Statistical description of some landslide inventories from Colombian Andes: study cases in Mocoa, Villavicencio, Popayán, and Cajamarca

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Abstract

Landslide inventories are nowadays one of the essential tools to develop mass movement susceptibility, hazard, and risk assessment maps since they compile valuable information related to the spatial-temporal distribution of these processes as well as crucial morphometric information. In the past three years, the Geological Survey of Colombia has been working on mapping landslide inventories in several localities across the Colombian Northern Andes. For instance, one of the most striking inventories relates to the rainfall-induced event in Mocoa, which partially destroyed this capital city in southwest Colombia in 2017. In this work, we compile and analyze four of these recently obtained inventories (Mocoa, Cajamarca, Villavicencio, and Popayán) whose information was gathered by remote sensing analysis and fieldwork. In each inventory, we carried out a morphometric description and discussed the geological and geomorphological contributors to the occurrence of these phenomena. Besides, in order to describe the landslide sizes, we perform a frequency-area distribution analysis and their fit to a power-law.

From the whole dataset, the most significant findings are that most landslides are triggered on steep slopes ranging from 35° to 55°, and their spatial distribution is strictly related to the tectonic framework, i.e., if they are nearby active faults such as the Servitá Fault in Villavicencio or the La Tebaida-Mocoa Fault in Mocoa. In such regions, where drainage incision creates a more dissected landscape with local relief values reaching up to 2000 m, hillslopes tend to be more susceptible to the occurrence of landslide phenomena. Finally, we discuss the representativeness of the fit of landslides magnitudes (areas) to a probability distribution, especially in those cases when landslide inventories were gathered from different information sources, as in the inventories here presented.

1 INTRODUCTION

Landslides are geomorphological processes that play an essential role in the evolution of the landscape, in addition to constituting one of the most significant hazards that every year produces human, economic, and environmental losses in Colombia (The World Bank & GFDRR, 2012). The study and mapping of the factors that affect its occurrence and most relevant environmental characteristics facilitate decision-making for territorial planning and disaster risk management.

Landslides inventories are a vital tool for the elaboration of maps of susceptibility, hazard, and risk of landslides since they record space-time information of the landslides such as location, date of occurrence, classification, geological and geomorphological characteristics, activity, size, detonating factors, among others (INGEOMINAS, 2001). This information is organized in databases constructed from different data sources such as mapping and interpretation of remote sensor images, fieldwork, and even media and archives of local authorities (Guzzetti et al., 2012).

In recent years, the Servicio Geológico Colombiano (SGC), a national authority in the study of hazards of geological origin, has developed landslides inventories in different locations in the Colombian Andes, some in response to emergencies as in the case of cities of Popayán and Mocoa. In other cases, such as the Cajamarca and Villavicencio cities, these inventories were prepared as input for the development of hazard and risk maps for territorial planning purposes.

For the preparation of inventories, traditional geomorphological mapping techniques with the interpretation of aerial images and photographs were used, as well as a detailed field survey. Despite the intention of preparing the most complete landslide inventories, there are difficulties related to the resolution of sensor images and the availability of aerial photographs, access to the areas of study and knowledge of the dates of occurrence, reason why historical or multitemporal geomorphological inventories are generally carried out (Rodríguez et al., 2017).

This paper describes the main geological and geomorphological characteristics (e.g. lithology, slope, and local relief) related to the occurrence of landslides in four inventories of landslides developed in the cities of Mocoa, Villavicencio, Popayán, and Cajamarca, as well as some characteristics related to their sizes, described using non-cumulative frequency area distribution (FAD) curves, in which the areas of the landslides are represented versus the corresponding frequencies (Tanyas et al., 2018).

Since only for the Popayán and Mocoa inventories it is possible to relate some landslides to a detonating rain event and considering the low amount of data for each inventory, the landslides are described from general descriptive statistics, as a starting point to understand the factors that control its occurrence in these areas of Colombia. In this sense, we discuss the need for completeness of landslides inventories, which allows us to better understand the factors that control their characteristics.

2 DATA SET

To develop this work, landslides inventories were carried out in four municipalities located in the Colombian Andes under the jurisdiction of the Servicio Geológico Colombiano (SGC, 2015; 2017; 2018a; 2018b): Popayán (PLI), Mocoa (MLI), Cajamarca (CLI), and Villavicencio (VLI). These landslide inventories correspond to historical inventories, elaborated with a combination of photointerpretation of remote sensors and field validation (Malamud et al., 2004), in which landslides characteristics such as type of landslide, local geology, magnitude, among others, were considered. Figure 1shows the location of the inventories on the map of Colombia.

A total of 1788 landslides were inventoried, distributed in each municipality, as shown in Table 1. Some landslides were classified as flows and included in the analysis because they began as surface landslides that moved downslope in the form of flows not channeled. Due to the low percentage of landslides verified in the field with respect to the total number of records, between 2,8% and 47,8% in Mocoa and Cajamarca, respectively, we obtained significant uncertainties when calculating landslide volume. Therefore, in this work, we solely analyze frequency distribution in terms of landslide areas.

The MLI contains a total of 650 landslides in an area of 46,8 km^2 (13,9 l/km^2), of which 534

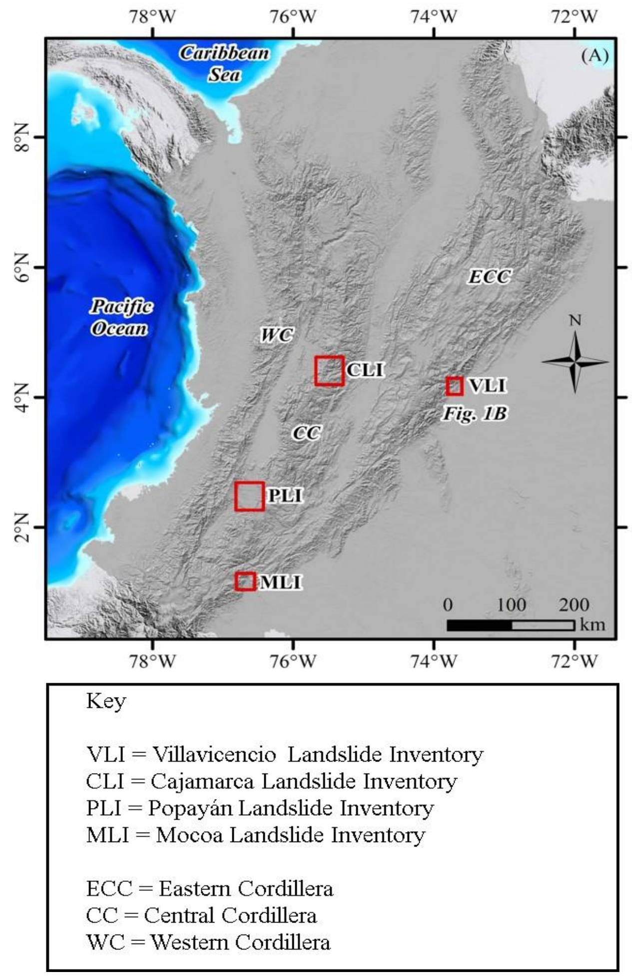

Figure 1. Geographical location of landslides inventories.

surface landslides occurred by a heavy rain of 129 mm in 3 hours (García-Delgado et al., 2019), measured at a station in the urban zone, 511 were classified as flows that contributed to the flow of detritus that affected the urban area of the municipality of Mocoa, Figure 2c. Of the 648 landslides, many were considered swarms with up to 4 fault escarpments that joined down the slope as flows. Due to the difficult access, only 193 landslides were verified in the field. The landslide areas ranged between 19,7 m^2 and 23.648 m^2 and occurred in the basins of the Taruca and Taruquita streams, in which the Mocoa Monzogranito mainly emerges, which has developed residual soils of thicknesses up to 1,5 m.

The VLI contains a total of 385 landslides in an area of 294,6 km^2 (1.3 l/km^2), for which there are no specific recorded events (Figure 2a). 16.9% (65) of landslides were verified in the field. Landslide areas are in a range between 128 m^2 and 165.691,5 m^2, the latter being between 3 and 7 times larger than the maximum areas of the other inventories of landslides and corresponds to digging processes. Landslides occur mainly in residual soils from shales, siltstones, and mudstones and metamorphic rocks.

Figure 2. Representative landslides of the study areas: (A) Villavicencio, (B) Cajamarca, (C) Mocoa and (D) Popayán.

The PLI contains a total of 492 landslides in an area of 478,3 km^2 (1,02 l/km^2), for which there are no specific recorded events, Figure 2d. The 47,8% (235) of landslides were verified in the field. Landslide areas are in a range between 40,1 m^2 and 35.225 m^2. Landslides occur mainly in residual soils, from primary and secondary volcaniclastic deposits and lahar deposits.

The CLI contains a total of 261 landslides in an area of 514 km^2 (50,8 l/km^2), for which there are no specific recorded events, Figure 2b. The 38,7% (101) of landslides were verified in the field. Landslide areas are in a range between 36,8 m^2 and 56.672 m^2. Landslides occur mainly in residual soils, sedimentary rocks, volcaniclastic deposits, and colluvium deposits.

3 METHODS

Each landslide inventory is collected according to the data and attributes model defined by Rodríguez et al. (2017), in which are identified characteristics such as geographical location, type of movement, affected area, morphometry, part of the landslide (e.g. escarpment or initiation area and deposit or accumulation zone), thickness, volume, type of material displaced, date of occurrence, conditioning, and triggering factors, among others. This information was reviewed in GIS in order to adjust possible errors of digitization of individual landslides, especially considering the various sources of information used, the activity and distribution of landslides (e.g. retrogressive, widened, or coalescing landslides).

To describe the influence of lithology on the occurrence of the mass movements, the analysis of the relationship between the area of the mass movements and the area of the different lithologies that emerge in each study area was taken into account, applying the "Lithological landslide enhancement factors-LEF" used by Borgomeo et al. (2014) cited by Roda-Boluda et al. (2018), which is defined in Equation 1:

$$\mathrm{LEF} = \frac{(A_{LL})/(A_{LT})}{(A_{Lit})/(A_{T})} \quad (1)$$

Where A_{LL} is the area that presents mass movements in each lithology, A_{LT} is the total area with mass movements within the study area, A_{Lit} is the emerging area of each lithology, and A_T is the total studied area.

The geomorphological characteristics are described according to the analysis of the terrain slope and the local relief. These geometric characteristics were obtained using the ALOS PALSAR DEM (ASF, 2011). To assess the influence of the slope, it was considered the hillslope inclination value at the initiation point of each movement. While, to analyze the representativeness of the local relief, verifying the height difference between the highest and lowest point of the hillslope and its spatial relationship with the initiation point of each landslide.

Since we worked with geomorphological inventories (which are considered as incomplete), the area (size) of the landslides is described according to the non-cumulative frequency density, proposed by Malamud et al. (2004) as:

$$f(A_L) = {}^{\delta N_L}/_{\delta A_L} = N_{LT}\,p(A_L) \quad (2)$$

Where $f(A_L)$ is the frequency density of landslide areas, δNL is the number of landslides with areas between AL and A_L and $A_L + \delta A_L$, N_{LT} is the total number of landslides in the inventory and $p(A_L)$ is the probability density function (PDF), which according to Malamud et al. (2004) can be represented according to a three-parameter inverse-gamma distribution. It is important to note that in this function, the value of N_{LT} is obtained from an inventory of substantially complete landslides.

For plotting the FAD, the bin width increase so that they are approximately equal in logarithmic coordinates. More details about this function are given in Malamud et al. (2004).

Several authors have stated that the majority of FAD of landslide areas can be adjusted according to a potential law for medium to large landslides (Guzzetti et al., 2002; Stark and Hovius, 2001; Malamud et al., 2004), and a divergence from the power-law toward high frequencies with a rollover point where frequencies decrease for smaller landslides (Tanyas et al., 2018). The point where the FAD diverges from the power law is defined as the cutoff point. Above the value of the cutoff, the distribution of non-cumulative areas is defined as a potential law of the form:

$$p(x) = Cx^{-\beta} \quad (3)$$

Where x is observed value (in this case, landslide areas organized in bins), C is a normalization constant, and β is the power-law exponent. The normalization constant, C, depends on the power-law exponent and a cutoff point.

Considering the limitations related to the completeness of the data, in this work the cutoff and power-law exponent values were determined with an adjustment according to the method of Clauset et al. (2009), which consists of a goodness-of-fit test to measure the distance between analyzed data and synthetic datasets from an accurate power-law distribution. To quantify the distance between the two distributions, Clauset et al. (2009) used the Kolmogorov – Smirnov (KS) statistic test. Parameter fitting is made using maximum likelihood estimators. Because there is not a well defined adjustment above the cutoff, the rollover range was estimated using the binning method (Tanyas et al., 2018).

4 RESULTS AND DISCUSSION

4.1 Lithology

When reviewing the area of mass movements and their relationship with the outcrops of the lithological units through the LEF of Equation 1, it was observed that in general, the behavior is variable (Figure 3a), for example, in the VLI there is a remarkable tendency of the lithological units in which the movements are overrepresented (LEF> 1), corresponding to residual soils (LEF = 4,8), colluvial deposits (LEF = 1,8) and sedimentary rocks of fine grain (LEF = 1,4), which means that these units are the most likely to develop morphodynamic processes (Roda-Boluda et al., 2018), while in the rest of the lithologies mass movements are underrepresented (LEF <1). In the MLI, there is no apparent predominance of any of the lithological units in the occurrence of

Table 1. Main characteristics of the inventories of this work.

Attributes	**Mocoa Landslide Inventory (MLI)**	**Villavicencio Landslide Inventory (VLI)**	**Popayán Landslide Inventory (PLI)**	**Cajamarca Landslide Inventory (CLI)**
Study area (km^2)	46,8	294,6	478,3	514
Total number of landslides	650	385	492	261
Type of landslides (l:landslide, fl:flow)	l:102, fl: 548	l:385	l:492	l:198, fl:63
Active (a), inactive (i) and reactivated (r) landslides	a: 533, r: 117	a:334, i:51	a:296, i:196	a:115, i:146
Field validated landslides	193 (29,7%)	65 (16,9%)	235 (47,8%)	101 (38,7%)
Type of remote sensing data; resolution (date)	UAV imagery – IGAC; 0,1 m (2017) Landsat 7; 7m a 30 m (2002, 2005, 2008, 2010) Landsat 8; 30m (2013) Sentinel 2A; 10 m (2016)	Digital Globe Imagery; 0,3 m to 1 m (2002, 2005, 2010, 2012, 2016, 2018) SPOT Imagery; 12 m (2007) Sentinel 2A; 10 m (2015) CNES/Airbus Imagery; 1 m (2017) PlanetScope Imagery; 3 m (2018)	Rapideye; 7m (2010) Google Earth Imagery; 15 m (2007, 2009, 2012, 2013, 2014)	Aerial photographs; 30m a 60 m (1979) Ultracam Imagery (2009) Sentinel 2A; 10 m (2015) Google Earth Imagery; 15 m (2015)
Landslide total area (km^2)	1,1	4,5	1,2	1,1
Maximum area (m^2)	23648	165691,5	35225,2	59672,0
Minimum area (m^2)	19,7	128,7	40,1	36,8
Landslide mean area (m^2)	1662	11639	2466,6	4087,7
Dominant lithology exposed	Mocoa monzogranite, sedimentary rocks of Pepino, Orito and Rumiyaco Formations	Sedimentary rocks of Macanal Shales, Red beds of Guatiquía, siltstones, and mudstones of Pipiral; metamorphic rocks of Susumuco Phyllites	Residual soils from primary and secondary volcaniclastic deposits of the Río Hondo Set, Polindará Member, Palacé Set, San Bernardino Set and lahar deposits in a smaller proportion	Sericite Schists, Chlorite Schists from Cajamarca Complex, Volcaniclastic deposits, and fluvio-alluvial deposits

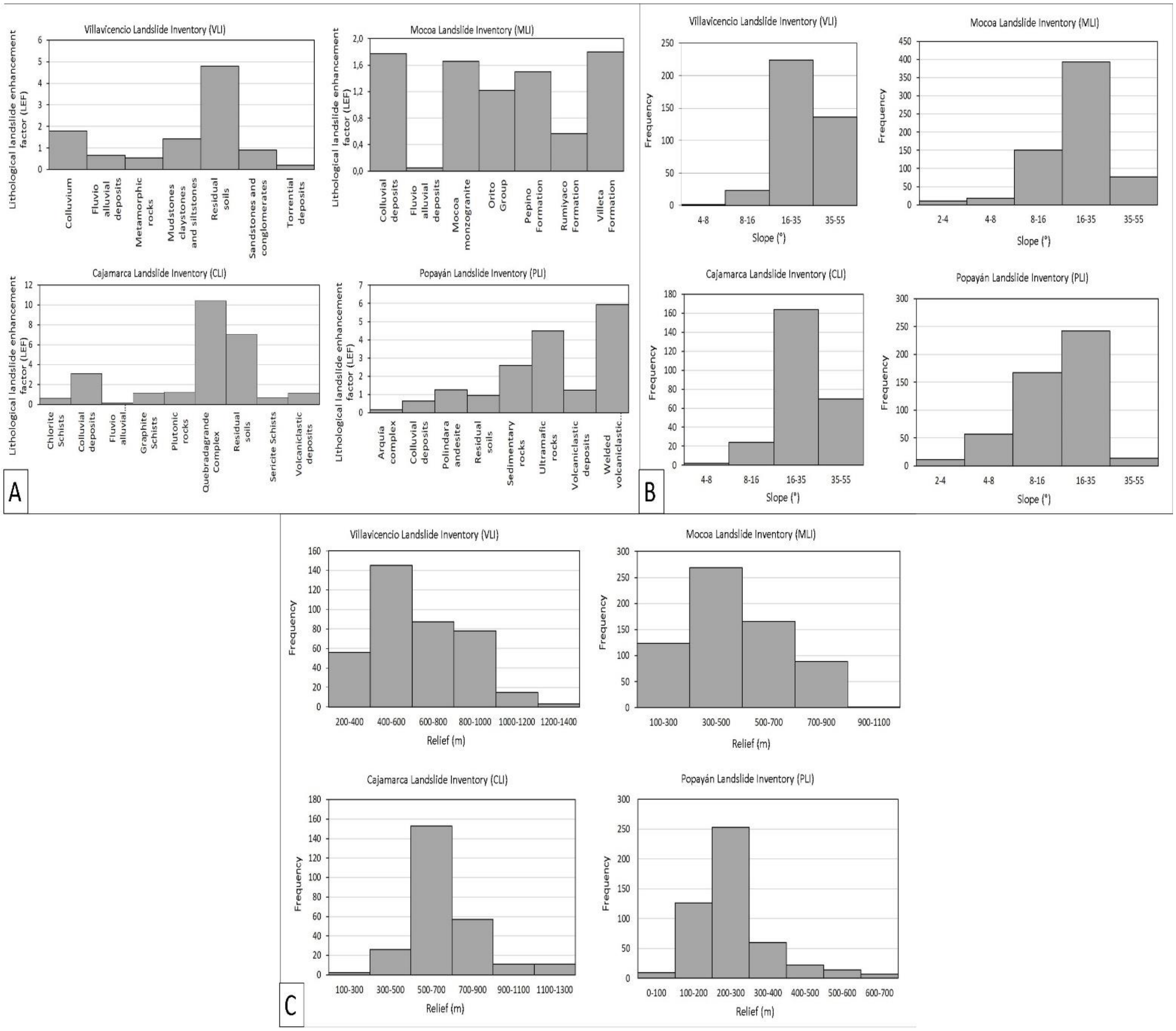

Figure 3. (A) LEF-Lithology graphic for the inventories of this work. (B) Slope histograms for the inventories of this work. (C) Relief histograms for the inventories of this work.

MM, since more than 70% of the lithological units with the presence of movements have LEF> 1, and there is no notable difference in these values since they range between 1,2 – 1,8. In the case of the CLI, it is similar to that of VLI, since there is a predominance of the lithologies with the highest values of LEF, which correspond to residual soils (LEF = 7), sedimentary rocks of the Quebradagrande Complex (LEF = 10,4) and colluvial deposits (LEF = 7,1).

In the case of the PLI, the trend is different from the previous ones, since the LEF has the highest value in welded volcaniclastic deposits (LEF = 6), followed by Ultramafic rocks (LEF = 4,5), and sedimentary rocks (LEF = 2,6), indicating that they are highly weathered and potentially more unstable materials; while the rocks of the Arquía Complex, Colluvial, Volcaniclastic Deposits, and Residual Soils have LEF values less than 1, indicating that in these lithologies, the movements are underrepresented. In the case of the MLI, it is considered that the precipitation event of March 31, 2017, that reached a maximum value of 129 mm in 3 hours and its involvement in the entire study area, controlled the spatial distribution of mass movements. Therefore, there is no specific predominance of any of the lithological groups as the primary conditioning factor in the occurrence of movements.

In the VLI, the highest LEF value is for the residual soils (primary material mobilized in the VLI), which were defined and mapped including horizons IV and V (saprolite) of the Dearman's weather profile (Dearman, 1974), which influenced the increase in the total sliding area and also the maximum thickness of the movements that reached 5 m. In the case of the MLI, the displaced material was not defined as part of the residual soil but was considered as highly and fully weathered rock units, which also determined that the LEF values were distributed homogeneously in the different lithologies.

4.2 Slope

The relation between the slope with the starting point of landslides showed that the highest density of these occurs in the range between 16° and 35°. However, the MLI and PLI have in common the second slope range with the highest number of movement start zones is between 8° and 16°, while in VLI and CLI, the next predominant slope range is 35° and 55° (Figure 3b).

The similar behavior observed between MLI and PLI is due to the presence of residual soils derived from rock units and waste, affected by detonating rain events, which affects the activation of MM in a slope range with lower values. While in the case of VLI and CLI, the material displaced in the movements corresponds mainly to heavily weathered rock and lower saprolite thicknesses, so it is expected that a range with higher slope values is required to detonate movements.

4.3 Local Relief

The local relief (LR) corresponds to a parameter that implicitly involves morphometric and topographic aspects and refers to the difference in elevation (expressed in units of length) that exists between the highest point of a slope and the lowest point of the respective valley that limits it. This is an indicator of the intensity or degree to which the earth's surface is affected by exogenous agents such as wind or rivers (Aili L., 2008).

When reviewing the results of the local relief for each inventory (Figure 3c), it was found that in the VLI and MLI, the maximum and minimum values are in the range of LRmin = 100-200 m and LRmax = 1100-1400 m, the largest concentration of mass movements occurs in reliefs between 500-700 m and the lowest occurrence of movements occurs in areas with LR>1000 m. This similar behavior is related to the geotectonic context in which they are found. These inventories were gathered from the eastern foothills of the Eastern Cordillera, where the recent tectonic activity of the Servitá Fault in the VLI and Mocoa-La Tebaida Fault in the MLI, might control river incision and hillslope instability. On the other hand, in the PLI there is a notable difference in terms of LR values ranging from 100 to 700 m, with greater occurrence of mass movements in the reliefs between 200 and 300 m, which can be explained by its different geotectonic context located in the western foothills of the Central Cordillera.

4.4 Frequency-area distribution

The FAD of the inventories analyzed is presented in Figure 4. As can be seen, for smaller landslide sizes, the inventories do not exhibit a clear pattern of behavior, so the definition of the rollover point is approximate in these distributions. The FAD for medium to large landslides barely matches the slope of the power-law exponent presented by Malamud et al. (2004). The form and position of the rollover do not follow the distribution proposed. Table 2 shows the adjustment parameters determined for each inventory. The determination of the parameters of the inventories was made to support the statistical description of the data and to be able to compare them. However, evaluation of the goodness of fit of these parameters is beyond the scope of this work.

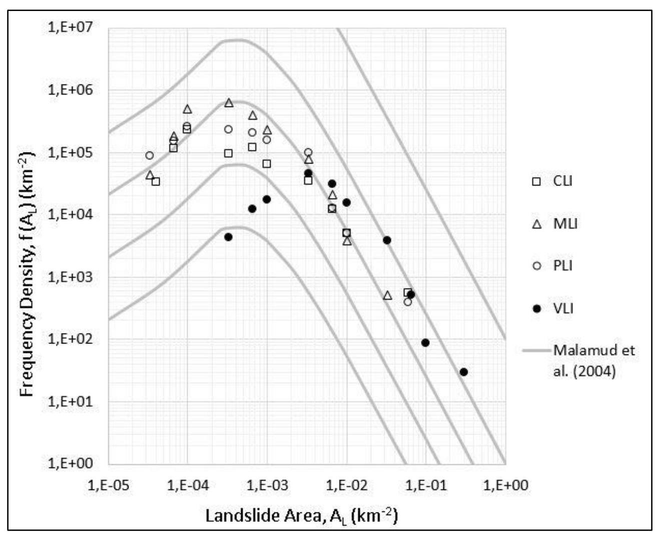

Figure 4. Frequency density distribution for analyzed landslide inventories; CLI: Cajamarca, MLI: Mocoa, PLI: Popayán and VLI: Villavicencio. The continuous line represents the general distribution proposed by Malamud et al. (2004) for a varying number of landslides NLT.

As can be seen in Table 2, the Mocoa inventory has a more adjusted rollover range, which may be related to the lower uncertainty in the process mapping. This is because the majority of the inventoried processes were triggered by the precipitation event of March 31, 2017. Besides, from the multitemporal image analysis, aspects such as reactivations or source, deposit, or runout areas could be differentiated. Although for the Villavicencio inventory there is also a low dispersion of the rollover data, a size of ≈ 0,003 indicates low representativeness of the data for the smaller slip sizes (Tanyas et al., 2018).

Tabla 2. Parameter estimates of the power-law model for each inventory.

ID	Cutoff point (km-2)	β	Approximate rollover range (km-2)
PLI	0,0017	2,548	0.0001 - 0.001
MLI	0,00183	2,305	0.00038 - 0.00044
CIL	0,0024	2,057	0.00037 - 0.0008
VLI	0,0083	2,196	0.003 - 0.0035

The larger values of rollover and cutoff presented by the Villavicencio inventory may correspond to landslide distributions rather than to the sources of information or mapping techniques, as some authors have discussed (Guzzetti et al., 2002). As presented in Figure 4, in this area, the processes tend to present retrogressive distributions due to erosion and instability of the areas adjacent to the landslides, presenting coalescence between different processes that make it challenging to define their sizes.

Although there is no clear relationship between the type of material and the rollover, the largest dispersions associated with medium-large sizes occur in areas where instability processes involve greater material thickness, as in the case of PLI and VLI. They also coincide with the presence of residual soils that allow the development of more deep-seated landslides. In the case of MLI and CLI, they have the same tendency in their frequency area distribution, but the data does not allow them to relate in terms of their geological and geomorphological characteristics.

The statistical parameters of the exponential law part of the Popayán and Mocoa inventories show a similar trend. The only aspect that relates to this trend is the fact of having the most significant amount of data, some of which could be related to a triggering event.

The analysis presented indicate high uncertainties and difficulty for data discrimination concerning the geoenvironmental characteristics of the study areas. However, given the small amount of data, all available landslides were analyzed, so aspects such as imagery spatial resolution, mapping methodology, triggering factors, distribution, and activity of the landslides are not sufficiently explained. Likewise, with the proposed adjustments to probability distributions such as those of Stark and Hovius (2001) or Malamud et al. (2004); For the amount of data analyzed, only one statistical trend was established in order to make the most of the amount of data available.

5 CONCLUSIONS

This study presents some geological characteristics of four inventories of landslides ocurred in the Colombian Andes. The landslides were statistically characterized to establish their general trends. Also, some factors that control the FAD of inventory of landslides are examined, discussing the need for sufficient data to be able to establish relationships with characteristics such as mapping resolution, lithologies, trigger factors, or subjectivity in the mapping.

Aspects such as activity and distribution of landslides or coalescence with other geomorphological processes such as erosion should be considered when describing the representativeness of the inventory in characteristics such as the size of the landslide. These characteristics mask the occurrence of slides of smaller sizes with a high frequency of occurrence.

The possibility of differentiating the parts of the landslides as source zone, deposit zone, or runout allows a better analysis of the FADs.

The uncertainties associated with the quality and quantity of the analyzed data do not allow us to establish the representativeness of the description of the inventories with a power-law adjustment. However, this paper presents some highlights that can serve as a starting point for the analysis of data under conditions similar to those described here.

The difference of criteria in the definition and cartography of lithological units in each study area, did not allow to establish a clear relation in the values of LEF.

The completeness, the certainty, and the number of movements mapped in a landslide inventory are the key factors to perform a proper statistical analysis of the relationship between the geoenvironmental characteristics of a territory and the frequency of the magnitude of landslides.

It is recommended that in order to carry out any type of analysis involving landslide magnitudes, the individual polygon cartography that represents the total area affected for each landslide be available.

The similarity in terms of slope ranges with greater frequency of landslides between records of landslides inventories is related to the lithological characteristics and the relief.

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