountainous catchments with rainfall data from rain gauges, with the information from the safety factor map resulting in the simulations calculated as the cumulative density function from the histogram of the distributed safety factor allowing the understanding of how the instability varies in a catchment during different storms events

1 Introduction

Landslides generate economic losses and human fatalities worldwide, especially in mountainous and tropical countries like Colombia. According to the Geohazards database (www.geohazards.com.co), 10.438 landslides have been registered in the Colombian Andean between 1921-2020, with almost 7.313 fatalities [1]. The Colombian Andean region exhibits a complex tropical hydrometeorological dynamic affected by different temporal and spatial scale climate processes. It is composed of a diverse geological and geomorphological setting characterized by high steep slopes and morphogenic conditions that are predisposed to gravitational hillslope processes [2,3]. Most of the Colombian population is established in the Andean region occupying large hilly areas without adequate planning control representing a risk condition that in recent years has encouraged the development of forecast models like Rainfall Thresholds and more complex and complementary tools like Early Warning Systems (EWS).

Early warning systems based on precipitation thresholds can be defined by empirical-statistical and physical methods. The empirical-statistical ones are based on historical rainfall and mass movement data, and the physically based models consider the effects of rainfall by coupling distributed hydrological and geotechnical models that provide the spatial distribution of landslides by calculating the distributed factor of safety. This paper presents the application of both methodologies for the definition of critical rainfall thresholds at basin scale in the Colombian Andean region. Rainfall thresholds are proposed for the Valle de Aburrá basin in Medellín, Colombia; from the intensity (I) or magnitude of a rainfall expressed in millimeters per hour, for a given duration (D), it is possible to generate the so-called ID curves, which allow, through the analysis of precipitation data, interpretation of variables and correlations, to identify minimum rainfall thresholds associated with the occurrence of landslides, serving as a starting point for knowledge and risk management. In this work, different sources of pluviometric data were used to compare and discuss the generation of thresholds for each of them. In this sense, use was made of two systems of hydrometeorological stations or terrestrial sensors, owned by the public companies of Medellín and the Área Metropolitana del Valle de Aburrá: EPM and SIATA; NASA's GPM satellite database; and data taken with radar, also owned by SIATA. Then, an inventory of landslides with a defined time of occurrence was carried out, from which pluviometric data of rainfall events recorded during or before the mass movement were associated, defined as triggering rainfall events, and managing to form a database of 63 landslides in the period 2008-2018 (Table 1).

2 Discussion

Much of the discussion generated in the study of the generation of thresholds with statistical methods from different sources focus on the comparison of the resulting ID plots in each case. In general, the rainfall data measured in the field by hydrometeorological stations allow for greater analysis and can be more easily associated with the recorded landslides, despite the great

Table 1. Precipitation data sources for statistical methodology. The type of data source, the available range of data, the number of landslides triggered by rainfall recorded in each source, the period in which the landslides are recorded, and finally the temporal and spatial resolution are detailed.

Source	Type	Range Available	Landslides	Period	Temporal	Source
EPM	Rain Gauge (14)	1948-2016	45	2008-2016	5 min- 15 min	-
SIATA	Rain Gauge (19)	2012-present	36	2013-2018	1 min- 5min	-
GPM	Satellite	2000- present	63	2008-2018	30 min	0.1°x0.1° (10x10 km)
SIATA	Radar	2013-2019	36	2013-2018	5 min	600x600m

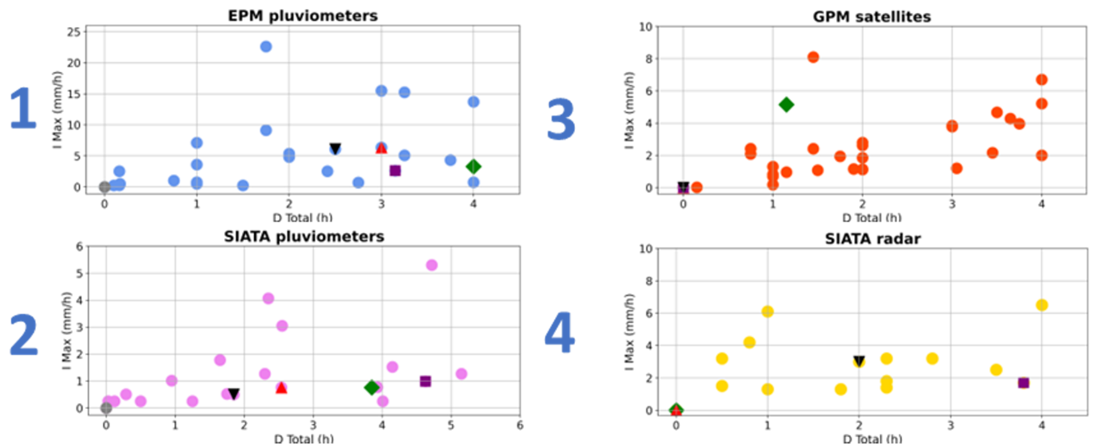

Fig. 1. Intensity-duration (ID) plots for each rainfall data source. Four points with different symbologies are distinguished, each representing the same triggering rainfall event captured independently by each source, reflecting that the rain gauge data are more useful for recording triggering rainfall events. Whereas the radar and satellite data omit local rainfall periods.

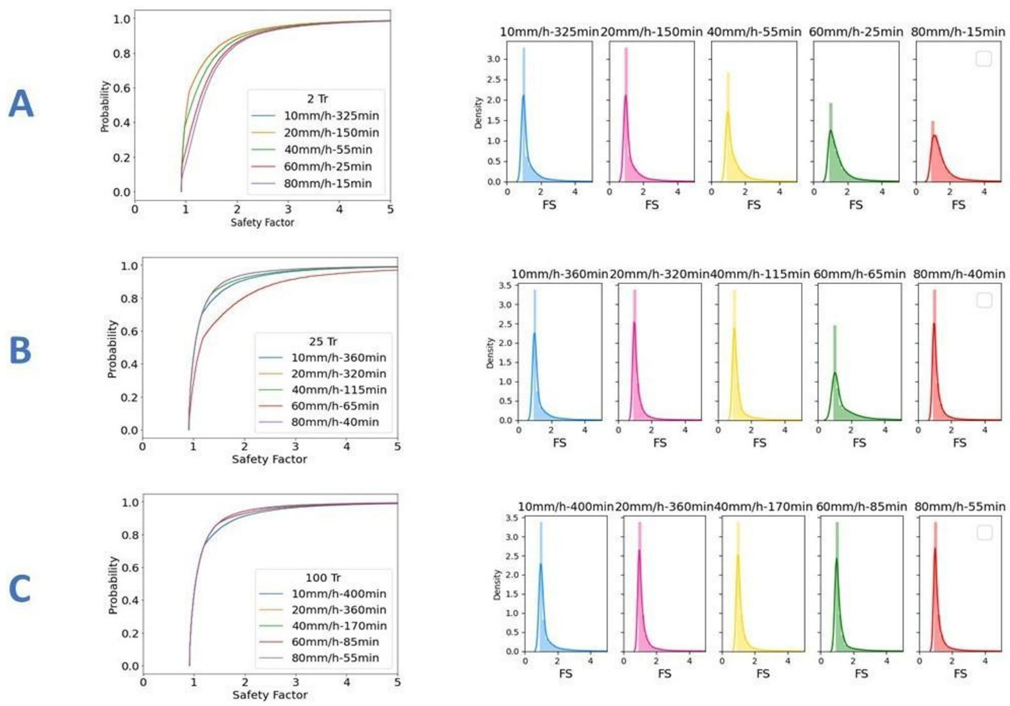

Fig. 2. Cumulative Density Function CDF Curves and Histograms of the distributed Safety Factor in Basin A for 2 years of return (Tr2) (A), 25 years of return (Tr25), 100 years of return (C)

variability in the intensity and duration conditions, which generally reflect intensities that do not exceed 8 mm/h and variable durations of up to 4 hours. On the other hand, radar or satellite-estimated rainfall data reflect a greater difficulty in capturing landslide-triggering rainfall events, mainly due to reduced spatial resolution (Figure 1).

Conversely, physically-based rainfall thresholds consider the spatial distribution or location of the landslides by approaches grounded on physical laws that consider the occurrence of landslides by calculating statistical or distributed safety factors. They are based on the physical relationship between soil resistance forces and hydraulic-dynamic forces associated with rainfall instability effects, considering the effects of rainfall coupling hydrological and geotechnical models. This dynamic nature of subsurface hydrology depends on the complex interactions among precipitation inputs, physical properties, and heterogeneity of soils, bedrock, local geomorphology, vegetation, and associated biomass. These factors influence (i) the timing of landslides with respect to precipitation inputs and antecedent soil moisture, (ii) landslide type and failure mode, providing a wide understanding of the physical behavior of the rainfall throw the hillslope and associated infiltration. These models provide the spatial and timing distribution of the phenomenon.

In this order of ideas, proposing an approach where the definition of the rainfall thresholds integrates IDF gauge-based rainfall data, and the physically-based model (TRIGRS) [4] allows performing simulations with different intensity rainfall values in some catchments in the Colombian Andean region. Moreover, calculating the cumulative density function from the histogram of the distributed safety factor (Figure 2) within a catchment resulting from the simulation provides a better comprehension of the instability and the response to heavy rainfall events from different years of return in a catchment scale in tropical mountainous terrains where the occurrence of debris flow is associated with shallow landslides from hillslopes from the upper part of the catchment.

3 Conclusions

The definition of precipitation thresholds using physically based models in the Colombian tropical Andean region at the basin scale could provide information on the timing and location of distributed instability reflected in shallow landslides considered the first trigger of debris flows in tropical regions. On the other hand, the statistically-based thresholds and ID relationship analysis generated in this study, allow an understanding of the influence of the triggering factor rainfall in mass movements in the Colombian Andes, particularly in densely populated areas, however, does not provide information on the location of the landslide, but allows using rainfall data in real-time to generate alerts and better assistance to the emergency, in addition to providing important information on the triggering rains of landslides in high mountains that can dam rivers and increase the chances of a debris flow. Therefore, the information resulting from this study can be used for the development of Early Warning Systems (EWS) to couple the occurrence of shallow landslides and subsequent debris flows considering the distribution of instability under different return years and extreme precipitation events associated with the dynamics of climate change.

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