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Spatial and temporal patterns of fatal landslides in Colombia

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Abstract

Colombia, due to its geographical conditions, has a long history of landslide disasters, which have caused 34,248 fatalities over a period of 99 years. Among the most important landslide related events are the one registered on November 13, 1985 in the city of Armero, causing more than 22,000 fatalities and the one registered in the city of Medellín on September 27, 1987, with approximately 500 fatalities. Recently, the most catastrophic event in Colombia occurred on April 1, 2017 in the Amazon region in the city of Mocoa, where the rains triggered several landslides that generated a debris flow that partially destroyed the city and left 333 fatalities. Detailed recordings of landslide occurrences and their associated losses are the basis for risk management and mitigation studies. This paper presents the distribution of landslide occurrences with associated deaths in Colombia, using a database composed of 2,338 landslide records collected over 99 years (1921 to 2019) and obtained from inventories registered in the DESINVENTAR and SIMMA databases. These databases have information on the location of the landslides with a 100 m uncertainty for 49% of the records and the remainder has information on the city location where they occurred. About 40% of the records have information on the trigger factor of the landslide; of these, precipitation is the most common cause, which is consistent with other studies that confirm the close relationship between precipitation and landslides. In addition, although landslides related to volcanic activity only represent 0.2% of total landslides, they cause 65% of fatalities. These types of studies provide an adequate understanding of the relationships between human losses from landslides, which is useful for formulating mitigation strategies and policies, such as land-use planning and developing early warning systems.

1 INTRODUCTION

Worldwide mass movement hazard and susceptibility studies highlight the negative effects of landslides, resulting in thousands of fatalities annually, as well as significant economic losses (Petley, 2012; Kirschbaum et al. 2015; Haque et al., 2016). Moreover, previous studies show the need to consider the geomechanical properties of the materials that compose the slopes, the active geomorphological processes and characteristics of the terrains in addition to landslide inventories in order to predict spatial patterns of future mass movement events (Stanley & Kirschbaum, 2017).

According to the world's non-seismic landslide database presented by Froude & Petley (2018), between 2004 and 2016, 55,997 people died in 4,862 events. They concluded that the occurrence of landslides is increasing due to human activities. For Latin America and the Caribbean, Sepulveda & Petley (2015) provided information on 11,631 fatalities due to 611 landslides in these regions, based on a landslide inventory for 2004 and 2013. In this study, they highlighted high landslide hazard areas in Haiti, Central America, Colombia and Southeast Brazil.

According to Aristizábal & Sánchez (2020), Colombia is one of the countries most affected by landslides in Latin America, with a total of 30,730 events occurring between 1900 and 2018, resulting in 34,198 fatalities and around US$654 million in economic losses. Among them are the event registered on November 13, 1985 in the city of Armero, causing more than 22,000 deaths and the one registered in Medellín on September 27, 1987, with approximately 500 victims. Recently, the most catastrophic event occurred on April 1, 2017 in the Colombian Amazon region in the city of Mocoa, where rains triggered 763 landslides that resulted in a debris flow that partially damaged the city and left 333 fatalities (García-Delgado et al., 2019).

Several studies have drawn conclusions on the close relationship between hydrometeorological conditions as triggers for landslides in the Colombian Andes (Aristizábal & Gómez, 2007; Aristizábal et al., 2010). At the same time, the National Unit for Risk and Disaster Management in Colombia emphasizes the need to carry out more detailed studies of landslide risk as a requirement for its incorporation into land-use plans, specifying technical conditions, scope, selection of study areas and expected products (Ávila Álvarez et al., 2016; GEMMA, 2007; DAGRD, 2015).

This paper presents the distribution of fatal landslides among the Colombia regions, through a database of 2,338 records, between 1900 and 2019. This analysis allows one to understand the causes of fatal landslides in Colombia and their spatial and temporal patterns. The results can be used as a basis for formulating landslide risk mitigation strategies, developing early warnings, and in land use planning policies.

2 STUDY AREA

Colombia is located in the north of South America (Figure 1), its tectonics and geomorphology are the result of the south-eastward movement of the Caribbean Plate in relation to the South American Plate and the eastward subduction of the Nazca Plate under the Andes Mountains along the western margin of Colombia (Kellogg et al., 1995; Taboada et al., 2000; Trenkamp et al., 2002). These tectonic conditions not only result in a medium to high seismic hazard for much of the territory (Vega & Hidalgo, 2016) but also in a mountainous relief with the presence of 63 volcanoes, of which 17 are active and most are commonly surrounded by densely populated areas with a long history disasters (AMVA, 2007; IDEAM, 2001; Taboada et al., 2000; Mann & Corrigan, 1990).

Colombia's equatorial location allows for high solar radiation and water availability throughout the year, resulting in the formation of thick soil profiles. On average, 70% of Colombia's territory is exposed to 2,000 mm of rain per year, with extreme contrasts on the Pacific coast, where annual rainfall can exceed 8,000 mm/year and desert environments in the north of the country (Eslava, 1993; Poveda et al., 2006). The displacement of the intertropical convergence zone (ITCZ) strongly controls the annual cycle of Colombia's hydroclimatology. Precipitation is characterized by two regimes: bimodal in the Andean zone, whose rainy quarters are March-April-May and September-October-November, and unimodal regimes in the eastern part of Colombia (Puertas & Carvajal-Escobar, 2008). The inter-annual variability of rainfall is mainly controlled by the effects of both phases of El Niño/Southern Oscillation phases, El Niño (warm phase) and La Niña (cold phase) (Poveda et al., 2007; Pabon et al., 2001).

The complex geographical and hydroclimatological environment mentioned above has resulted in a very diverse country that is divided into five natural regions, as shown in Figure 1, Andean, Caribbean, Pacific, Orinoco and Amazon regions (DANE, 2005).

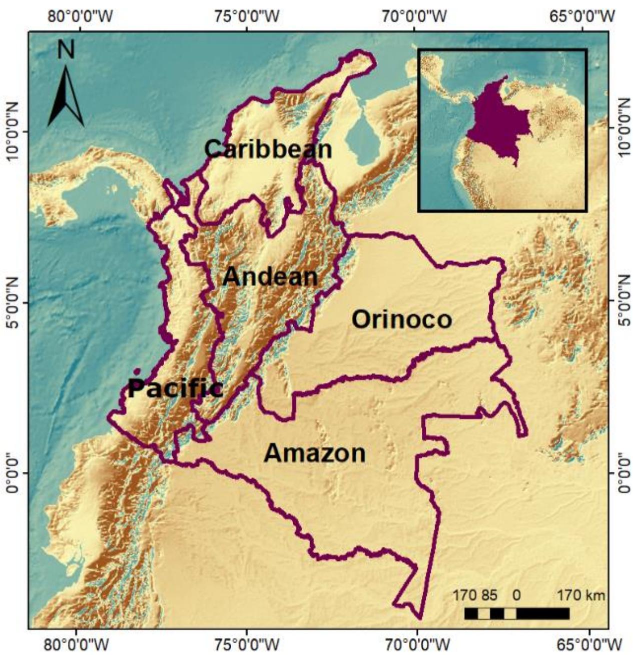

Figure 1. Location of the study area

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 34 million people and an average density of 110 inhabitants/km^2. The Caribbean region covers an area of 132,288 km^2, with a population of 10 million people and an average population density of 74 inhabitants/km^2. The Pacific region is in the western part of Colombia, with an area of 116,290 km^2, a population of one million people and a low density of 31 inhabitants/km^2. Finally, the Orinoco and Amazon regions occupy approximately 830,000 km^2; less than 3% of the total population resides in these lowland areas, with an average population density of less than 6 inhabitants/km^2 (DANE, 2005; IDEAM, 2004).

3 THE COLOMBIAN LANDSLIDE DATASET

For this work, the landslides recorded in Colombia were taken from two databases. The Disaster Inventory System—DesInventar (www.desinventar.org)—of the Social Studies Network on Disaster Prevention in Latin America—LA RED, and the Landslide Information System—SIMMA (http://simma.sgc.gov.co)—of the Colombian Geological Service (SGC). Both databases were purged to avoid repeated landslides records. Additionally, the information in these databases were corroborated and complemented with local and regional landslide catalogues from government offices, reports from aid agencies, scientific articles and newspapers. All types of mass movements proposed in the classification by Cruden & Varnes (1996) were considered, according to the descriptions available in the records. For this study, only landslides with associated fatalities were considered to reduce the under-reporting typically associated with landslide inventories. As expressed by other authors, fatal landslides have higher visibility and therefore, a higher possibility of being included in databases.

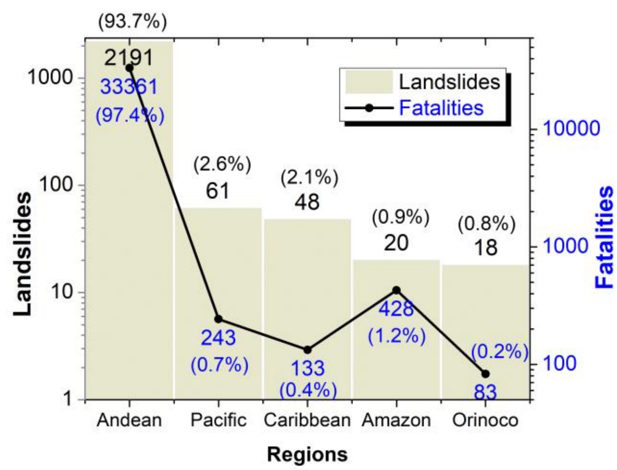

Figure 2. Number of landslides events and fatalities in the geographical regions of Colombia

Figure 2 shows the relationship between the recorded landslides and the number of fatalities for each of the geographical areas presented in Figure 1.

A total of 2,338 landslides with associated fatalities were recorded in Colombia, resulting in 34,248 fatalities over a period of 99 years (1921-2019). 49% of the records have precise locations with a level of uncertainty of 100 m. The remaining 51% only present the location of the municipality where the event occurred and were, therefore, spatially located at the centre of the municipality. Figure 3 shows the points corresponding to the landslides with precise location and those events for which it was necessary to assume coordinates.

Figure 3 shows the distribution of fatal landslides in Colombia. The density of fatal landslides is low for the Orinoco and Amazon regions, which comprise flat plains on which landslides are not very common, with 8 and 20 landslides, respectively, in the 99-year series. In contrast, it is notable that the landslide density is higher for the mountainous regions, especially in the Andean region, concentrating 93.7% of the data recorded in the database.

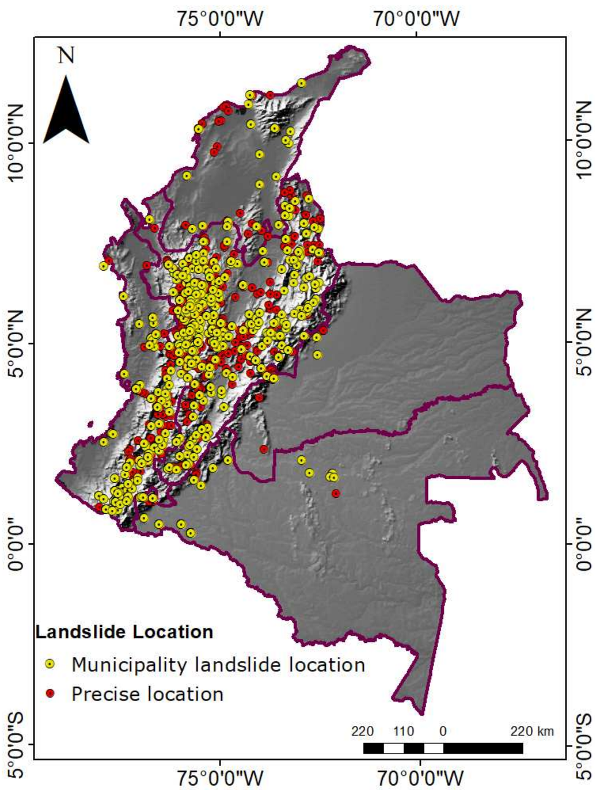

Figure 3. Location of landslides registered in Colombia.

The recorded fatalities are also concentrated in the Andean region with 97.4% and a total of 33,361 fatalities. This is followed by the Amazon region, with 428 victims, exceeding the Pacific and Caribbean coastal regions. Although the number of landslides was lower, the number of human losses exceeded the sum of both regions (376 fatalities); this is due to the recent event in the city of Mocoa with 333 fatalities, representing 78% of the total fatalities in this region. Finally, the Orinoco region registered the lowest number of fatalities and landslides.

4 ANALYSIS OF THE TEMPORAL AND SPACE PATTERNS OF LANDSLIDE FATALITIES IN COLOMBIA

Table 1 lists the seven most catastrophic events presented in the historical series that have been caused by debris flows. Figure 4 presents the annual historical record of both the landslides and the fatalities recorded by the events, highlighting in blue the extreme events listed in Table 1.

Table 1. Information on the seven most representative events in relation to the number of recorded fatalities.

#	DATE	TYPE	CITY (REGION)	FATAL.	TRIGGER.
1	Nov 26, 1933	Debris flows	La Paz (Andean)	300	Unknown
2	Aug 11, 1938	Debris flows	Andes (Andean)	200	Rainfall
3	Jun 28, 1974	Debris flows	Guayabetal (Andean)	300	Rainfall
4	Nov 13, 1985	Debris flows	Armero (Andean)	22100	Volcanic activity
5	Sep 27, 1987	Complex slide-mud	Medellin (Andean)	500	Human activities
6	Jun 6, 1994	Debris flows	Páez (Andean)	1100	Earthquake
7	Apr 1, 2017	Debris flows	Mocoa (Amazon)	300	Rainfall

Figure 4 shows that the lowest number of fatalities occurred in 1961, with only one death recorded from a landslide, while the highest number of fatalities was 22,216 in 1985, with 35 landslides recorded that same year, but the count is dominated by the event in the city of Armero in 1985 with 22,000 fatalities in total. In contrast, the year with the most events was 2011 with 137 events and 395 fatalities.

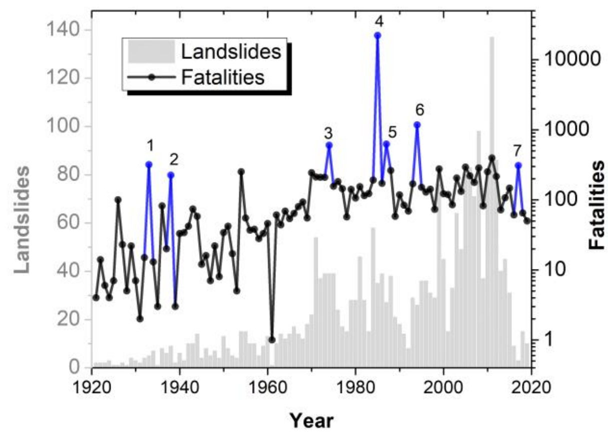

Figure 4. The number of slides and fatalities per year.

Figure 4 shows a general upward trend in both recorded landslides and fatalities, especially since 1970. Two factors could explain this situation, a considerable improvement in systematic data collection associated with an increase in information on landslides in regional and national entities over the last few decades and the increase in the urban population in Andean cities (Aristizábal & Sánchez, 2020). However, in 2018 and 2019, fatalities due to landslides tended to decrease, which could be attributed to efforts by the authorities to mitigate human and economic losses in recent years. Of this historical series, the ten deadliest years occurred in the 1985–1995 period, with more than 25,000 fatalities among the extreme events mentioned in Table 1, such as the Nevado del Ruiz disaster in the cities of Chinchiná and Armero in 1985 that caused 22,100 victims (Voight, 1990); additionally, other landslides that, although small, also caused great human losses, such as those that occurred in 1974, 1985, 1987 and 1994, registered total human losses equal to 301, 116, 126 and 74 fatalities, respectively.

Table 2 presents a list of the landslides organized by their type of trigger. This table shows that most of the landslides recorded (60.3%) have no record of their triggering mechanism. This can be explained by a poor culture of recording these events in previous decades, as well as a lack of knowledge about the mechanisms that triggered them. The landslides triggered by rainfall correspond to 35.2%. Those triggered by human activity, which includes illegal mining and the construction of civil works, among other unspecified activities, correspond to 4.2%. Finally, 0.2% are associated with earthquakes and volcanic activity in the mountainous region of the Colombian Andes.

Table 2. Landslides events and fatalities organized by their triggering mechanisms.

Triggering	Landslides	Landslides (%)	Fatalities	Fatalities (%)
Volcanic Activity	4	0.2	22,126	64.6
Unknown	1,410	60.3	5,049	14.7
Rainfall	822	35.2	4,920	14.4
Earthquake	4	0.2	1,149	3.4
Human activity	98	4.2	1,004	2.9
Total	2,338	100	34,248	100

Figure 5 presents the location of the slides according to their trigger factor. With respect to fatal landslides with known causes, precipitation is the most common trigger, registering 4,920 fatalities, mainly in the Andean region, with 93% of the 822 events presented.

With respect to the number of recorded fatalities associated with each trigger, the trigger that has claimed the most lives in the historical series is volcanic activity, with 22,126 fatalities reported in the entire database. The effect of the earthquakes recorded, 1,149 fatalities among 4 landslides, presented only in the Andean region in the years 1936, 1938, 1994 and 2005, highlighting the one that occurred in 1994 in the city of Paez in the Department of Cauca with 1,100 fatalities.

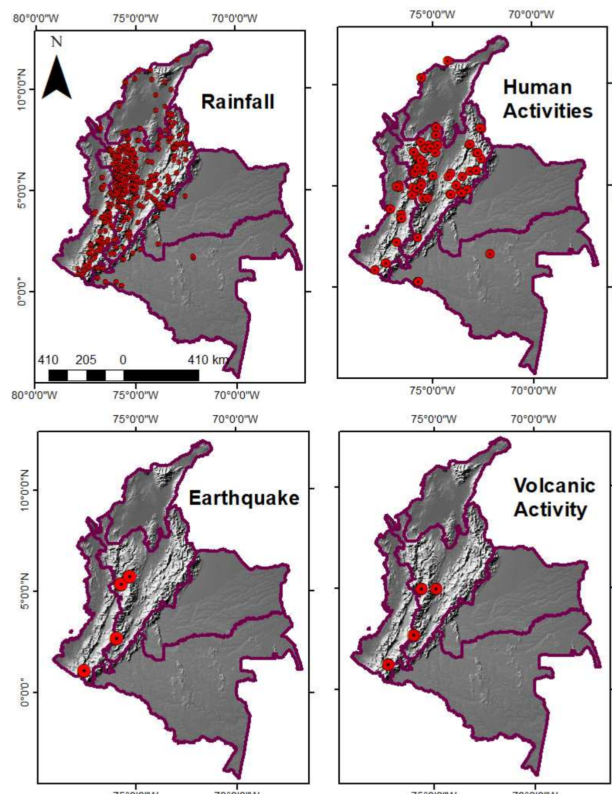

Figure 5 Information on triggering factors, number of fatal landslides associated with each type of trigger, and their respective location on the map of Colombia.

The effect of human activities caused 1,004 fatalities in 98 landslides in the Andean, Caribbean and Pacific regions (91, 3 and 4 landslides, respectively). The most notable was the 1977 landslide in the city of Los Andes in the Department of Antioquia, due to the collapse of a mine, according to the newspaper El Colombiano, which caused 100 fatalities. Also, in the city of Medellín, in the Villatina neighbourhood, approximately 500 fatalities were recorded in 1987 due to various factors, including the construction of a water pipeline on top of the slope, which could have caused the failure of a 30,000 m^3 soil mass (Coupé et al., 2007).

The above is consistent with the conclusions made by Froud & Petley (2018), who mentioned that the occurrence of deadly landslides caused by human activity is increasing, mainly due to the construction of civil works, illegal mining and illegal cutting of hills. This is related to urban settlements that are often built in hazardous locations and do not have the resources to finance expert guidance when building their homes. Finally, the cases for which there is no knowledge of the landslide trigger are related to 5,049 fatalities.

Figure 6 shows the map of Colombia with average annual satellite rainfall values, which shows the Pacific region as the rainiest in the country. These rainfall data were obtained from the satellite precipitation database CHIRPS Daily: "Climate Hazards Group InfraRed Precipitation with Station Date" (Funk et al., 2015), corresponding to records from 1981 to 2017 obtained from the Google Earth Engine website (https://earthengine.google.com/).

At the bottom of Figure 6 are the monthly distributions of fatal landslides triggered by rainfall and presented by region and with their average monthly rainfall cycles. Analysis of the relationship between the rainfall and the fatal landslides by region shows bimodal and unimodal monthly rainfall and landslide patterns, confirming the conclusions of previous work on the strong influence of rainfall on the occurrence of landslides (Aristizabal, 2017; Ma et al., 2014; Ran et al., 2018). In the Andean, Pacific and Caribbean regions, the bimodal pattern is observed, with maximum rainfall values in April and September of 270, 420 and 230 mm, respectively, as well as maximums for the occurrence of fatal landslides in the months of April, May, October and November.

The unimodal patterns of precipitation in the Orinoco and Amazon regions are similar, with a maximum peak in May and April, respectively, and average monthly precipitation of 380 mm. However, the maximum number of records of fatal landslides for these regions is displaced compared to the maximum peak of rainfall. For the Orinoco region, the maximum number of fatal landslides occurred in August, with 30% of the records, and in the Amazon, 40% of the events occurred in July. This trend could reflect the influence of preceding rain on the occurrence of fatal landslides because after several months of rain, the water content of soils increases and the susceptibility to landslides also increases under low intensity or short duration rain (Álvarez-Villa et al., 2010; Poveda, 2011; Aristizábal & Sánchez, 2020).

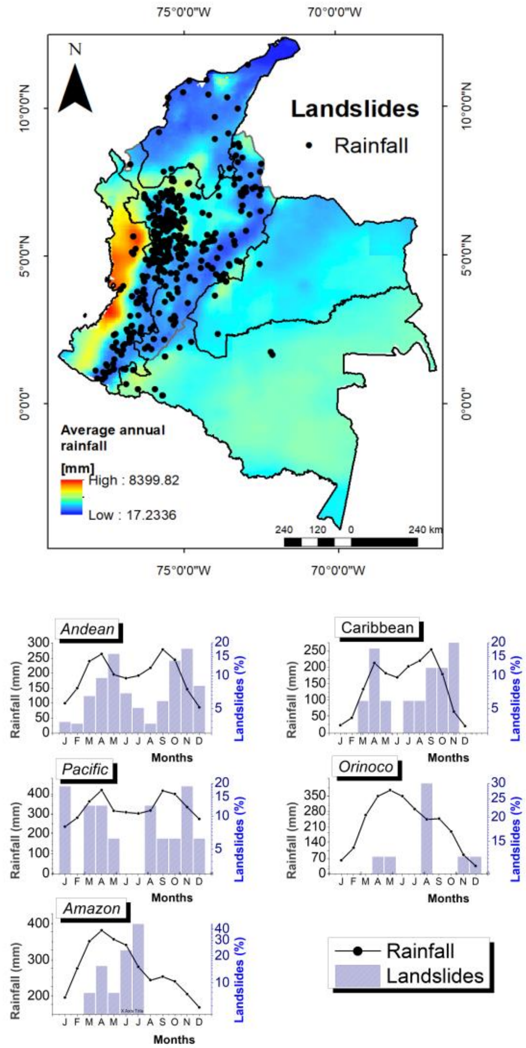

Figure 6. Map of average annual satellite rainfall in Colombia and fatal landslides triggered by rainfall. At the bottom: the relationship between the cycle of average monthly precipitation (black line) of each region in Colombia and the fatal landslide events (blue bars).

Finally, Figure 7a shows the cumulative number of fatal landslides in Colombia from 1921 to 2019. Figure 7b shows the cumulative number of fatal landslides in Colombia from 2004 to 2019, including the cumulative number of fatal landslides presented by Petley (2020), for different regions of the world. In this figure, it can be seen that the cumulative number of landslides for Colombia is greater than that reported for South America. This is because the databases used in this study has more records of fatal landslides. In addition, this figure shows that for Colombia there is a trend towards an increase in fatal landslides between 2009 and 2012, the same as in South America, as showed by Petley (2020). This particular trend could be associated to extreme rainfalls during "La Niña" season in 2010-2011; although, this trend needs further study.

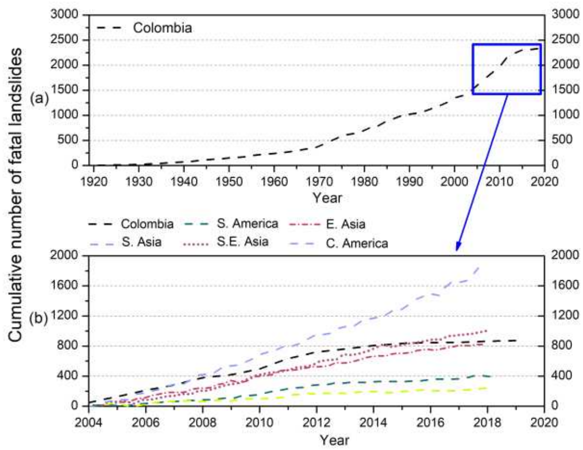

Figure 7. Cumulative number of fatal landslides in Colombia. (a) 1921-2019 (b) 2004-2019

5 CONCLUSIONS

This paper examined the occurrence of fatal landslides in Colombia between 1900 and 2019, by compiling records from national and regional databases and local studies. This study was carried out with the intention of showing the distribution of these landslides in the different regions of Colombia, and at the same time, pointing out the distribution of associated fatalities in each of the regions of the country according to their triggers. From the results obtained, in the Andean region, the number of landslides with fatal consequences corresponds to 93.7% of the total in Colombia, while for the Orinoco, Amazon, Caribbean and Pacific regions the percentage of landslides registered is considerably reduced to 0.8%, 0.9%, 2.1% and 2.6%, respectively. Of the fatal landslides with known causes, precipitation is the most common trigger for these landslides.

The information presented also highlights the contrast between fatal landslides according to the trigger factor. Although landslides triggered by volcanic activity account for 64% of fatalities, with 22,126 victims recorded in only 4 events, indicating their destructive capacity due to the magnitude in terms of volume and area that they can affect, fatal landslides triggered by rain represent 14% of fatalities, with 4,920 deaths in 822 recorded events, corresponding to 35% of the total events. According to the data presented by Aristizábal & Sánchez (2020) regarding the number of landslides triggered by rainfall, only 3% of the registered landslide events generate fatalities in Colombia, which means a great challenge for the risk management offices in each region to reduce the number of victims of these events.

Additionally, this study is considered useful to understand the causes and trends of the overall impacts associated with landslides that cause fatalities in Colombia and can be used as a basis for formulating risk mitigation strategies, developing early warnings and in land use planning policies. Finally, it is necessary to incorporate the direct and indirect economic losses from the landslides, the exact location of each event and other detailed information useful for calculating the socio-economic impact associated with the landslides in Colombia into the databases.

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