The relationship between rainfall and landslide in the Aburrá Valley, northern Colombian Andes

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Abstract

Landslides triggered by rainfall are one of the most frequent causes of natural disasters in the tropical and mountainous terrains of the Colombian Andes. All over the world, research studies related to real-time monitoring and definition of critical rainfall thresholds have become fundamental tools for implementing early warning systems (EWS). Although critical rainfall thresholds have been widely incorporated in EWS, in Colombia, few studies have been conducted regarding the influence of rainfall as a trigger for landslides. In this study, a temporal analysis, which includes the correlation between rainfall and landslides for the Aburrá Valley, in the northern Colombian Andes, is carried out. The temporal variability of precipitation was studied, analysing the daily, monthly and annual cycles and patterns and their relationship with landslide occurrence. Landslide occurrence and mean rainfall correlate on a monthly temporal scale, with a clear bimodal temporal pattern. Relationships between rainfall and the recorded landslides for the Aburrá Valley, using different time scales, allowed the correlation of relevant aspects of the landslides triggered by rainfall, such as the ENSO effect and the accumulated and previous precipitation influences. Likewise, it was possible to observe the dependence of landslides on the type of rainfall cycle, with differences in the rainfall-slides correlations for El Niño, La Niña and normal years. This implies a high dependency of soil instability on the type of rainfall, as well as the need to link infiltration analyses with soil stability analyses for the study of landslides triggered by rainfall infiltration processes.

1 INTRODUCTION

Rainfall is the most common cause of landslides (Guzzetti et al. 2007; Iverson 2000; Zêzere et al. 2005) and landslides triggered by rainfall are one of the most frequent causes of natural disasters in tropical and mountainous terrains, such as the Colombian Andes (Schuster and Fleming 1986; Schuster et al. 2002; Sepulveda and Petley 2015; Varnes 1981). Landslides triggered by rainfall account for 89.6% of landslide fatalities worldwide (Petley 2008). Based on the EM-DAT database from OFDA/CRED, a world annual average of 914 deaths were reported between 2005 and 2014 due to landslides triggered by rainfall (Guha-Sapir et al. 2016).

In the last two decades, investigations related to rainfall forecasting, real-time monitoring and defining critical rainfall thresholds have become fundamental tools for implementing early warning systems (EWS). The advantages of EWS based on critical rainfall thresholds are supported by the fact that rainfall is relatively simple and costs little to measure across large areas (IEWP 2005). Such EWS indicate the possibility of landslide occurrence in advance, which allows notifying and evacuating people to protect their lives.

Rainfall thresholds for landslide forecasting can be defined in two ways, (a) using empirical or statistical methods and (b) using physically-based models. Empirical rainfall thresholds are very popular within EWS for their easy implementation (Guzzetti et al. 2008). The thresholds defined by empirical or statistical methods are based on historical rainfall and landslide databases. In general, these methods relate the occurrence of the event with the rainfall intensity, duration and/or accumulated rainfall antecedent (Terlien 1998). However, thresholds defined by physical methods are based on numerical models that incorporate the result of hydrological and geotechnical analyses that relate rainfall, infiltration, pore pressures and slope stability. To develop this type of threshold, hydrological, lithological and morphological information and the characteristics of the soils that control the activation of landslides are required (Crosta 1998; Aleotti 2004).

In this way, when a reliable and good quality historical record of rainfall and landslide database is available, the thresholds can be defined by empirical or statistical methods; otherwise, when some of this information is restricted or scarce, physical models are more recommended (Terlien 1998). Additionally, physical models provide information about the spatial distribution of the landslide hazard, unlike empirical models, which only provide information on the temporal distribution of landslides.

Although critical rainfall thresholds have been widely incorporated in EWS, in Colombia, few studies have been conducted regarding the influence of rainfall as a trigger for landslides (Paz and Torres 1989; Echeverri and Valencia 2004; Moreno et al. 2006). van Western and Terlien (1996) established relationships between landslides and daily and accumulated rainfall in the central Colombian Andes. Later, Terlien (1998) tried combinations of daily rain and accumulated rain antecedent of 2, 5, 15 and 25 days, proposing that 15 days of accumulated rainfall antecedent is sufficient to trigger landslides, and recommended that empirical thresholds should be developed for each region independently.

In terms of EWS, for the entire country, the Institute of Hydrology, Meteorology and Environmental Studies (IDEAM, 2002) implemented a model for the real-time forecast of landslides triggered by rainfall in Colombia, for which they use an accumulated rain term from 1 to 180 days and the short term from 1 to 24 hours. This information is published daily on its website (www.ideam.gov.co). At the local level, in the northern Colombia Andes, the Aburrá valley has an EWS based on a Band C meteorological radar, which is called SIATA (www.siata.gov.co), but it does not have established rainfall thresholds.

In this study, temporal analysis of rainfall and landslides were studied for the northern Colombian Andes, specifically in the Aburrá Valley, where landslides are a critical and destructive phenomenon, mainly triggered by rainfall. Temporal variability of precipitation was studied, analysing the diurnal, interannual and intra-annual cycles and patterns and their relationship with landslide occurrence. This paper contributes both to the understanding of this phenomenon and to the development of an EWS based on rainfall for the northern Colombian Andes.

2 GEOMORPHOLOGICAL AND HYDROMETEOROLOGICAL SETTING OF THE COLOMBIAN ANDES

The Colombian Andean Mountain ranges are a tectonically active region with a complex hydro-climatological pattern, which creates a multi-hazard setting where natural hazards are frequent. The geomorphological configuration of the Colombian Andean ranges result from the south-eastward movement of the Caribbean Plate relative to the South American Plate and the eastward subduction of the Nazca Plate beneath the northern Andes along the western margin of Colombia (Kellogg et al. 1995; Taboada et al. 2000; Trenkamp et al. 2002). The Andean region has an area of 282,540 km^2, which constitutes 33% of the country's land area. It is the most populated region of Colombia, with a population of around 34 million people and an average density of 110 inhabitants/km^2. It includes the most important economic centres of Colombia.

Because of the equatorial location, Colombia exhibits rainfall with a highly intermittent nature in space and time, influenced by different elements, such as the atmospheric circulation patterns over the neighbouring tropical Pacific and Caribbean Sea and the combined hydroclimatic and ecological dynamics of the Amazon and the Orinoco basins (Poveda et al. 2007). Additionally, the Andean Mountains influence the dynamics of weather patterns and rainfall over the region. Strong topographic features induce local atmospheric circulations that enhance deep convection, in turn leading to highly intense storms in space and time, triggering flash floods and landslides (Álvarez-Villa et al. 2010; Poveda 2011).

The displacement of the intertropical convergence zone (ITCZ) strongly controls the bimodal annual cycle of precipitation with marked high-rain seasons during March-April-May (MAM) and September-October-November (SON), and low-rain seasons during December-January-February (DJF) and June-July-August (JJA) (Eslava 1993; Mesa et al. 1999; Pabon et al. 2001; Poveda 2007). The interannual rainfall variability is mainly controlled by the effects of both phases of El Niño/Southern Oscillation (ENSO): El Niño (warm phase) and La Niña (cold phase) (Eslava 1993; Mesa et al. 1999; Pabon et al. 2001; Poveda 2007).

In addition to these complex natural conditions, during the last few decades, population growth and increasing urbanization of areas prone to landslides have increased the hazard and risk conditions (Aristizábal 2004). By 2016, the estimated population was about 48 million and the urban population increased to 75% (Departamento Administrativo Nacional de Estadística – DANE 2017).

The most important urban centres are located in the highlands and valleys of the Andes Mountains. Due to these natural conditions, Colombia has a long history of landslide disasters. A debris flow on November 13, 1985 devastated the city of Armero, killing approximately 22,000 people and causing economic losses totalling over $339 million (Garcia 1988; Mileti et al. 1991; Voight 1990). In the city of Medellin on September 27, 1987, a 20,000 m^3 mudslide destroyed more than 80 houses and killed approximately 500 people (Tokuhiro 1999). More recently, on April 1, 2017, a total of 130 mm of torrential rains triggered several landslides in the mountainous terrain of the southern Colombian Andes, causing a flash flood and debris flow along the Mocoa, Sangoyaco and Mulato rivers that destroyed 17 neighbourhoods in the city of Mocoa that were built along the river banks. At least 333 people were killed, and an additional 106 people were missing (García-Delgado, Machuca, and Medina 2019).

The World Bank (2012) presented a general report on the causes and losses of disasters in Colombia during the period 1970–2011. According to this study, the highest percentages of lost lives and homes destroyed correspond to landslides and floods. Aristizábal and Sanchez (2020) compiled a total of 32,022 landslides in the 116-year period between 1900 and 2016, including those triggered by earthquakes, volcanic activity, and rainfall. Their results showed that 93% of the landslides registered are concentrated in the Andean region, where about 80% of the Colombian population is located, and rainfall shows a dominant influence on landslide occurrence, with 92% of the landslides triggered by rainfall, showing a bimodal annual pattern in the Andean region.

In the case of Aburrá Valley, landslides correspond to 3 out of 10 disasters in the region, with 75% of disaster fatalities occurring annually. For the 1880–2007 period, landslides left 1,390 people dead and caused huge economic losses (Aristizábal and Gómez, 2007). Currently, the Aburrá Valley has an estimated population of 3.3 million inhabitants, where 95% is an urban population located in only 26% of the territory (340 km^2 of urban area). The most populated municipalities, Medellín (2.2 million), Bello (372 K) and Itagui (230 K), concentrate a large part of their population on the valley slopes. This population growth has been extremely rapid; in a century, the population of the valley has multiplied by 30, from 103,305 inhabitants in 1905 to 3,317,166 inhabitants in 2005. Figure 1 shows the Metropolitan Area of the Aburrá Valley, which is located to the north of the Colombian Andes. This figure spatially locates the recorded landslides and the rainfall gauges used to establish the relationships between rainfall and landslides that will be presented later.

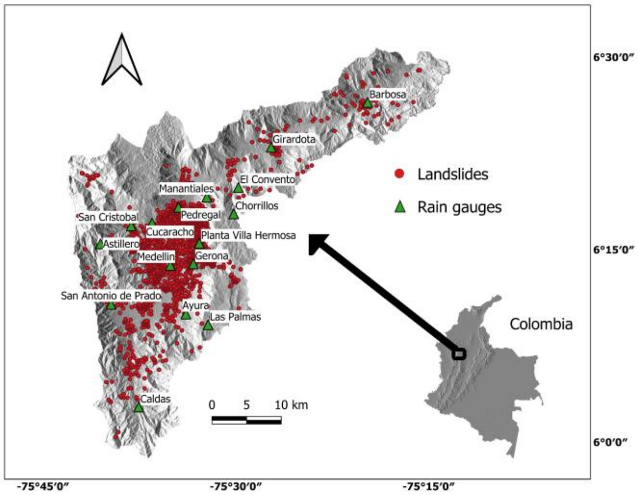

Figure 1. Study area location. Red points correspond to landslide historical data, and green points to rain gauges used for the study.

3 HISTORICAL DATA

The analysis of rainfall as triggering factor in the Aburrá Valley was performed based on 3101 landslides reports from a local landslide database, DESINVENTAR (www.desinventar.org), and a national landslide database, SIMMA (www.simma.sgc.gov.co). 68 years of historical precipitation from 16 homogeneously distributed rain gauges with a 15-minute sampling frequency were used. Table 1 shows the list of rain gauges used in this study. This table presents the period of record, the missing and registered data, and the landslides associated with each rain gauge.

As well as landslides, 12 rain gauges were georeferenced and their area of influence was determined. Within each of the polygons of influence, the rainfall distribution is considered homogeneous and equal to that of the station in which it is measured. This simplifying hypothesis is a source of error. For determining the area of influence for each rainy season, the ArcGis ArcToolbox application was used, through which Thiessen polygons were created; however, taking into account the inconvenience of this method of interpolation to define areas of influence in mountainous regions, we proceeded to modify these polygons considering mainly the topographic features of the valley by constructing a digital elevation model (DEM) of the region, as well as the isohyets of annual average precipitation of each one of the monitoring stations. The modified version of the Thiessen polygons was obtained based on these considerations.

Cross-linking the landslide database and rainfall record and considering the location and date of occurrence of landslides, 2117 landslides could be correlated to the rainfall data available.

Table 1. Rain gauges used in this study.

Rain gauge	Starting measuring range	Missing data (%)	Rainfall data (%)	No. Landslides
San Antonio de Prado	1999	0.0	20.6	109
Villa Hermosa	1948	0.0	17.8	392
San Cristobal	1949	0.0	17.1	194
La Ayurá	1972	0.0	17.6	99
Cucaracho	1992	1.9	16.8	152
El Astillero	1990	0.0	21.3	13
El Convento	1995	0.0	15.9	11
Aguinaga	1954	1.0	14.9	424
Manantiales	1986	2.7	12.1	286
Chorrillos	1948	0.0	19.8	1
Gerona	1996	16.3	15.9	147
Pedregal	1996	1.4	17.1	110

4 RESULTS

To analyse the relationship between the recorded rainfall and the reported landslides for the Aburrá Valley, annual, monthly, and daily temporal scales were considered. Figure 2 shows the spatial distribution of annual accumulated precipitation in the Aburrá Valley, obtained using Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS) with daily temporal data from 1980 to 2018 and 5 km spatial resolution. Higher precipitations occur to the southern and northern region of the Valley, reaching annual precipitation over 3000 mm. In the central valley, annual precipitations are around 1550 to 20000 mm.

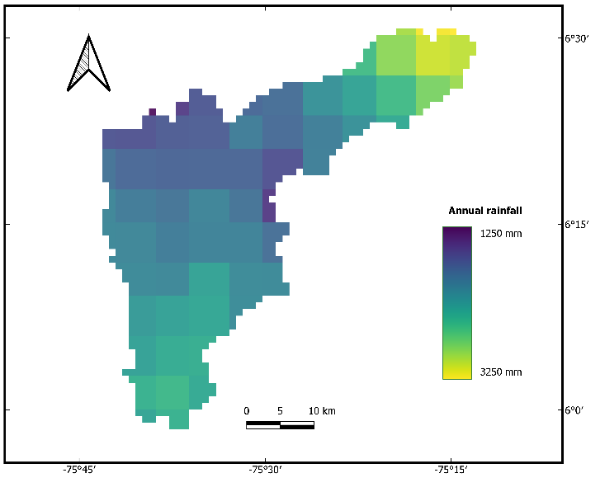

Figure 2. Rainfall spatial variability in the Aburrá Valley using Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS) with daily temporal data from 1980 to 2018 and 5 km spatial resolution.

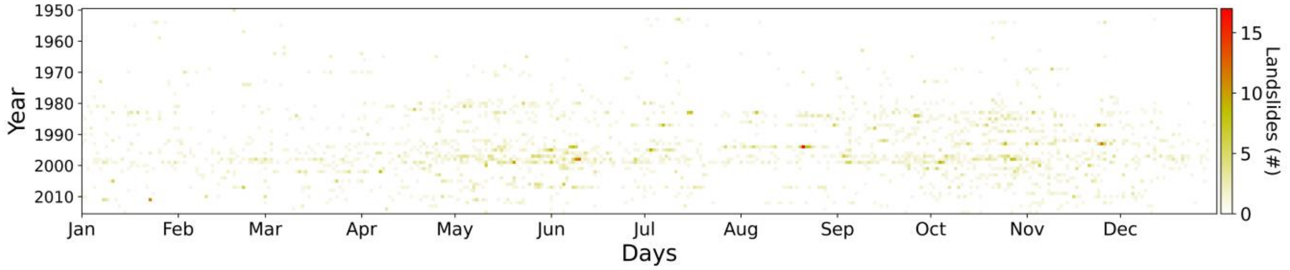

Figure 3. Daily landslide occurrences in the Aburrá Valley from 1950.

Figure 3 presents the daily historical landslide occurrences for the Aburrá Valley since 1950. This figure shows that most landslides have occurred after 1980. Very few landslides were registered in the ’50s and ’60s. However, after the '70s, some landslides start to appear, and they considerably increase after the 80´s. This could be associated to both a greater tendency in more recent decades for government entities to register those landslides, which did not exist previously, and the urban explosion along landslide-prone areas of the valley slopes during the ’60s. In this decade, the Colombian population changed from a predominantly rural population to a mostly urban population.

The localization of landslides is also observed in Figure 1, where the landslide spatial distribution is concentrated in the urban area of the Aburrá Valley. Rural slopes of the valley show just a few and isolated landslides.

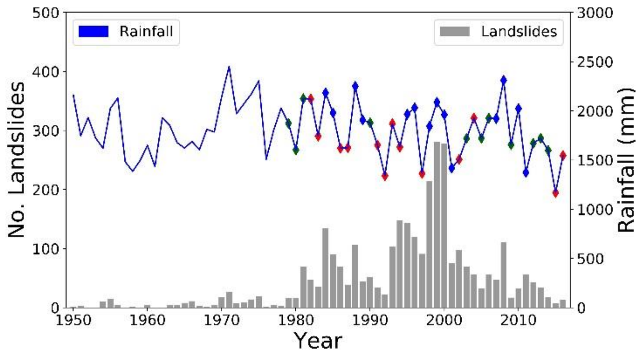

Figure 4. Landslide occurrence and rainfall on an annual temporal scale. Red dots indicate El Niño years and Blue dots mean La Niña years.

Figure 4 shows annual accumulated landslide occurrence and rainfall according to the El Niño South Oscillation (ENSO). This figure shows annual accumulated rainfalls ranging from approximately 1200 mm to 2500 mm. Higher accumulated annual rainfalls and landslides occurrence peaks are associated with the La Niña ENSO phase, which correspond to a rainy year. There was also a landslide occurrence reduction during the last decade, which correlates to a significant reduction in accumulated annual precipitation. The highest annual landslide occurrence corresponds to 1999 and 2000 when four consecutive La Niña years were reported. The rainiest year registered was 1971 with 2451 mm, where 27 landslides were reported.

Figure 5 shows the landslide occurrence and mean rainfall in a monthly temporal scale, with a clear bimodal temporal pattern, two rainy seasons September-October-November (SON) and March-April-May (MAM); and two “dry” seasons December-January-February (DJF) and June-July-August (JJA). Monthly rainfall is a little higher for the rainy season (SON), and less precipitation is presented for the dry season (DJF). However, the dry season (JJA) shows higher values of rainfall.

Additionally, Figure 5 shows a larger number of landslides registered in the second half of the year (July to December); of these, the months with the highest number of landslides correlate directly with the second rainy season of the year (SON). However, for the first half of the year and the first rainy season (MAM), there is no direct correlation between rainfall and landslides, noting that for this rainy season the number of monthly landslides is lower. Once this rainy season ends, the months of June and July show an increase in the number of landslides, even for lower monthly accumulated rainfall. The increase in landslides in June and July indicates a relationship between landslide and antecedent rainfall, associated with the increase in soil moisture from the first rainy season.

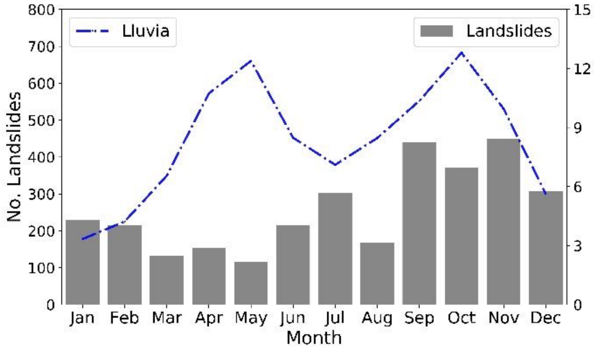

Figure 5. Landslide occurrence and rainfall on a monthly temporal scale

Figure 6 shows the mean monthly precipitation and landslide occurrence considering the ENSO phenomena. For rainfall occurrence, there is a clear bimodal pattern independent of the ENSO phase (El Niño, La Niña, or Normal), while for landslide occurrence, the bimodal pattern is only marked for El Niño and La Niña years.

Additionally, Figure 6 shows that during the first four months of the year, a greater number of landslides are observed for La Niña years and fewer landslides associated with El Niño years. Subsequently, there is an increase in landslides for the months of May, June and July compared to the normal years. From the results in Figures 5 and 6, the peak landslides in the months of June and July are associated with normal rainfall years. Landslides are concentrated in the second rainy season (SON). During a normal year, landslide occurrences are in a similar proportion from June to November. Furthermore, a landslide peak occurs in the month of May, when the first rainy season ends.

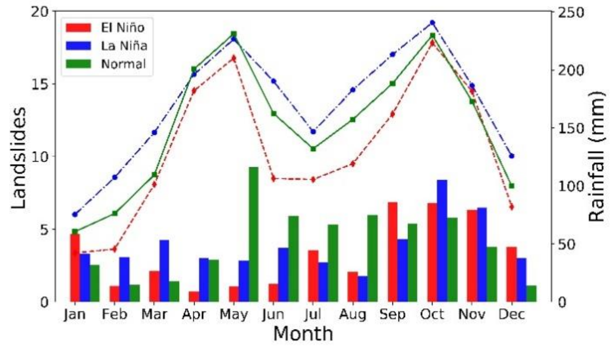

Figure 6. Landslide occurrence and rainfall on a monthly temporal scale, considering the ENSO phenomena.

According to Figure 6, ENSO effects are different between years. During the rainy seasons (MAM and SON), the precipitation is a little higher for La Niña years than for the El Niño years; this difference is increased for the dry season (DJF and JJA), where precipitation in La Niña years is considerably higher compared to El Niño years. Moreover, during the JJA dry season, the precipitation during La Niña years is higher than in the El Niño years, with mean monthly values between 150 and 200 mm, while for the DJF dry season, the mean precipitation is less than 100 mm. The notably larger precipitations during the (JJA) dry season in the La Niña years compared to the El Niño years, could explain the landslide concentration in the second rainy season (SON) because soils are in a more saturated condition before the start of the rainy season.

Finally, Figure 7 shows the percentages of rainfall and landslide occurrence on a temporal daily scale. The bimodal pattern is observed as well, but there is a difference between both rainy seasons. The MAM rainy season is temporally shorter with a higher value of accumulated precipitations, which means less rainy days but more rainfall volume, so higher intensities. The second rainfall season (SON) shows more rainy days with less rainfall volume.

Figure 7 also shows a large number of landslides during the second semester of the year, where the rainfalls have less intensity and longer duration, which suggests that there is a larger effect of this kind of rainfall on soils in the Aburrá Valley. Larger rainfall durations induce more infiltration within the soil, thus, larger water contents, which leads to reduced suction and slope stability.

A final important observation is that landslide occurrence peaks on a daily temporal scale are displaced with respect to the peak rainfall events. The landslide maximum peaks occur several days after the rainfall peak, confirming the importance of antecedent precipitation and precedent humidity conditions of soils in the Aburrá Valley.

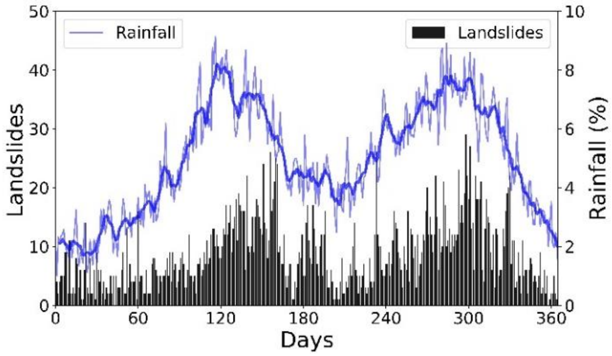

Figure 7. Landslide occurrence and rainfall on a daily temporal scale.

5 CONCLUSIONS

This study analyses the relationship between rainfall and landslides for the Aburrá Valley region in the north part of the Colombian Andes. The analyses focused on the correlation between rainfall and landslides records for the period 1948-2016, at annual, monthly and daily scales.

Rainfalls are the most common triggering factor of landslides in the Aburrá Valley, with a bimodal pattern with peaks during the rainy season (MAM and SON), in a similar way to the temporal precipitation pattern in the northern Colombian Andes.

According to the results, landslide occurrence is concentrated in the second rainy season (SON) because of a previous dry season (JJA) with higher values of precipitation, generating a more saturated soil.

ENSO effects are different between years. During the rainy seasons (MAM and SON), the precipitation is a little higher for La Niña years than for El Niño years; this difference is increased for the dry season (DJF and JJA) where the precipitation in the La Niña years is considerably higher compared to El Niño years.

Additionally, during the first four months of the year, a greater number of landslides are observed for La Niña years and fewer landslides are associated with El Niño years. Subsequently, there is an increase in landslides for the months of May, June and July. Peak landslides in the months of June and July are associated with normal rainfall years.

Landslide occurrence peaks are displaced in relation to rainfall peaks, indicating the important role of antecedent precipitation in the Aburrá Valley, especially for low permeability soils.

The analysis of the relationships between rainfall and the recorded landslides for the Aburrá Valley, using different time scales, allowed the correlation of relevant aspects of the landslides triggered by rainfall, such as the ENSO effect and the accumulated and antecedent rainfall. Likewise, it was possible to observe the dependence of landslides on the type of rainfall cycle, with differences in the rainfall-slides correlations for El Niño, La Niña and normal years. This implies the high dependency of soil instability on rainfall, as well as the need to link infiltration analyses with soil stability analyses for the study of landslides triggered by rainfall.

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