

Effect of rainfall variability and El Niño-Southern Oscillation (ENSO) on landslide susceptibility affecting roadway corridors in the Colombian Andean mountain region

Efecto de la variabilidad de las lluvias y de El Niño-Oscilación del Sur (ENOS) sobre la susceptibilidad a deslizamientos que afectan a los corredores viales de la región montañosa Andina Colombiana

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ABSTRACT: Global warming significantly influences geo-hydrological hazards, such as rainfall-related landslides, posing serious hazards to human lives and the natural and built environment. They cause damage to transportation infrastructure, disrupting communication and affecting vast geographic regions. Road transportation infrastructure faces considerable challenges, as landslides frequently occur on the national road network, especially during the winter season. Understanding the complex and non-linear space-time relationship and dynamics between rainfall, El Niño-Southern Oscillation (ENSO), and landslides in the Colombian Andean Mountain region (CAMR) requires a thorough analysis. We present a comprehensive space-time analysis using Continuous Wavelet Transform, Hot Spot Analysis (Getis-Ord G_i^*), Multi-Criteria Decision-Making (MCDM) methods, and remote sensing data. Preliminary findings reveal a strong correlation between landslides and rainfall patterns, with significant influence from the ENSO phenomenon, particularly during La Niña years, in an area characterized by steep slopes and intense rainfall. This makes the region susceptible to landslides and economic losses.

KEYWORDS: Colombia, ENSO, Landslide susceptibility, Rainfall, Roadways

1 INTRODUCTION

Landslide is a general term used to describe the down-slope movement of soil, rock and organic materials under the influence of gravity (Varnes, 1984). The variability in different climatic factors influences its occurrence, mostly rainfall, by far the main trigger of mass movements in most areas of the world (Gariano and Guzzetti, 2022), which is one of the fundamental climate variables (Jemec-Auflič et al., 2021) greatly impacted by the climate change and climate variability (Lim and Kim, 2022).

Globally, rainfall-induced landslides account for a staggering 89.6% of all landslide fatalities (Petley, 2008), with a strong seasonal pattern of landslide occurrence through the annual cycle, as noted by Petley (2012). The EM-DAT database from the Centre for Research on the Epidemiology of Disasters (CRED) reports an average of 914 deaths per year worldwide between 2005 and 2014 due to landslides triggered by rainfall (Aristizábal and García-Aristizábal, 2020). According to the World Health Organization (WHO), from 1998 to 2017, landslides impacted about 4.8 million individuals, resulting in over 18,000 global fatalities (Ortiz-Giraldo et al., 2023). In 2020, the United National Office for Disaster Risk Reduction (UNDRR) noted an average annual economic loss of US\$ 151.6 billion. These incidents are

particularly prevalent in mountainous tropical regions, where the intensity and duration of rainfall can trigger shallow landslides (Cullen et al., 2022). Remarkably, over 80% of fatal landslides occur in the tropics (Ozturk et al., 2022).

In the case of Colombia, hydrometeorological events account for a significant 88% of natural disasters, with landslides causing 93.7% of the total fatalities in the country (Gómez et al., 2021). These landslides occur more frequently during the months of May to July and September to November, coinciding with the rainfall patterns associated with the Intertropical Convergence Zone (ITCZ) (Hidalgo and Vega, 2021).

The country is highly influenced by climate variability and is one of the most vulnerable countries in the world to climate change due to its tropical condition, its geography, its particular and heterogeneous ecosystemic biodiversity, and its socioeconomic conditions (Mintransporte et al., 2014). The local topographic configuration plays a crucial role in inducing atmospheric circulations, which in turn promote the development of deep convection—a fundamental mechanism in the formation of tropical rainfall. This process is primarily influenced by the phases of the "El Niño/Southern Oscillation" (ENSO). In terms of seasonality, 92% of rainfall-triggered landslides exhibit a bimodal annual pattern in the Andean region (Aristizábal and García-

Aristizábal, 2020), with a notable prevalence of mixed seasonality (Urrea et al., 2019). Moreover, in the 2nd National Communication to the United Nations Framework Convention on Climate Change, a relationship has been established between the monthly occurrence of the number of mass wasting processes and the monthly distribution of rainfall (IDEAM et al., 2010), experiencing in recent years an increase in the frequency, intensity and duration of extreme weather events (MinTransporte et al., 2014).

Nevertheless, not only affectation is caused to life of people, because when geohazards occur, damage to communications and transportation infrastructure may occur. One of the economic sectors most affected by landslides in Colombia is transportation, especially road transportation, given the recurrence of landslides on the national road network, mainly during the winter season, because the climate is changing and this has significant effects on the road infrastructure (Bles et al., 2016).

Roads are vital for the socio-economic growth of isolated regions with an impoverished population, especially in developing countries like Colombia (García-Delgado et al., 2022). Thus, the national road network is exposed to various types of risks associated with climate variability, resulting in increasing road closures, delays, and costly damage to infrastructure (MinTransporte, 2013).

The costs of disruption to road networks can be several orders of magnitude higher than direct clean-up and repair costs. Damage to the road network is usually associated with phenomena such as landslides (54%), floods (30%) and torrential floods (World Bank, 2012). According to information from the National Unit for Disaster Risk Management (UNGRD, in Spanish), the history of landslides that impacted the road network, mainly affected the Andean region (MinTransporte, 2013), precisely where some of the country's main roadway corridors are located. Translational landslides occur most frequently on moderately steep slopes of crystalline rocks, on which heterogeneous saprolites have developed, where high moisture concentrations during rainy periods seem to be the most frequent triggering mechanisms for landslides on the roads (Montero et al., 1988).

A precedent on the effect of extreme weather conditions and their impact on the road sector was presented in the case of the 2010-2011 “La Niña” phenomenon, which significantly affected the country's road infrastructure. Colombia suffered losses and damage to the national road infrastructure, which is estimated to have cost the transportation sector close to \$3.2 billion, being the most affected road mode, registering 31,635 km affected (MinTransporte, 2013).

In this paper, in first place, a spatio-temporal analysis of the relationship between landslides occurrence, rainfall variability and ENSO on roadway corridors in the Colombian Andean mountain region (CAMR), using a forty-two-year (1981–2022) rainfall and Multivariate ENSO Index v2 time series is presented. Then, using conditioning and triggering covariates, two MCDM methods, Weighted Frequency Ratio (WFR) and Fuzzy Gamma Operator (FGO) were used for landslide susceptibility analysis into the roadway corridors.

2 STUDY AREA

Situated in the northwestern region of South America, Colombia spans latitudes 4°S to 12°N and longitudes 67°W to 79°W. It shares borders with Panama to the northwest, Brazil and Venezuela to the

east, and Ecuador and Peru to the south (Figure 1a). With coastlines along the Caribbean Sea and the Pacific Ocean, Colombia is traversed by the Andes Mountain range, resulting in diverse climates and ecosystems. Covering a continental area of 1,141,748 km², the country boasts a population exceeding 50 million people. The Geographic Institute Agustín Codazzi (IGAC, in Spanish) has classified Colombia into five natural regions: Caribbean, Pacific, Andean, Orinoco, and Amazon.

The Colombian Andean ranges' geomorphological structure is a consequence of a convergence zone shaped by subduction processes at the plate junction of the Nazca, Caribbean, and South American plates along the country's western margin. This region is characterized by rugged terrains with steep slopes dominating the landscape. The hillslopes are covered by substantial weathering profiles, comprising residual soils, saprolites, and weathered rock horizons. Colombia experiences a tropical climate, with a mean annual temperature exceeding 25°C at sea level. The country's overall mean annual precipitation is around 2,830 mm. In the Andean region, the mean annual precipitation varies between 1,000 and 3,000 mm/year, influenced by strong topographic features that generate local atmospheric circulations and convective rainstorm events (Cullen et al., 2022; Mesa et al., 2021). The El Niño-Southern Oscillation (ENSO) plays a crucial role in Colombia's tropical climate and is a significant factor influencing its hydrology. Potential trends in ENSO frequency or spatial patterns are expected to leave an imprint on Colombian rainfall trends (Mesa et al., 2021). Notably, the interannual variability in rainfall is primarily controlled by the impacts of both phases of ENSO—El Niño (warm phase) and La Niña (cold phase) (Poveda et al., 2007).

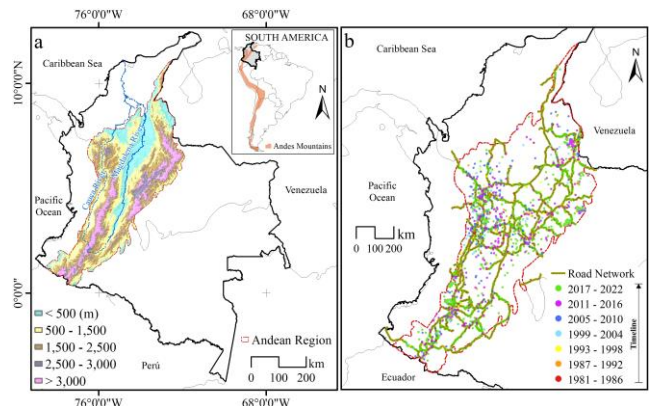


Figure 1. a) Geographical context of Colombia. The elevation is highlighted in the Andean region. b) Space-time distribution of the analyzed landslide records categorized by 6-year periods and National Road Network in CAMR.

3 MATERIALS AND METHODS

3.1 Datasets

According to the geographical data collected and used in this study, 4,976 landslides occurred in the CAMR between the years 1981 and 2022 were analyzed. The data were collected from The Colombian Geologic Service (SGC, in Spanish) through the Mass Movement Information System (SIMMA, in Spanish, <https://simma.sgc.gov.co>) and the Universidad Nacional de

Colombia through the Geohazards research group (<https://geohazards.com.co>) and then were merged into a unique database classified by types (flow, slide, spread, fall, topple and creep).

Regarding the rainfall, for this study, The Climate Hazards Group Infrared Precipitation with Stations (CHIRPS) Monthly data version 2.0 was retrieved from UCSB data portal (<https://www.chc.ucsb.edu/data/chirps>) for the time period 1981-2022.

The Multivariate ENSO Index (MEI) were used to establish the prevalent ENSO phase for each year from monthly records. The MEI values obtained from the Physical Sciences Laboratory of the National Oceanic and Atmospheric Administration (NOAA) (<https://psl.noaa.gov/enso/mei/#data>) were used to quantify the ENSO variability (Wolter and Timlin, 2011). Negative values of the MEI represent the cold phase of ENSO (La Niña), while positive values represent the warm phase (El Niño).

In terms of roadways, the cartographic information of the National Road Network of Non-Concessioned Roads under the administration of the National Roads Institute (INVIAS, in Spanish), concessioned roads under the administration of the National Infrastructure Agency (ANI, in Spanish) and secondary roads (Regional Road Plan Programme - PVR) (Figure 1b) was obtained from the open data portal of the National Roads Institute (<https://inviasopendata-invias.opendata.arcgis.com/>).

3.2 Conditioning factors

In this study, slope gradients were computed using a 30-meter spatial resolution Digital Elevation Model (DEM) sourced from the Shuttle Radar Topography Mission (SRTM) acquired from IGAC (<https://geoportal.igac.gov.co/contenido/datos-abiertos-igac>).

Geological data was based on the re-classification proposed by (Gomez et al., 2023), utilizing the lithological units map from the Colombian Geological Service (SGC, in Spanish) at a scale of 1:1,000,000 (<https://datos.sgc.gov.co>).

Landcover types were determined from the 1:100,000 landcover map provided by Institute of Hydrology, Meteorology and Environmental Studies (IDEAM), employing the CORINE Land Cover Colombia classification (<http://www.ideam.gov.co/geoportal>).

To enhance our analysis, soil moisture data were extracted from the FLDAS Noah Land Surface Model L4 Global Monthly dataset (MERRA-2 and CHIRPS), accessible through the NASA Earth Observation data portal (<https://www.earthdata.nasa.gov>).

3.3 Spectral analysis using Continuous Wavelet Transform

Continuous Wavelet Transform (CWT) can be used to analyze the frequency and phase variations across time in a signal at several scales simultaneously, considering non-stationary power at many different frequencies (Díaz and Villegas, 2022; Torrence and Compo, 1998). Wavelets allow to study localized periodic behavior looking for regions of high-power in the frequency-time plot. In this study, CWT analysis was used to investigate the time-frequency patterns of monthly landslide, rainfall, and ENSO MEI Index time series, as well as their collective dynamics at the regional scale. CWT, based on the methodology introduced by Torrence and Compo (1998), was executed utilizing the Waipy toolkit version 0.0.1.4.0. (<https://github.com/mabelcalim/waipy>).

3.4 Hot Spot analysis using Getis-Ord G_i^* method

Spatial patterns in aggregated data at the municipal level were analyzed by spatial statistics, using landslide densities and hot spot (cold spot) analysis test using the Getis-Ord G_i^* statistic to identify the location of local clusters for landslides occurrence. In the Getis-Ord G_i^* method (Getis and Ord, 1992), a local weighted mean around each observation including the observation itself is compared to the mean of the entire dataset (Gökkaya, 2016). The analysis specifies the spatial relationship of the feature to neighboring features and a threshold distance beyond which adjacent features are ignored. A fixed distance band spatial relationship with Euclidean distance and a 50 km threshold distance were used in this analysis. The landslide densities and hot spot (cold spot) analysis were performed in ArcGIS 10.7 software (<https://www.esri.com>).

3.5 Multicriteria Decision-making methods for landslide susceptibility analysis

With the aim to compare the results of our approach with the National map of "Zoning of the General Susceptibility of the Terrain to Landslides at a scale of 1:500,000", prepared jointly by IDEAM with the SGC in 2010, a Weighted Frequency Ratio (WFR) method and a Fuzzy Gamma Operator (FGO) model were used.

The application of fuzzy set theory in GIS environments is investigated as a potential regional scale landslide susceptibility method, as it provides a way to deal with spatial uncertainties and complex relationships between conditioning factors and landslide occurrence (Kritikos and Davies, 2015). According to the results of some papers in literature (Lee, 2007; Pradhan and Kim, 2016; Vega and Hidalgo, 2023), the Fuzzy Gamma operator is more suitable that fuzzy operators AND, OR, Product, and Sum. To enhance the analysis, the Gamma operator was employed to preprocess the original covariate values before converting them into fuzzy values. The conversion was carried out using the Gauss fuzzy function, considering the landslide density associated with each class of covariates. This approach allowed for a more refined representation of the covariate data, incorporating the variability and distribution of landslide occurrences within different classes.

On the other hand, Frequency Ratio (WFR) method calculates the ratio of landslides in a desired class of a conditioning factor, as a percentage of all landslides to the area of the class as a percentage of the entire map (Silalahi et al., 2019). Subsequently, a weight was computed for each factor by considering the range of frequency ratios. These weights were then superimposed to assess the overall susceptibility to landslides in the designated study area. By overlaying the weighted factors, a comprehensive evaluation of landslide susceptibility was obtained, considering the relative importance of each individual factor in contributing to the overall susceptibility. The susceptibility categories (very low, low, moderate, high and very high) were defined using the Jenks natural break (Ye et al., 2022).

4 RESULTS AND DISCUSSION

4.1 Landslides and conditioning factors

This study examined 4,976 landslides occurring between 1981 and 2022 in CAMR. Regarding the characteristics of slope gradient

(Figure 2a), we found that the mean slope values for landslides before February 2000 (date of the SRTM mission) were $10.4^\circ (\pm 8.4^\circ)$, while for later events, the mean slope values were $16.4^\circ (\pm 9.9^\circ)$. It is important to clarify these findings because the DEM used might depict conditions after the landslide, potentially failing to accurately capture the pre-landslide conditions. In terms of soil moisture (Figure 2b), the mean value at the location of the landslides (at a depth of 40-100 cm) was $39.6\% (\pm 3.4\%)$.

Analyzing the landcover (Figure 2c) in landslide-prone areas, we observed that approximately 65.1% of landslides occurred in agricultural lands, followed by forested areas comprising 16.3%. Areas adjacent to water surfaces accounted for 2.7% of the landslides, while the remaining 15.9% were associated with urbanized land. This observation can be attributed to two factors. Firstly, human activities have a significant influence on slope stability, as landslides in Colombia are six times more likely to occur on non-forested land compared to forested land (Grima et al., 2020). Secondly, the landslide inventories used in the study often lack precise spatial information, with many records reported at the municipal or village level, introducing inherent spatial uncertainty.

Based on the classification of lithologic units (Figure 2d) proposed by Gomez et al., (2023), our results indicated that landslides were distributed among different lithologic units as follows: sedimentary units accounted for the highest occurrence at 45.9%. This high percentage suggests that sedimentary units are particularly vulnerable to slope instability. Igneous units, including granitic rocks, basalts, and andesites, accounted for 25.8% of the landslides. This finding is noteworthy because igneous rocks are generally considered more resistant to weathering and erosion compared to sedimentary rocks. Landslides in metamorphic units were reported at 16.3%. While metamorphic rocks are generally considered more resilient than sedimentary rocks, the occurrence of landslides in this unit suggests that certain types of metamorphic rocks may exhibit weaker stability characteristics. Lastly, 12.0% of the landslides occurred on colluvial and alluvial deposits.

In the initial inventory of landslides on roads in Colombia conducted by Montero et al., (1988), several primary factors were identified as contributors to landslide occurrences. These factors included the presence of soil-mantled slopes, which were found to be present in approximately 90% of the observed failures. Additionally, landslide-prone lithologies, such as pyroclastic deposits, were identified as contributing to the instability of road cuts.

4.2 Landslides and rainfall variability

The Andean region exhibits a distinct bimodal precipitation pattern, with the highest number of landslides observed in the March-April-May (MAM) (31%) and September-October-November (SON) (26%) seasons, and the lowest in December-January-February (DJF) (19%) and June-July-August (JJA) (24%) seasons. Figure 3 illustrates the average annual rainfall and landslides categorized by seasons. Landslides primarily align with the extension of the mountain ranges, with peak occurrences observed in the years 2010-2012, 2017, and 2020-2022. The highest number of landslides usually occurs in April-May and October-November, which are the months with the highest rainfall intensity in many areas of the region. Regarding landslide types and seasons, slides are most prevalent in MAM (32.9%) and SON (26.7%), while flows dominate in DJF (43.4%) and falls in JJA

(42.1%). Other types of movements display a more consistent seasonal distribution.

In the lower box of each subfigure of Figure 3, the temporal distribution of landslides and the mean total seasonal rainfall in the CAMR are shown. The analysis revealed that a significant majority, specifically 64% of the landslides studied, took place within a notable area of influence spanning 5 kilometers on either side of the roadway alignment. The detailed findings can be observed in upper box of each sub-figure of Figure 3, which visually presents the results.

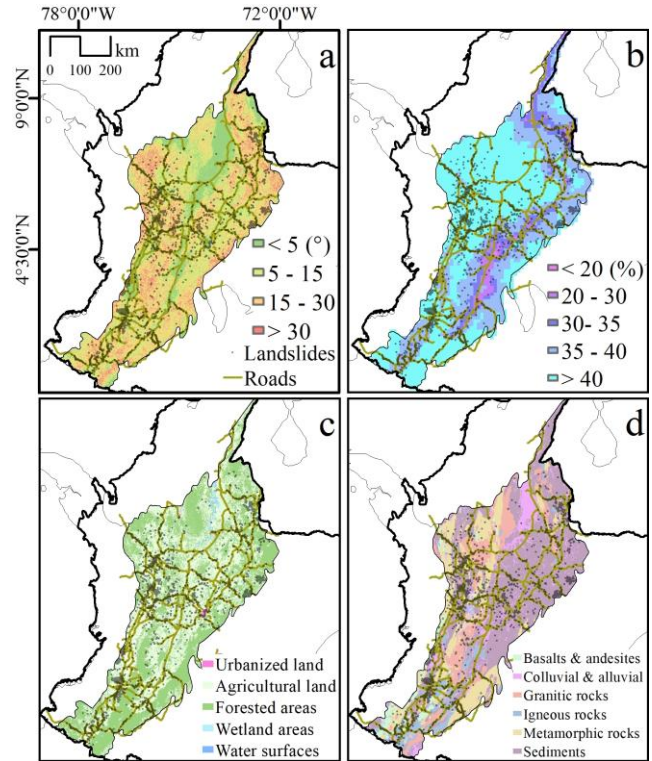


Figure 2. Spatial distribution of landslides and national roadway network over conditioning factors in the CAMR: a) Slope gradient, b) Soil moisture, c) Landcover and d) Geological units.

4.3 Landslides and ENSO

The results showed that landslide peaks coincided with negative values of the MEI ENSO index, particularly during La Niña periods where the wet seasons in Colombia become not only more intense but also longer (Poveda et al., 2014). The highest occurrence of landslides was observed in 2010-2011 and 2020-2022, which coincided with La Niña years and the highest average rainfall in the study region. Some landslide peaks were also observed in La Niña periods following strong El Niño events. La Niña years accounted for the highest percentage of landslide occurrences (56.7%), followed by Neutral (36.5%) and El Niño (6.8%) years (Figure 4).

Spatial distribution analysis showed that a majority of landslides were related to La Niña years, particularly along the western and eastern mountain ranges. Monthly variations in landslides and rainfall exhibited a bimodal behavior, with peaks in

April-May and October-November. The bimodal pattern was more pronounced in Neutral years and less apparent during La Niña and El Niño years.

Overall, the findings highlight the influence of ENSO on landslide occurrence, with variations observed across different ENSO years. La Niña years generally experienced higher landslide occurrences during both rainy and dry seasons compared to El Niño years. The study underscores the importance of considering ENSO effects and rainfall patterns in understanding landslide dynamics and their relationship with climate variability.

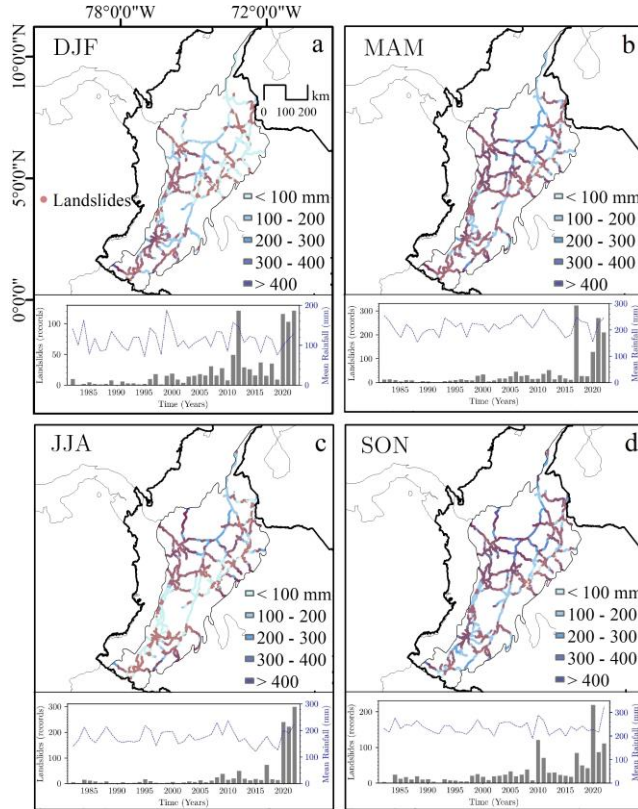


Figure 3. Spatial distribution of landslides and rainfall in the CAMR's national roadway network. Averaged total seasonal rainfall and number of landslide records in the study period.

4.4 Frequency domain analysis of landslide and rainfall

This study used continuous wavelet analysis to explore the connections between atmospheric modes and the periodicity of landslides and rainfall (Figure 5). The landslide time series was normalized to monthly landslide rates by the annual totals to improve the interpretability of the results. The wavelet analysis decomposed the time series into time and frequency space, and the global wavelet spectrum is presented. The analysis revealed that there is a bimodal behavior in rainfall, with main peaks at 0.5-year and 1-year periods. These peaks correspond to the annual cycle of rainfall. The power on these scales explained most of the rainfall variance.

There were also other periodicities with high power, such as periods of 3-4 years, which showed a strong relationship between landslides and rainfall. The study found that certain time intervals,

including the periods of Strong La Niña in 2010-2011 and 2020-2022, were associated with the largest number of landslide events in the region.

The analysis indicated that there is a strong connection between the variability mode of annual rainfall and landslides, particularly in the first half of the year. There was also a certain in-phase behavior between the variables for periods of 3-4 years, which corresponded to the quasi-periodic occurrence of ENSO and its extreme phases (Díaz and Villegas, 2022; Salas et al., 2020).

In terms of amplitude in the landslide time series, the major peaks were observed in 2010-2011, 2017, and 2020-2022, coinciding with moderate and strong episodes of the La Niña phase.

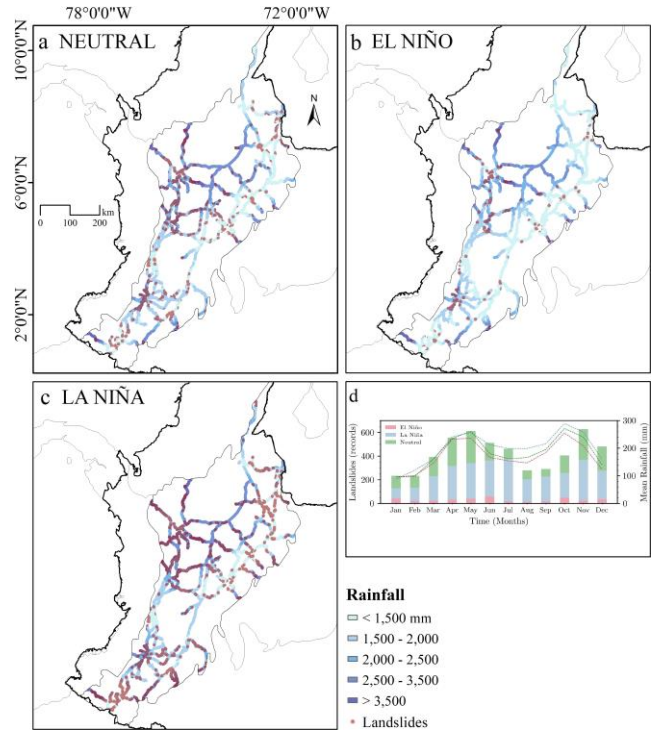


Figure 4. Temporal distribution of landslides and rainfall in the CAMR's national roadway network between 1981-2022, considering ENSO years: a) Neutral, b) El Niño and c) La Niña, and d) Averaged annual cycle of rainfall (dashed lines) and all registered landslides (color bars) in CAMR.

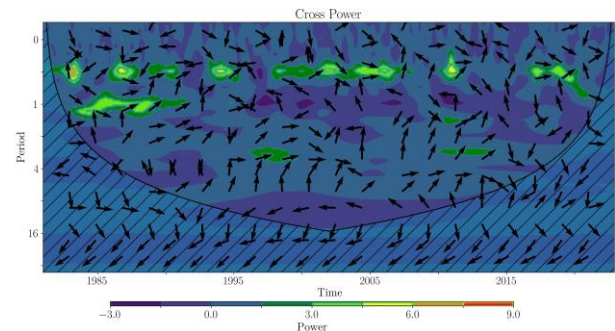


Figure 5. Cross power wavelet spectrums of time-series rainfall, and landslides in CAMR. The arrows indicate the relative phase relationship between the two variables, with in-phase pointing right.

4.5 Hot Spot and kernel density analysis of landslides and rainfall

Figure 6a provides an initial analysis of the spatial and temporal distribution pattern of landslides in the CAMR, focusing on density. The figure displays landslide clusters aggregated by municipalities, along with the Getis-Ord Gi* confidence intervals.

The analysis revealed two highly significant clusters, or hot spots. The first hot spot was identified in the southwestern municipalities of Antioquia as well as in the northern region of the "Eje Cafetero" (coffee-growing area). The second hot spot was found in the central municipalities of the Cauca department, particularly in Cajibío, La Sierra, and Sotará. It is noteworthy that the mean total multi-annual rainfall within these hot spots was approximately 2,200 mm, consistent with previous analyses.

Figure 6b presents a space-time kernel density map of landslides in the CAMR. The kernel density values were classified using manual intervals based on histograms. These maps exhibit a similar pattern to the results obtained from the space-time permutation scan statistics model conducted by Vega et al., (2024), showing a high degree of spatial and temporal overlap. The landslide activity initiates in the western mountain range and gradually extends to other mountain ranges in the Andean region. In addition to the dense core of the previously mentioned hot spots, a significant density of landslides can be observed in the vicinity of the Norte de Santander department during the periods of 2005-2010 and 2011-2016, coinciding with the occurrence of several La Niña phenomena.

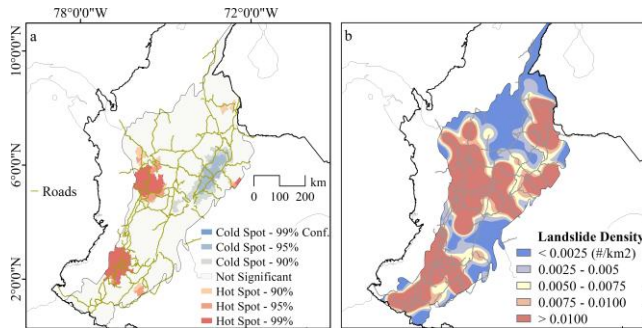


Figure 6. a) Hot spots (cold spots) of landslides in each municipality of the CAMR in the period 1981-2022 over the national roadway network. b) Space-time kernel density map of all landslides. Densities are measured in terms of numbers of events/km².

4.6 Landslide susceptibility analysis in national roadway network

According to the results shown in Table 1, the highest landslide occurrences in the CAMR occurred for rainfall levels between 2,000-2,500 mm, average soil slopes between 15-30°, soil moisture in the order of 20%, in areas of igneous rocks with a high degree of weathering and in agriculture lands and areas highly intervened by anthropogenic actions. This is not a minor issue, as one of these contributing/triggering factors is the presence of roads. Poor construction practices can increase landslide activity in linear infrastructure (García-Delgado et al., 2022).

Table 1. Frequency ratio and landslide density in CAMR

Factor	Values	% Domain	% Landslide	Freq. Ratio	Landslide Dens.
Rainfall (mm)	< 1500	19.4	16.2	0.8	0.0001
	1500 - 2000	29.9	23.5	0.8	0.0001
	2000 - 2500	16.8	34.0	2.0	0.0003
	2500 - 3500	24.4	20.5	0.8	0.0001
	> 3500	9.5	5.8	0.6	0.0001
Slope (°)	0 - 5	21.5	14.6	0.7	0.0001
	5 - 15	33.0	32.9	1.0	0.0001
	15 - 30	36.5	43.0	1.2	0.0002
	> 30	9.1	9.5	1.0	0.0001
Soil Moisture (%)	< 20	0.1	0.2	1.9	0.0002
	20 - 30	4.5	3.1	0.7	0.0001
	30 - 35	8.9	5.8	0.7	0.0001
	35 - 40	33.2	30.0	0.9	0.0001
	> 40	53.4	60.8	1.1	0.0001
Geology	Sediments	47.9	43.7	0.9	0.0001
	Igneous rocks	6.9	8.6	1.2	0.0002
	Metamorphic rocks	16.6	16.7	1.0	0.0001
	Granitic rocks	12.6	15.0	1.2	0.0002
	Basalts and andesites	3.4	4.0	1.2	0.0002
	Colluvial and alluvial	12.6	11.9	1.0	0.0001
	Water reservoirs	0.0	0.0	0.0	0.0000
Landcover	Urbanized land	0.8	13.3	17.8	0.0024
	Agriculture land	52.4	67.7	1.3	0.0002
	Forest	44.3	16.7	0.4	0.0001
	Wetlands	0.6	0.0	0.0	0.0000
	Water surfaces	0.9	1.0	1.1	0.0001
	Others	1.2	1.3	1.1	0.0002

According to results, the most affected roadways are located in the western and central mountain ranges. Roadway corridors such as the Troncal de Occidente (sectors: Rumichaca-Pasto, Cano-Mojarras, Mojarras-Popayán, Popayán-Santander de Quilichao, La Virginia-Remolinos, La Felisa-La Pintada, La Pintada-Primavera, La Pintada-Peñalís, Bolombolo-Santafé de Antioquia, Hoyo Rico-Los Llanos), Troncal Central (sector Puente Nacional-San Gil, connection Málaga-Los Curos), Troncal de Uraba (sector Dabeiba-Cañasgordas), Troncal del Magdalena (sector La Lizama-Rio Sogamoso), Troncal del Eje Cafetero (sector Armenia-

Pereira), Transversal Medellín-Bogotá (sector Peaje Cocorná - Caño Alegre), Transversal Las Animas - Bogotá (sector Puente La Libertad-Fresno), Transversal Tribuga-Arauca (sector Cisneros-Alto de Dolores), Transversal Rosas-Condagua, and Transversal Buenaventura-Villavicencio-Puerto Carreño, are highly susceptible to landslides (Figure 7). Some of the aforementioned roads have a long history of landslide occurrences and have been analyzed and documented in different studies (García-Delgado et al., 2022; Herrera-Coy et al., 2023; Martínez-Carvajal et al., 2021; Ruiz et al., 2018; SGC and INVIAS, 2018)

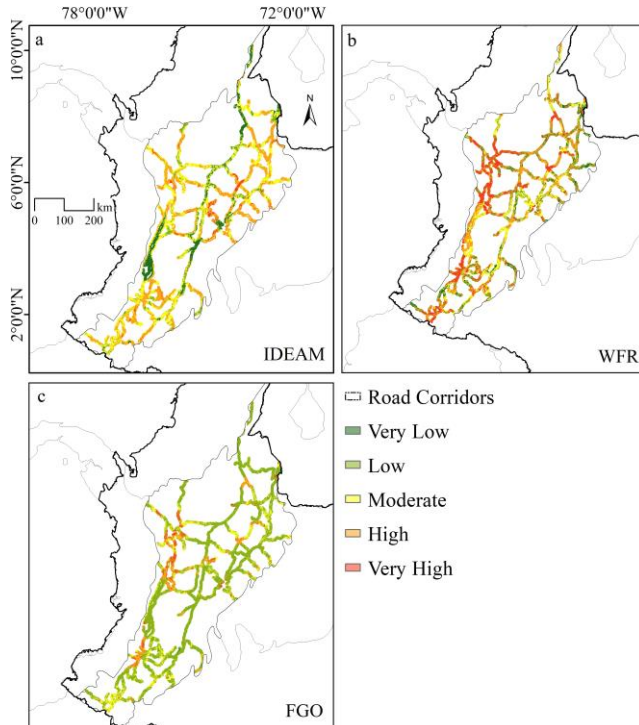


Figure 7. Landslide susceptibility maps of National Road Network: a) Multicriteria method by IDEAM in 2010, b) Weighted Frequency Ratio method, and c) Fuzzy Gamma Operator.

The FGO results demonstrate a notable consistency with the IDEAM map, which further strengthens their reliability. By incorporating a 42-year period of landslide events and accounting for relationships between landslide frequency and density, the FGO model captures the dynamic nature of landslide occurrences. It also takes into consideration the impact of multiple La Niña phases that occurred, even 12 years after the implementation of the 2010 reference map.

On the other hand, the WFR method, while also utilizing a 42-year record, takes a more practical approach by focusing on the frequency ratio of landslides. This approach resulted in a susceptibility map that identifies a greater number of zones classified as having high and very high susceptibility. Thus, the WFR method provides a more conservative scenario for decision-making regarding prevention activities along the analyzed roads.

In summary, the FGO analysis offers a comprehensive understanding of landslide susceptibility, considering a longer timeframe and accounting for the dynamic nature of landslide occurrences. Meanwhile, the WFR method, with its emphasis on

frequency ratios, takes a cautious approach by identifying more areas as highly susceptible. Both approaches contribute valuable insights to decision-makers involved in prevention activities, enabling a thorough assessment of landslide risks along the analyzed road corridors.

It is worth highlighting the differences between the methodologies employed and the one used as a reference (IDEAM in 2010), since the latter considered a large number of weighted terrain variables or components such as lithology, fracture density, fold density, basin shape, drainage density, slope steepness, relative relief index, morphogenic systems, erosive processes, soils and their relationship with water dynamics, soils, and their constitution and vegetation cover. Despite the large number of variables considered, this methodology considers neither the effect of rainfall variability nor the frequency of landslide occurrence on each class of covariates, as was considered in the case of the WFR and the FGO. Nevertheless, the results are correlated with the results of the Hot Spot analysis conducted using Getis-Ord G_i^* method. However, the fuzzy logic approach presents much lower susceptibility level results, which differ somewhat from the analyses of other studies.

Grima et al., (2020) conducted a study utilizing data from the SIMMA database covering the period from 2013 to 2017 to investigate the influence of land use on landslide occurrences in Colombia. They observed that non-forested regions experienced up to six times more landslides compared to forested regions during this timeframe. The study also highlighted the presence of linear infrastructure, in grassland areas that are susceptible to mass movements. Notably, fatal landslides associated with roads have increased since the 2000s, and one potential factor contributing to this trend is land use changes and deforestation (García-Delgado et al., 2022). This is in line with the results obtained in this work, since the covariate with the highest contribution to landslide occurrence according to the frequency and density ratio values corresponds to changes in land cover, followed by rainfall and soil moisture content variability, the main covariates of this analysis.

The spatial distribution of most landslides on roadway network is concentrated in central and western mountain ranges. The most affected departments are Antioquia, Caldas, Cauca, Tolima and Nariño. In the CAMR, the occurrence of landslides is influenced by the relationship between antecedent rainfall and soil moisture. This relationship is particularly evident in notable cases such as the events that took place on the Medellín-Bogotá Highway in 2016, the Panamerican Highway in Rosas-Cauca in 2023, and Chocó-Antioquia roadway in 2024. These instances highlight the importance of longer periods of rainfall rather than isolated episodes of high intensity rainfall in triggering landslides. The deep weathering profiles of tropical soils in the region contribute to longer periods of rainfall accumulation, which subsequently increase the water content within the soils and enhance landslide susceptibility. Consequently, there is a delay of one month between the peak of landslides, which occurs in November, and the peak of rainfall, which occurs in October during the second half of the year. This delay signifies the influence of antecedent rainfall and the subsequent increase in soil moisture on the occurrence of landslides, even in the absence of direct correlation between rainfall and landslides. Similarly, during the dry season in June and July, there is a high rate of landslides due to the relationship between landslides and antecedent rainfall, as the soil moisture increases from the first rainy season. Overall, understanding the

impact of antecedent rainfall and soil moisture is crucial in assessing the susceptibility and occurrence of rainfall-induced landslides affecting National Roadway Network in the CAMR.

5 CONCLUSIONS

According to the results and the analysis the major conclusions are:

Landslide occurrence in Colombian Andean Mountain region (CAMR) correlates closely with rainfall patterns, notably during the bimodal annual rainfall cycle, with peaks aligning with high-intensity months like MAM and SON seasons. These patterns are influenced by the El Niño-Southern Oscillation (ENSO), which add complexity, especially La Niña phase, characterized by consistent and substantial rainfall. Nevertheless, ENSO-landslide relationship is non-linear, with varied responses depending on ENSO event characteristics and locations.

In the CAMR, the occurrence of landslides is influenced by the relationship between antecedent rainfall and soil moisture. According to results, the highly susceptible roadway corridors to landslides are concentrated in central and western mountain ranges. Particular details need to be focused in the Troncal de Occidente, Troncal Central, Troncal del Eje Cafetero, Transversal Medellín-Bogotá, Transversal Las Animas – Bogotá, Transversal Rosas-Condagua, and Transversal Buenaventura-Villavicencio-Puerto Carreño.

Conducting landslide susceptibility assessments in roadway corridors plays a vital role in determining intervention priorities for governmental entities responsible for managing the national road network. By gaining insights into the susceptibility of landslides along roads, authorities can effectively allocate resources and prioritize interventions to ensure the safety and reliability of the roadway infrastructure.

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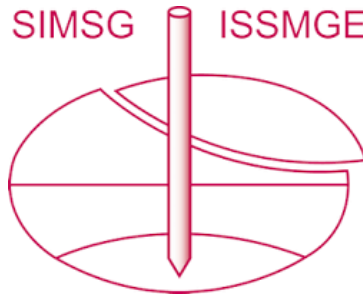
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