A review of the relation between climate variability and mass removal processes. Tunja-Páez case study

Una revisión de la relación entre la variabilidad climática con procesos de remoción en masa. Caso de Estudio Tunja-Páez

Uma revisão da relação entre a variabilidade climática e os processos de remoção de massas. Estudo de caso Tunja-Páez

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Abstract

This literature review paper is a product of the Research Project "Relation Between Climate Variability with Mass Removal Processes. Tunja-Páez case study", developed in the Universidad Pedagógica y Tecnológica de Colombia in the year 2020.

Introduction: This paper focuses on the review of research studies and advances made during the last decade regarding the influence of climatic variability on the dynamics of slopes.

Objective: To determine the influence of climatic variability in areas that present slope instability in the Tunja-Páez road corridor located in the department of Boyacá.

Methods: A systematic review of information from books, manuals, reports, guides, and scientific papers on climate change, climate variability, mass removal processes, meteorological variables, and their influence on the resilience and adaptation of infrastructure related to containment and slope drainage projects.

Results: The studies indicate criteria that relate temperature, precipitation and seismic activity with the occurrence of mass movements.

Conclusion: Climatic anomalies in terms of precipitation and temperature have allowed research methodologies using probabilistic models to be developed for estimating the occurrence of said phenomena in future scenarios.

Originality: The presented literature indicates the influence of climatic variability in the resulting mass removal processes as evidenced in studies at the global and national level.

Limitations: This paper's compiled scientific studies contrast the problems in the stability of slopes of the Tunja-Páez road corridor, without going into the details of these problems.

Keywords: Climate change, climate variability, mass removal, precipitation, roadway infrastructure, adaptation.

Resumen

Este artículo de revisión de literatura es producto de la investigación "Relación entre la Variabilidad Climática con Procesos de Remoción en Masa. Caso estudio Tunja-Páez", desarrollada en la Universidad Pedagógica y Tecnológica de Colombia en el año 2020.

Introducción: este artículo se centra en la revisión de trabajos de investigación y avances durante la última década, relacionados con la influencia de la variabilidad climática en la dinámica de los taludes.

Objetivo: establecer la influencia de la variabilidad climática en zonas que presentan inestabilidad de taludes aplicado a la vía Tunja-Páez en el departamento de Boyacá.

Métodos: revisión de información proveniente de libros, manuales, informes, guías y artículos científicos en materia del cambio climático, variabilidad climática, procesos de remoción en masa, variables meteorológicas, resiliencia y adaptación de la infraestructura relacionada con la contención y obras de drenaje de taludes.

Resultados: los estudios señalan criterios que relacionan la temperatura, precipitación y actividad sísmica con la ocurrencia de movimientos en masa.

Conclusión: las anomalías climáticas en términos de precipitación y temperatura permiten establecer metodologías de investigación mediante el desarrollo de modelos probabilísticos para la estimación de ocurrencia de dichos fenómenos en escenarios futuros.

Originalidad: la literatura presentada señala la influencia de la variabilidad climática en la activación de los procesos de remoción en masa, evidenciado en estudios a nivel global y nacional.

Limitaciones: el presente artículo trata de recopilar los estudios científicos que contrasten con las problemáticas en la estabilidad de taludes del corredor vial Tunja-Páez, sin entrar en los detalles de dichas problemáticas.

Palabras clave: cambio climático, variabilidad climática, remoción en masa, precipitación, infraestructura vial, adaptación.

Resumo

Este artigo de revisão de literatura é o produto da pesquisa "Relação entre Variabilidade Climática com Processos de Remoção de Massa. Tunja-Páez Caso de Studo", desenvolvido na Universidade Pedagógica e Tecnológica da Colômbia em 2020.

Introdução: este artigo tem como foco a revisão de trabalhos de pesquisa e avanços durante a última década, relacionados à influência da variabilidade do clima na dinâmica de encostas.

Objetivo: estabelecer a influência da variabilidade climática em áreas com instabilidade de taludes aplicada à rodovia Tunja-Páez no departamento de Boyacá.

Métodos: revisão de informações de livros, manuais, relatórios, guias e artigos científicos sobre mudanças climáticas, variabilidade climática, processos de remoção de massa, variáveis meteorológicas, resiliência e adaptação de infraestrutura relacionada às obras de contenção e drenagem de encostas.

Resultados: os estudos indicam critérios que relacionam temperatura, precipitação e atividade sísmica com a ocorrência de movimentos de massa.

Conclusão: as anomalias climáticas em termos de precipitação e temperatura permitem estabelecer metodologias de pesquisa através do desenvolvimento de modelos probabilísticos para estimar a ocorrência desses fenômenos em cenários futuros.

Originalidade: a literatura apresentada indica a influência da variabilidade climática na ativação de processos de remoção de massa, evidenciada em estudos a nível global e nacional.

Limitações: este artigo procura compilar os estudos científicos que contrastam com os problemas de estabilidade de taludes do corredor rodoviário Tunja-Páez, sem entrar nos detalhes de tais problemas.

Palavras-chave: mudanças climáticas, variabilidade climática, remoção de massa, precipitação, infraestrutura rodoviária, adaptação.

1. Introduction

Climate Change is a phenomenon that has involved a series of climatic events which include extreme variations in temperature and precipitation on a global scale as a result of natural and anthropic conditions [1].These anthropic sources include greenhouse gas emissions discharged into the atmosphere since the creation of large industries in most first world countries [2].

Although Colombia is not a significant contributor to greenhouse gas (GHG) emissions, it is impacted by the climatic variations produced by them. It is estimated that between 2071 and 2100, there will be an increase in rainfall of 30% in the central zone of the country [2, p. 21]. This increased rainfall will give rise to events such as the "La Niña Phenomenon" that occurred in 2010. These phenomena impact society and the economy of the country leading to 21 300 people affected by the constant landslides presented in vulnerable areas as a result of the increase in rainfall [3].

The current paper focuses on the review of recent research studies and advances related to the influence of climatic variability on the dynamics of slopes. It also aims to establish a relationship between precipitation and temperature along with seismic activity as triggers for mass removal in the Tunja-Páez road corridor. This paper aims to identify the existing geotechnical problems and find a way of adapting vulnerable zones to be more stable.

2. Materials and methods

the current research study utilizes a systematic review of the latest studies carried out at the national and international level regarding the relationship between climatic variability and mass removal processes. Figure 1 presents this process through the research methodology.

2.1. Databases

Scientific papers were obtained from databases such as: Ebsco Host, Web of Science, and SCOPUS, which were combined with scientific advances from the main research journals in the world.

2.2. Search Criteria

The compilation of information involved 190 different sources including books, manuals, reports, guides, and scientific papers published in the last decade. These sources focused on climate change, climatic variability, mass removal processes, and meteorological variables and their involvement in the resilience and adaptation of infrastructure related to slopes, containment, and drainage projects.

2.3. Selection of Information

The information was ranked based on relevance to the topic of study and utilizing currently available research papers. There were 73 references that were found to be similar to the intended application for the Tunja-Páez highway in the department of Boyacá, Colombia. This section of roadway presents instability problems in different areas of the slopes along the corridor. The instability may be caused by meteorological events such as the variation in precipitation and temperature and seismic activity in this area. This analysis facilitates the identification of adaptation guidelines for the infrastructure related to the containment and drainage of slopes.

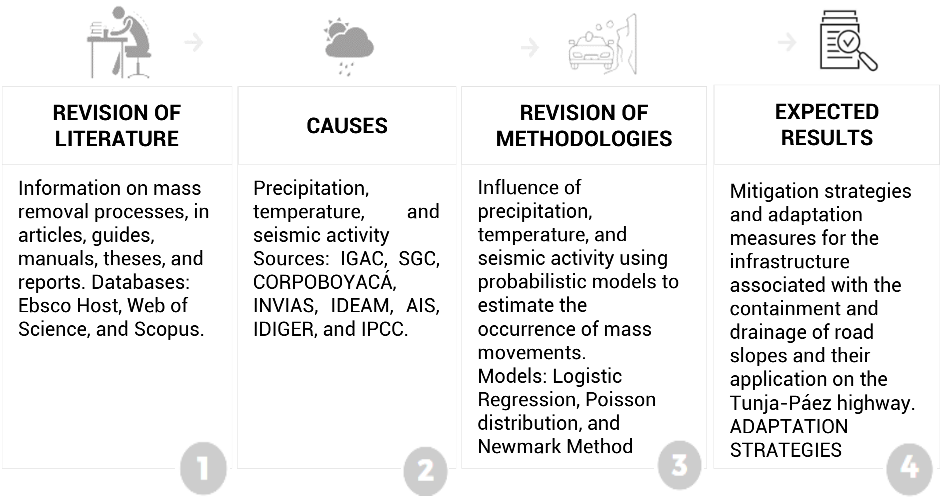


Figure 1. Research Methodology
Source: own work

3. Results

3.1. elements of Climate Variability

Figure 2 suggests monitoring the elements that make up the relationship between climatic variability and mass removal processes.

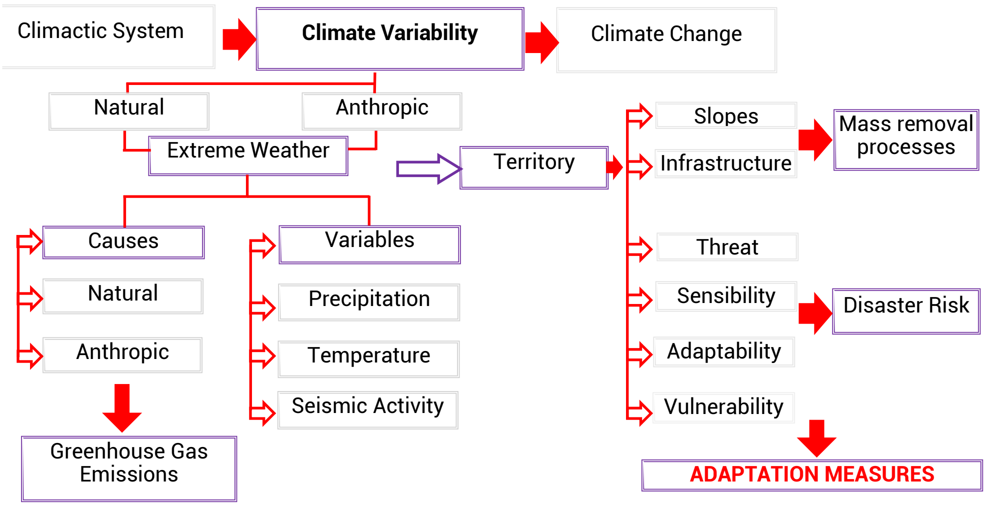


Figure 2. Elements of climate change and its impact on mass removal processes
Source: own work

3.2. Climate Variability

The changes observed in the atmosphere, oceans, cryosphere, and Earth's surface are recorded using direct measurements and satellite mechanisms [4]. During the last decade, there has been evidence of the adverse effects of this variability in various communities with economic, social, and environmental implications in varying order. Since there has been a direct impact on transportation infrastructure, it is necessary to adequately study the meteorological and geological variables that have been altered over time by natural and anthropic processes and how these are impacted by current climate behavior [4, p.15].

Climate variability manifests itself through variations in the statistical behavior of climate, with temporal and spatial amplitudes greater than those presented by meteorological events according to the Intergovernmental Group of Experts on Climate Change (IPCC). This variability originates from natural processes or from activities attributed to humans [5]. The Institute of Hydrology, Meteorology, and Environmental Studies (IDEAM) establishes the difference between variability and climate change, indicating that for the latter, climate records must be considered and alterations must be evidenced in periods greater than or equal to 30 years [6].

When analyzing the behavior of climatic variability in terms of temporal patterns throughout the years, IDEAM ensures that there are intercalated periods grouped into three types of seasonal variations: intra-seasonal, inter-annual, and interdecadal [5, p. 17]. The difference between the three lies in the fluctuations of the climate at different time scales, thus these variations are presented in the month, year, and decade intervals, respectively [7].

When changes in climate occur, they are related to extreme atmospheric conditions that exceed the average [8]. These phenomena translate to extreme weather, which are a representation of climatic variability and have been recorded since the 1950's [5, p. 8]. Human activity has contributed to these changes by increasing greenhouse gas concentrations since the industrial revolution. These changes translate into daily increases and decreases in temperature as well as increases in the intensity of precipitation [5, p. 112].

Despite the fact that the atmospheric conditions that exceed the statistical average are observations of extreme weather, IDEAM suggests not to associate it with meteorological events such as tidal waves, hurricanes, and torrential rains. These events are punctual and do not follow a pattern of recurrence over time, but rather many years later severely impacting society [7, p. 40].

According to the analysis of the changes produced in the hydrological cycle, an increase in water vapor in the atmosphere determines the intensity of the precipitation and the alteration of its cycle [9]. Other studies carried out by the IPCC indicate a high probability of impacting the hydrological cycle due to human activities, which have generated an increase in the moisture content in the atmosphere throughout the world [5, p.143]. This could be mitigated by setting priorities and implementing adaptation strategies in time [10].

3.3. Temperature

The climate supports life on Earth through the interaction of different chemical compounds, which produce Greenhouse Gases. During the last century however, anthropogenic processes have caused the concentration of these gases to increase to the point of exceeding natural thresholds, resulting in global warming [11]. The effect of this on the Earth's surface is evidenced by the significant increase in temperature in 2016 of 0.56°C. With respect to the average of the period between 1986-2010, these changes result in extreme weather events related to the El Niño Southern Oscillation (ENSO) [12].

The picture is more critical when it comes to global surface temperature in the late 21st century, as the latest IPCC report estimates an average increase of 1.5°C between 1850 and 1900. This indicates that a rapid warming in the Arctic of up to three times the global average has occurred [4, p. 19].

The global fluctuation of temperature reached 1°C above the pre-industrial level in 2017. If the actions to control GHG emissions are not undertaken, a warming of the earth's surface of 1.5°C will be achieved by the year 2040 (Figure 3). Although the situation is alarming, there is a perception that a temperature rise of 0.5°C is insignificant. The global consequences of such a small rise in temperature would be considerable, which is why there has been a proposal to limit carbon dioxide (CO2) emissions by approximately 45% by 2050 [13].

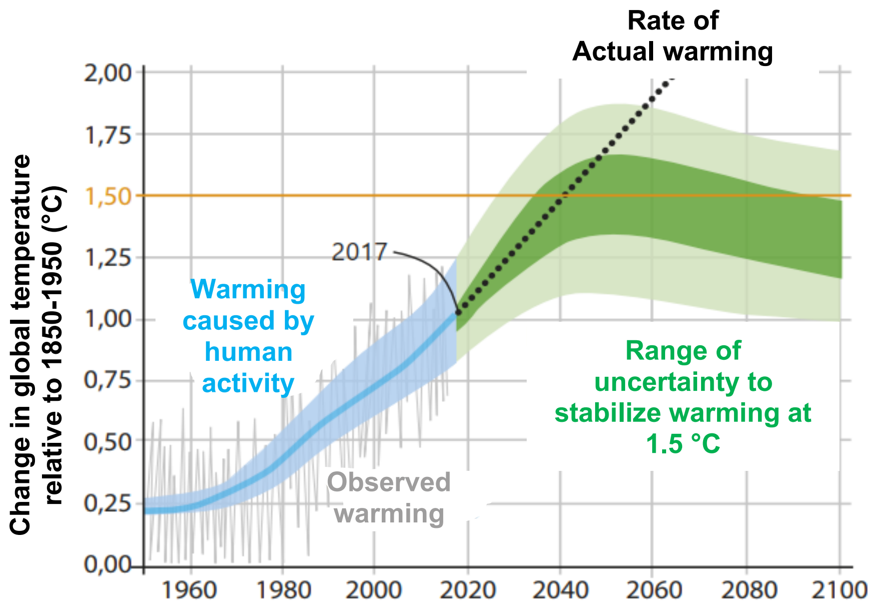


Figure 3. Change in global temperature between 1960 and 2017
Source: Adapted from [13, p. 13]

There is a close spatial-temporal correlation between mass movements and variables such as seismic activity, precipitation, the wet-dry cycle, and the freeze-thaw cycle. Both the wet-dry cycle and the freeze-thaw cycle originate from temperature variation and are responsible for the cracking in rocky matrices [14]. Temperature also influences the sequence of drought periods that can trigger mass removal processes taking into assumption that previous dry periods are triggers for extreme rainfall [15].

Heat waves as a result of transport processes caused by changing climatic phenomena constitute another possible risk of significant damage to infrastructure and the elements associated with it. This phenomenon is produced by the accumulation of days with high temperatures that exceed 30°C in the day and may trigger storms that increase the risk of landslides of soil masses later [16].

3.4. Precipitation

Precipitation is the process of falling water particles which originated from clouds crossing different atmospheric layers and finally being deposited on the ground [17]. The study of this variable is carried out by measurements of intensity, duration, and frequency. A determining process in the fluctuations of atmospheric weather is defined by the hydrological cycle, which is altered by external anthropogenic agents inducing anomalies in the natural behavior of rainfall [18]. This is caused by changes in ocean currents and the increase in sea surface temperature, which impact the climate of the equatorial strip of the Pacific; thus creating the El Niño-Southern Oscillation phenomenon (ENSO) which alternates with the cold phase phenomenon known as La Niña [19].

Between 2010 and 2011 these strong oscillations generated a chain of losses and damages in various regions of Colombia due to the cold front unleashed by the alteration of the ENSO cycle. Extreme rainfall in the Caribbean and Andean regions caused floods, avalanches, and mass removal processes. [20]

Rainfall is described as extreme when its intensity at any given time exceeds historically recorded averages. Extreme precipitation can cause soil saturation and flooding from additional rains [20, p. 20]. To measure the impact and damages caused by these events, the State Meteorological Agency AEMET, defines the quantification of this variable under severity levels according to intensity and duration in terms of millimeters per hour (mm/h) [21], as shown in Table 1:

Table 1. Characterization of precipitation according to intensity

Type	Intensity/hour (mm/h)
Weak	≤ 2
Moderate	> 2 ≤ 15
Strong	> 15 ≤ 30
Very Strong	> 30 ≤ 60
Torrential	> 60

Source: Created using data from [21, p.21]

The World Meteorological Organization (WMO) establishes the intensity of rainfall in mm/year; where less than 200 mm is considered low, between 200 and 500 mm scarce, between 500 and 1000 mm as normal, and more than 2000 excessive.

Mass movements can be attributed to different parameters associated with the behavior and history of rainfall in a certain geographical area. This includes any accumulated rainfall preceding the landslide, the critical rainfall that arises from the moment that rainfall intensity drastically changes, the daily rainfall when the landslide occurs, and the duration of the rainfall among other factors [22].

One specific study which took place in the United States between 2016 and 2017 involved a series of strong storms which hit the city of Oroville and produced severe structural damage to the dam in this city. Heavy rainfall over a 6-month period equivalent to 2406 mm was the primary culprit for the cause of the structural damage [23].

Another similar case was reported in the coastal region of Peru in the first quarter of 2017. This time of year is considered to be landslide season due to the heavy annual rains which occur every year. The atypical variations of the average rainfall for the time of the year were around 50 to 80 mm, while the total precipitation in that area reached approximately 5 standard deviations above the historical average. This resulted in heavy human and economic losses. Heavy precipitation is estimated to have a probability of occurring almost twice that of normal due to the warming of the ocean surface [24].

The final example is the analysis of the behavior of extreme rainfall which occurs in the river basin of Uruguay during the months of April and May of 2017. The area has an average annual rainfall of 1750 mm; however, since the end of the 21st century, annual rainfall has been increasing and has caused large-scale water flows to start. Furthermore, an increase in the intensity, duration, and frequency of rainfall has been observed which may increase the risk factor of these extreme events occurring by a factor of 5 in the near future [25].

Although the correlation between precipitation and temperature creates a strong variability over time [26], the climate scenarios presented in the framework of the fifth report presented by the IPCC are considered the fundamental basis for the joint modeling of precipitation and temperature trends. The alteration of precipitation and temperature in the arid zone of the Kerman Province in Iran was studied to determine its impact on agricultural production and hydrological phenomena such as floods and droughts. This study involved the analysis of historical data between 1961 and 2005 [27].

The relationship between rainfall and mass movements requires that rainfall be identified prior to the mass movement. The landslides that occurred between 1993 and 2013 in Bogotá, Colombia were the result of four days of heavy accumulated rainfall along with steep slopes [28].

An estimate of the threat of landslides triggered by rains can be determined by analyzing the data recorded by rainfall stations according to the events which took place in the Aburrá Valley of Colombia. Here an analysis of rainfall in periods ranging between 20 and 50 years resulted in spikes of accumulated rainfall between 3 and 15 days providing the possibility of determining landslide risk [29].

The mass movements which occurred in 2018 in the municipality of Mocoa, Colombia were the result of a monomodal precipitation event which occurred during the month of August. The average rainfall for the month of August is 340 mm, which was taken from data between 1981-2010. On the day of the landslide, 119 mm of rain was recorded and resulted in the cause of the landslide. This value represents a third of what it normally rains in the month and is what caused the removal processes in the basins involved and erosion which occurred in the territory [30].

A similar event occurred in the towns of Roccafluvione and Acquasanta Terme (central Italy) where they recorded a maximum accumulated rainfall of 500 mm in 3 days. This amount of rainfall unleashed a chain of landslides that impacted the secondary road network [31].

In order to determine the precipitation thresholds that create mass movements, a study was carried out in the northern part of Turkey. It affirmed that landslides do not occur constantly due to extremely intense rainfall but are the product of events that occur over days and even up to months. Therefore, the intensity and accumulated precipitation of 3, 5, 10, 15, and 30 days prior to mass removal events are associated [32].

An influential factor in the stability of slopes is the relationship between precipitation and intensity. For the Colombian Andean region this is constituted by average annual rainfall ranging between 1 300 mm and 2 500 mm and monthly intensity amounts of 300 mm to 500 mm in rainy periods and 50 mm to 100 mm in dry periods. Thus, mass removal events can occur at the time or even after 50 mm to 100 mm of rainfall [33].

Changes in precipitation in Colombia between 2001 and 2010 vary between 10% and 40% with respect to the period 1971-2000 in departments such as Guajira, Magdalena, Atlántico, Chocó, and part of the coffee zone. In areas such as Huila, Cundinamarca, and Santander, there have been below average fluctuations between -40% and -10% [34].

According to the climate change scenarios presented by the Regional Administrative and Special Planning Department of Colombia (RAPE); the department of Boyacá will see increases in rainfall in the Central, Eastern, and Márquez provinces. There will also be a variation between 20% and 40% with respect to the reference scenario between 1976-2005, which recorded average annual precipitation that varied between 1000 mm and 5000 mm. For the case study referring to the Tunja-Páez roadway in the department of Boyacá, the reference levels include annual rainfall ranging between 2000 and 4000 mm [35].

Precipitation as a generator of mass movements in the department of Boyacá, are represented by climatic zoning maps from the Climatological Atlas of Colombia. They are created by analyzing the average annual precipitation and the isohyet curves of maximum daily rainfall for a 25-year return period [36].

3.5. Seismic Activity

The tendency of soil to be susceptible to mass movements is intensified by seismic activity in the area. The increase in horizontal acceleration at the rock level causes an increase in the acting forces and a decrease in the value of soil resistance as a result of the increase in pore pressure [36, p.36].

Seismic activity depends on different variables associated with the seismic event such as the magnitude and the propagation of the wave. As the magnitude parameter increases, the number of landslides increases as well. Landslides are primarily associated with peak ground acceleration and the direction of maximum acceleration [37].

Landslides caused by earthquakes can be estimated by analyzing probabilistic models of slope stability by taking into consideration the physical characteristics of the area such as geomorphology, topography, and hydrology among others [38]. The determination of these factors makes it possible to establish an estimate of the areas susceptible to landslides. This is done using the probability of slope failure, maximum horizontal acceleration values obtained by the seismic zoning of the area, and the safety factor. Within these probabilistic models in the Aburrá Valley of Colombia, research has found that with an acceleration of 0.2g, the maximum probability of a landslide occurring corresponds to 99.96% when the soil meets its natural humidity, while in a saturated state the probability rises to 100% [39].

As already mentioned, the seismic activity represents a triggering factor of the mass removal processes of natural origin. In order to determine its relationship, the magnitudes of the telluric movements are correlated with the different types of mass events. This dependency is presented in the table shown below (Table 2) [40].

Table 2. Minimum Local Magnitude (ML) of earthquakes by type of mass movement

M_L according to Keefer (1984)	M_L according to Rodríguez (1999)	Type of mass removal
4.0	5.5	Falling rocks (debris or soil) Rock and soil landslides.
4.5	5.5	Landslides of soil in blocks.
5.0	6.5	Landslides of rocks in blocks Land flows (slowly and quickly) Lateral spread Underwater landslides
6.0	6.5	Rock avalanche
6.5	6.0	Land avalanche

Source: Taken from [40, p.10]

A threat analysis of the area potentially exposed to mass removal events can be established which includes the incidence of seismic activity in terms of horizontal acceleration. This is performed by applying a seismic curve from the case study for a determined period of return. This allows for the probability of exceeding a certain acceleration, one that can generate mass movements, to be known. In the event that the area to be analyzed does not have a seismic hazard study, the threat curve of the capitals defined in the General Study of the Seismic Threat of Colombia 2009 (AIS 2009) [41] is applied.

For the case study corresponding to the Tunja-Páez roadway, the seismic hazard curve that was applied for the probability analysis of the maximum acceleration belongs to the city of Tunja in the department of Boyacá, as shown in Figure 4 [42].

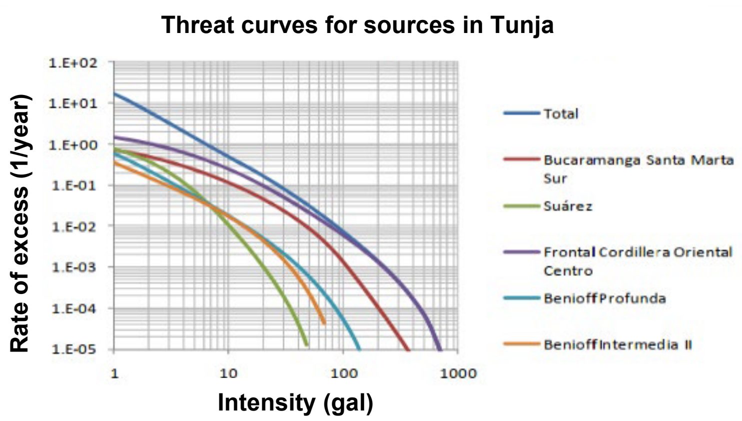


Figure 4. Threat curve for the city of Tunja in the department of Boyacá
Source: Adapted from [42, p. 96]

Figure 4 correlates the exceedance rate of a seismic event given its intensity for each of the sources that generate it. These include the Bucaramanga Fault, Santa Marta Sur, Suárez, Frontal Cordillera, Oriental Centro, Benioff Profunda, and Benioff Intermediate II.

Since the magnitude of earthquakes can act as possible generating factors for mass removal processes, a study in the Biobío region in Chile analyzed the effect produced by an 8.8 Mw earthquake that unleashed 22 mass movements resulting in falling rocks and soil, landslides, and lateral spread, among others. These events were generated by the combination between the increase in shear stress, the low resistance of the ground material (a product of the increase in pore pressure), and the propagation of the seismic wave, which triggered the detachment of the rocky matrix and the soil in the area [43].

3.6. Mass Removal Processes

The Andean Multinational Project: Geosciences for the Andean Communities (WFP: GCA), categorizes these events into falls, overturns, landslides or rockslides, lateral propagation, flow, creep, and deep gravitational deformations. Likewise, other types of movements are attributed to each category, called subtypes, which are represented in Table 3 [44].

Table 3. Classification of the principal mass movements

Type	Subtype
Falls	Falling rocks (debris or soil)
Overturning	Block rock overturning - Flexural overturning of rock or rock mass
Land or rock slides	Translational slip, wedge slip - Rotational slip
Lateral spread	Slow lateral spread - Lateral spread by liquefaction (quick)
Flow	Debris flow - Debris flood - Mud flow - Earth flow - Peat flow Debris avalanche - Rock avalanche Landslide by flow or liquefaction (sand, silt, debris, fractured rock
Creep	Soil creep - Solifluction, gelifluction (in permafrost)
Deep gravitational deformations	

Source: Taken from [44, p.3]

Within the different typologies of mass movements, falls are characterized by the detachment of fragments of soil or rock in sloping terrain. The latter can reach material displacement speeds of 100 m/s [44, p. 4]. Overturning occurs by sliding rocks or soil grouped into blocks with rotational movements towards the front [45].

Another feature of mass removal processes are rock or soil landslides. These result in translational landslides of rock material on generally shallow, smooth, or undulating surfaces and rotational landslides which occur on steep slopes, where material displacement combines concave and convex shapes [46] (Figure 5).

a) Falling rocks b) Overturning c) Translational slip d) Rotational slip

Figure 5. Classification of the principal mass movements
Source: Taken from [47]

In land where there is a flat relief, lateral propagation movements occur where the mass of the removed material is displaced due to its internal deformation. This type of movement is classified as slow lateral propagation, attributed to rocky matrices and whose displacement occurs slowly. Rapid lateral propagation occurs in loamy clay soils and sands with little cohesion where the detachment of the material is carried out quickly generating liquefaction [48] (Figure 6).

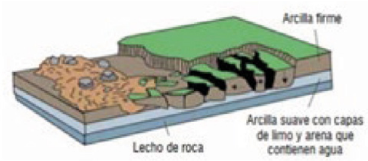


Figure 6. Lateral spread. Classification of the principal mass movements
Source: Taken from [47]

Mass movements that occur at high speeds and that glide over a dense liquid mass belong to flows, which are composed of fine and granular materials that do not exceed 50%. These are classified as debris flows which are triggered by rains which saturate the material of the slope and cause a loss of resistance [49]. Mud flows are caused by sudden rains which reach very high speeds and are integrated with clays, silts, and very fine sands [50] (Figure 7).

Creeping is another form of mass movement which is identified by undulating surfaces, cracking of the pavement surface, inclination of the vegetation in the area, and the displacement of the mass of soil and rock. It is relatively slow because it occurs in terrains with little inclination and tends to occur in mostly temperate and tropical climates [33, p. 471] (Figure 7).

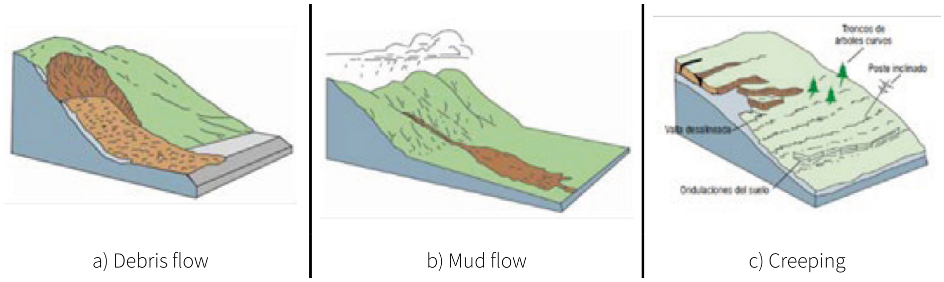


Figure 7. Classification of the principal mass movements
Source: Taken from [47]

Mass removal processes are the product of a series of triggers with a certain correlation between both natural and artificial conditions and processes that increase the probability and occurrence of these events [45, p. 87]. Among the triggering factors are the conditions of the terrain made up of the physical characteristics of the area, the natural processes responsible for climatic phenomena, earthquake movements, and external activities caused by human intervention [51] (Figure 8).

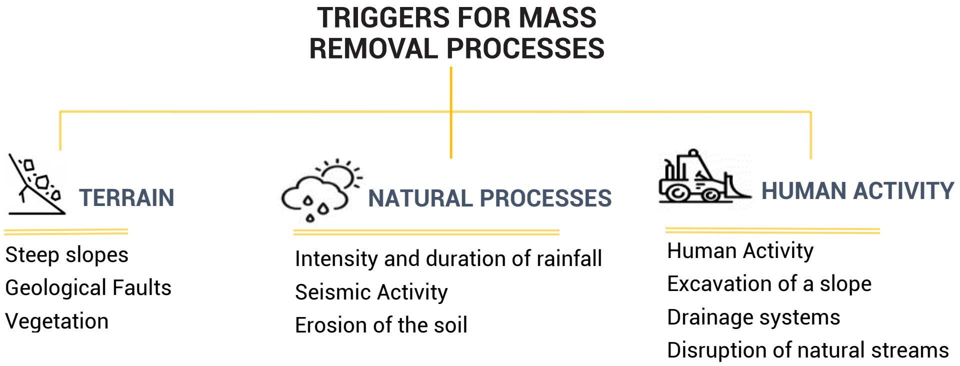


Figure 8. Triggers for mass removal processes
Source: Adapted from [51]

3.7. Territorial Impacts

Advances in scientific research have provided the ability to analyze the dynamics of these events in order to determine a means of prevention for these natural disasters and impacts on the territory to the point of developing electronic early warning systems that can detect these types of events [52]. This detection is carried out by relating rains to landslides, establishing accumulated precipitation thresholds of several days that when exceeded, can trigger mass movements. These thresholds establish the definition of warning levels in the place and formulate alert measures on the occurrence of these events [53].

A clear example of this is the advances in the mathematical models used to evaluate the vulnerability of landslides that occurred in Nova Friburgo, Brazil as a result of extreme rains. The study suggests keeping records about these types of events which include the geotechnical parameters that relate the intensity of the landslide and the resistance of the structure, together with the date of occurrence of these phenomena (deterministic approach) [54].

Another of the methodologies developed corresponds to the elaboration of landslide susceptibility maps through the application of Geographical Information Systems (GIS). Together with the implementation of the logistic regression (heuristic approach) involving variables such as lithology, altitude, slope, and index of topographic humidity, among others, a map which may prevent landslides can be created. In Nancheng County, China, where landslides with magnitudes in the order of 15 m2 to 18,000 m2 had taken place, susceptibility maps facilitated the dynamic analysis of the area and allowed for the evaluation of new mass removal events [55].

One of the approaches to analyze climatic anomalies and trends in specific cases is developed by correlating precipitation and temperature variables obtained from the historical records of a particular study. When these variables are assigned to discriminant and Bayesian function models, it allows for the determination of the trend of climatic scenarios and the analysis of their fluctuation in time [56].

Research which took place in the state of Colorado in the United States, evaluated landslide susceptibility based on a study area called Paonia McClure located in the central western part of the state. In this region, 735 mass movements were registered and triggered by different factors such as earthquakes, heavy rains, vegetative cover, and subsoil hydrology among others. The mass movements resulted in 85 m^2 to 160 300 m^2 of material being moved. This problem has been the reason for developing precise methods that involve deterministic approaches that consider the specific dynamic nature of the location. It also provides the ability to differentiate the areas susceptible to landslides and determine the probability of the landslide occurring using logistic regression [57].

These advances make a fundamental contribution to the prevention of natural disasters in areas where mass movements occur frequently. The analysis considers a set of geo-environmental conditions that can simulate the occurrence of these events in places prone to the occurrence or even in the formation of mass removal processes [58].

Table 4 demonstrates the events that have occurred and their triggering factors, its influence on the territory in terms of social, local, and economic impacts and what research methodology was developed to mitigate its adverse effects.

Table 4. Summary of territorial impacts for mass movements on a global scale

Event	Cause	Territorial impact	Methodology
Precipitation in 2017 in the Uruguay river basin (South America) [25]	Precipitation	Social: displacement of more than 3 500 people in Uruguay due to increased flooding along the Uruguay river. Economic: losses close to 102 million dollars in Brazil.	Probabilistic analysis of rainfall using Kolmogorov-Smirnov for the estimation of floods in the Uruguay river. This method helped establish how representative the precipitation is in a climate model (HadGEM3-A) which allowed for the evaluation of the influence of anthropogenic factors on the behavior of the precipitations. This probabilistic analysis verifies whether the precipitation and the simulations in the models belong to the same distribution.
Landslide in Mocoa on March 31, 2017, Putumayo (Colombia) [59]	High intensity accumulated precipitation	Social: 332 deaths, 398 injured, and 77 missing. Territorial: 420 mass movements left behind: 11 km of destroyed roads and damage to 1 462 homes. Damage was also done to water supplies and power stations.	Description of the study area and the behavior of the accumulated daily precipitation of the last year before the event that occurred in 2017. The analysis demonstrated that the accumulated precipitation of 4 continuous days exceeded the rainfall thresholds of the area, stating that the mass movements that occurred in 2017 were associated with heavy rains concentrated in short periods of time and not with prolonged rains.
Landslides on the road network in Sicily (southern Italy) on October 1, 2009 [31]	High intensity precipitation	Social: 31 deaths, 7 missing. Territorial: 1 480 landslides that caused damage to 12.79 km of roads (54% of total primary roads), railways, and public buildings. Economic: repairs that reached €193 688 223	Estimation of the costs of landslides and their impact on the territory through inventory of mass movements and application of geomatic tools to evaluate the road network.

continue

Event	Cause	Territorial impact	Methodology
Precipitation in 2017 in the Uruguay river basin (South America) [25]	Precipitation	Social: displacement of more than 3 500 people in Uruguay due to increased flooding along the Uruguay river. Economic: losses close to 102 million dollars in Brazil.	Probabilistic analysis of rainfall using Kolmogorov-Smirnov for the estimation of floods in the Uruguay river. This method helped establish how representative the precipitation is in a climate model (HadGEM3-A) which allowed for the evaluation of the influence of anthropogenic factors on the behavior of the precipitations. This probabilistic analysis verifies whether the precipitation and the simulations in the models belong to the same distribution.
Landslides in Nova, Freiburg (Brazil) on November 11 and 12, 2011 [53]	High intensity precipitation	Social: approximately 1 000 deaths. Territorial: 1 620 landslides in urban areas and 7 000 landslides in rural areas.	Development of a mathematical model for the assessment of physical vulnerability based on the ***principle of natural proportionality*** and calibrated with field observations of mass movements recorded on the related date.
Landslides and floods in Peru, March 2017 [24, p. S31] [60]	Extreme rains	Social: 91 fatalities, 122 788 victims, 797 789 affected, and 348 injured. Territorial: collapse of 14 661 homes. Economic: losses of US $3.124 billion (representing 1.6% of GDP).	Analysis of climatological thresholds to examine the records of extreme rainfall that triggered the mass movements.

Source: Created from [25], [31], [53], [59] and [60]

The largest natural disasters in history ranging from 1970 to 2011 occurred on the Asian continent with a percentage of 39%, followed by Africa with 24%, Oceania 20%, America with 12%, and finally Europe with 5%. There were a total of 10 632 natural disasters which were primarily attributed to hydrometeorological causes representing 72% of total disasters; 12.3% correspond to biological disasters and 15.7% to geophysical disasters as shown in Figure 9 [61].

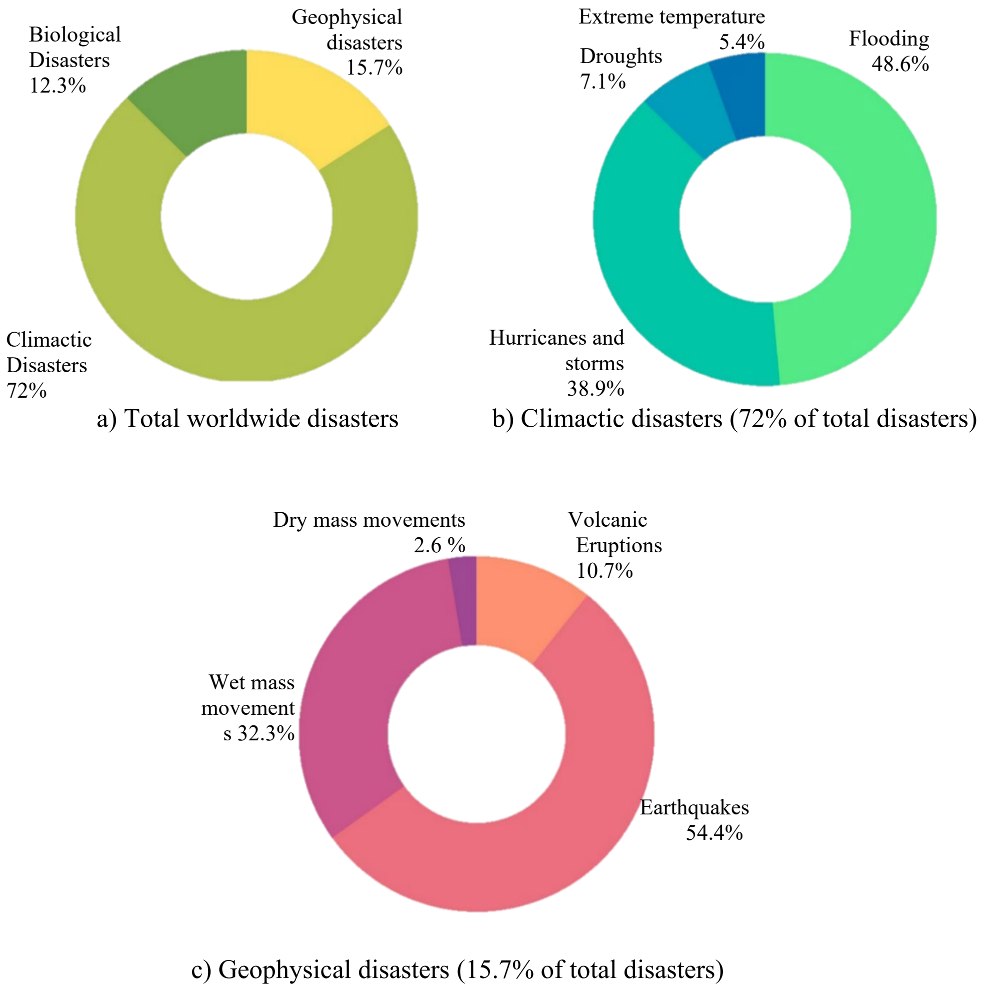
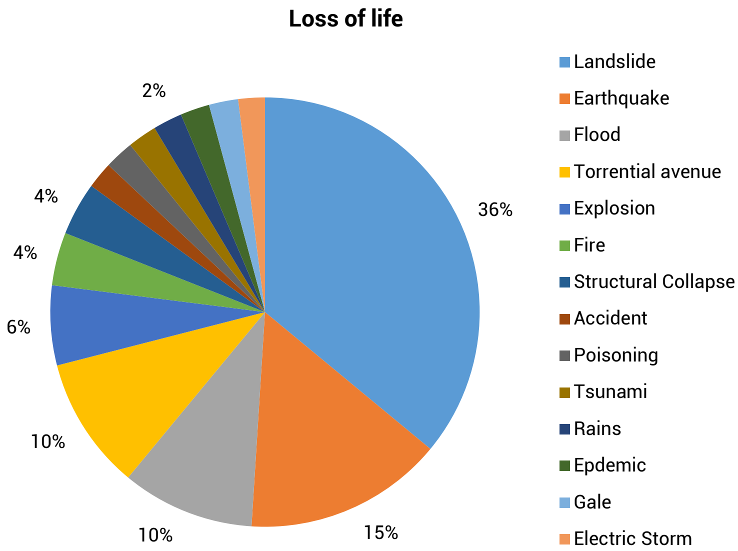
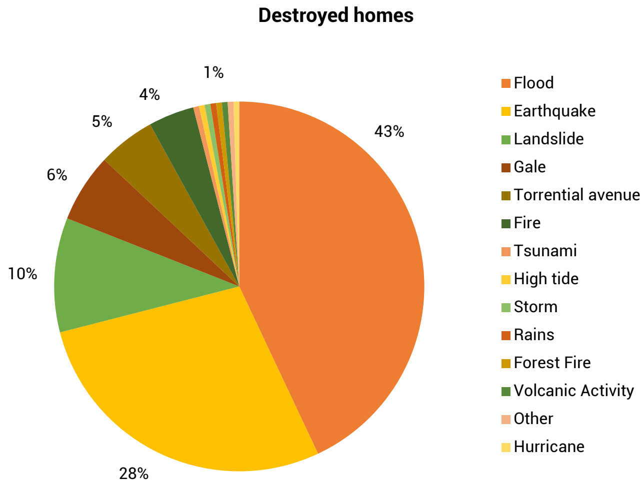


Figure 9. Distribution of disasters on a worldwide level between 1970 and 2011
Source: Created from [61, p. 23]

In Colombia, landslides during the period from 1970 to 2011 represent discouraging figures regarding their impacts to human life and economic damage as represented below in Figure 10 [62]



a) Loss of life



b) Destroyed homes

Figure 10. Percentage per event type between 1970 and 2011 in Colombia
Source: Adapted from [62, p. 35]

The percentage distribution by type of event in the period from 1970 to 2011 in Colombia demonstrates that landslides generated 36% of fatalities and 10% of destroyed homes. In comparison, seismic activities resulted in 15% of fatalities and 28% of destroyed homes [62, p. 35].

The figures presented by the National Planning Department (DNP) between 1998 and 2016 have shown that 88% of disasters in Colombia are attributed to hydrological and climatic factors. Of these, 35% were caused by floods, 15% mass movements, 1% torrential flows, 37% droughts and fires, 11% geological faults, and 1% other events. The total number of natural disasters (marked by the blue line) is shown in Figure 11 below [63].

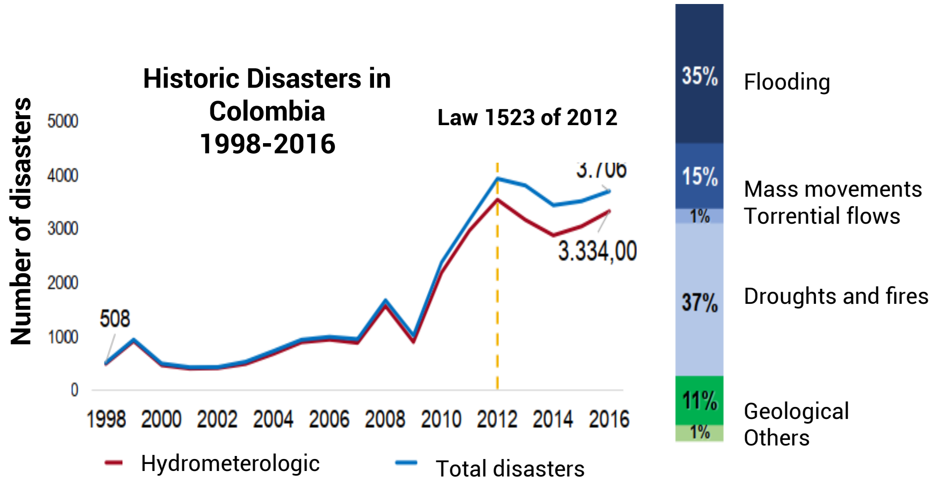


Figure 11. Historical disasters in Colombia from 1998 to 2016
Source: Adapted from [63, p. 11]

According to the historical data from Colombia during the period between 1998 and 2016, a peak was seen in 2012 in which 4 000 total disasters were recorded. Of these, approximately 3 600 were triggered by hydrometeorological events. In 2012, a National Policy for Disaster Risk Management was adopted by creating the National Unit for Disaster Risk Management UNGRD in response to the events that occurred in 2011 with the La Niña Phenomenon. That year, almost 500 deaths throughout the country were attributed to climactic events [63, P. 12].

4. Discussion

4.1. Territorial Impacts

The measurement that leads to a numerical expression for the proportion of the population susceptible to damage from disasters is called the disaster risk index. This index creates a relationship between the population exposed to the threat (product of population density and the threatened area of the analysis region), the vulnerable population, and the total population [63, p. 37]. This index can be adjusted by referring to the management abilities of territorial entities which respond to these events. It consists of factors such as risk and capacity as shown in Figure 12 below [64].

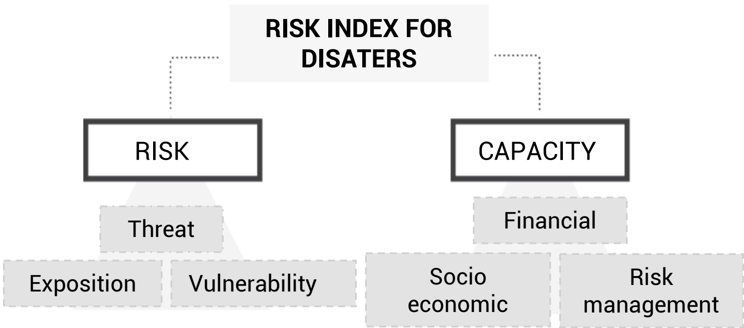


Figure 12. Disaster Risk Index adjusted for Capacities
Source: Created from [64, p. 9]

The three components of risk are correlated with the area susceptible to a territorial affectation. This relationship categorizes the risk zone on a scale from 0 to 100, with zero being low vulnerability and 100 being high vulnerability. Risks from events related to floods, mass removal processes, and other phenomena of this nature are shown below [64, p. 10].

$$RISK_i \; EXPOSITION_i \; (THREATi) * VULNERABILITY_i \; \text{Where i: City}$$

Source: Taken from [64, p. 10]

Within the threat component, there are three factors that impact a particular area: floods (related to precipitation events and extreme temperatures such as the La Niña and El Niño phenomena), torrential flows, and mass removal processes. In 2015, according to the Colombian Geological Service, 11.7 million hectares were classified as having a greater susceptibility to mass movements. They also found that 12.4 million hectares had the potential for high torrential flows.

Seven departments have more than 50% of their population exposed to hydroclimatic threats. Boyacá occupies fourth place in the country at 59.6% with the municipalities of Maripi and Muzo most at risk. 29.3% of the population of Boyacá is considered vulnerable, ranking 27th in the departmental ranking according to the Multidimensional Poverty Index (IPM) [65].

The proportions by risk component, according to the correlation between threat, exposure, and vulnerability as well as the Municipal Index of Disaster Risk in the department of Boyacá, are shown below. Data has been taken from the municipalities of Tunja, Ramiriquí, Zetaquira, Miraflores, and Páez (main municipalities of the Tunja-Páez road) and is shown in Figure 13.

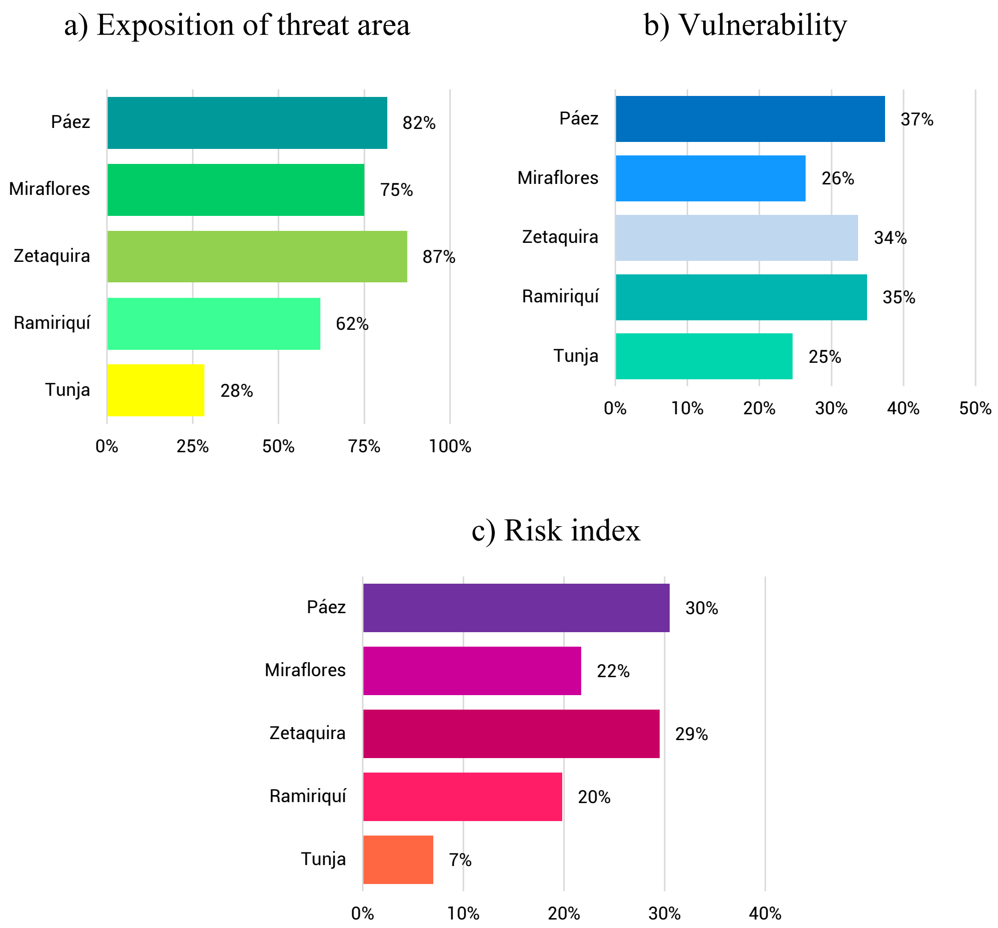


Figure 13. Composition of the Disaster Risk Index adjusted for Capacities
Source: Created from [66, p. 145, 146, 147]

According to the Municipal Disaster Risk Index shown in Figure 13c, Páez is the municipality with the highest value of this indicator with 30.49%, while the lowest value is held by Tunja with 6.99%. The number of emergency events registered in the department of Boyacá for the period between 2014 and 2018 includes 75 mass movements associated with landslides and other removal processes [66].

Mass removal processes occur primarily along the Tunja-Páez highway according to data from the Colombian Geological Service recorded in the relative threat map for mass movements in the department of Boyacá. This map classifies threats on a scale of four levels ranked as very high, high, medium, and low according to the colorimetry of the areas at risk presented below in Figure 14.

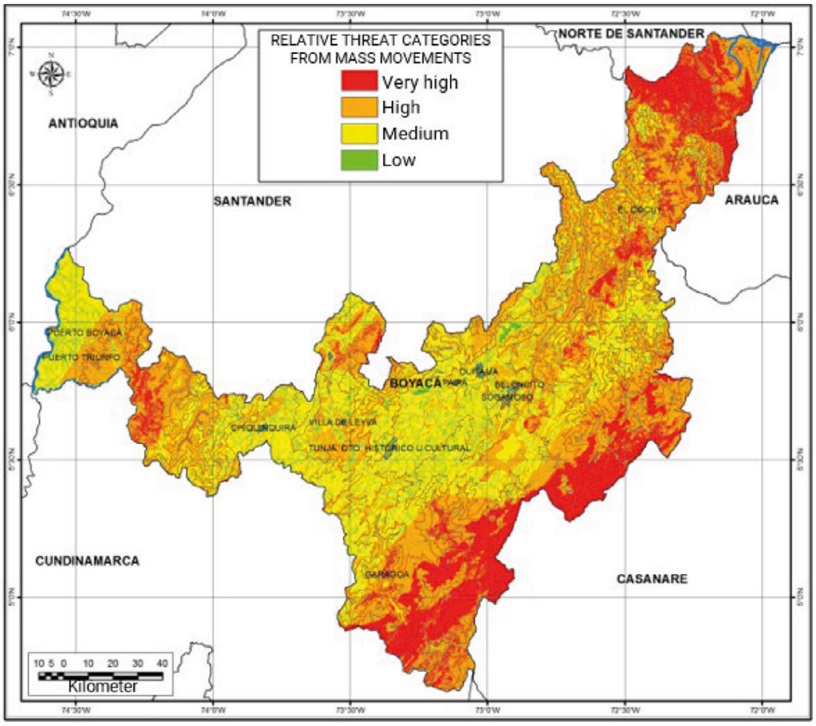


Figure 14. Threat map for the department of Boyacá
Source: Adapted from [67, p. 127]

The southern part of the department of Boyacá presents a very high threat from mass movements in 17.29% of its total area, with the municipality of Páez being the most affected, at 80% in this category. The high-risk threat makes up 46.62% of the total threats for the department and is also where the municipalities of Miraflores and Zetaquira are located [67, p.127].

The Tunja-Páez corridor is located in the southern central strip of Boyacá (Figure 15). It coincides with the areas of mass movement classified as high and very high threat zones. This is geologically composed of colluvial deposits and masses made up of clay matrix blocks of colluvial origin. The slopes have undercut events at their base due to the natural channels produced by high intensity rainfall in the area and it is characterized by a steep mountainous relief [68].

Due to its location on the Eastern Cordillera, roadway characteristics include large slopes, instability problems, and complicated drainage projects in order to control abundant water runoff. The corridor has elevations above sea level, which vary between 1 300 and3 000 meters and extend over about 1.7 km^2, benefiting 53 000 inhabitants [68]. Table 5 summarizes the characteristics of the Tunja - Páez study road.

Table 5. Characteristics of the Tunja-Páez roadway in the department of Boyacá

Parameter	Characteristic
Length	118 Km
Code	6009
Territory	Boyacá
Section	Transversal Puerto Boyacá - Monterrey
Sector	Tunja – Páez
Administrator	INVIAS
PR Initial	0+000
PR Final	118+000

Source: Made from [69]

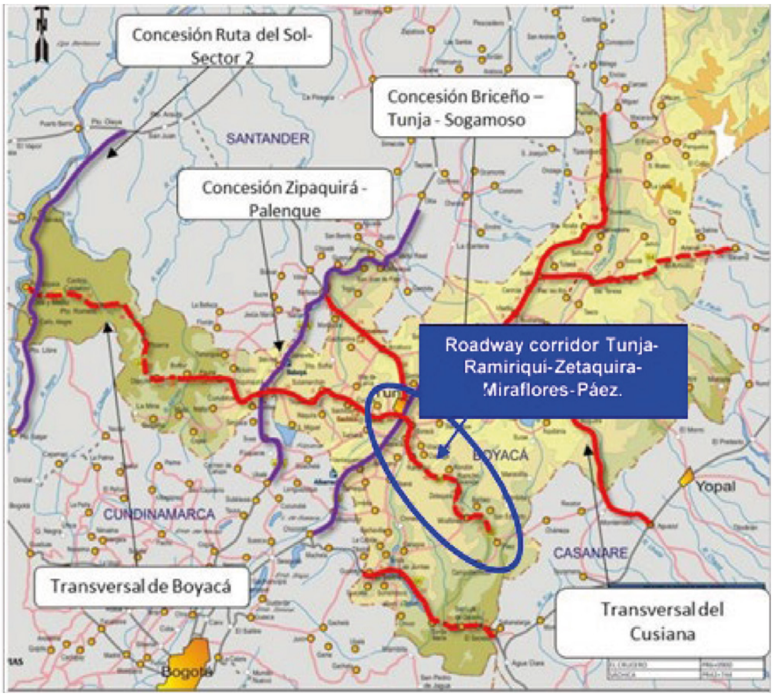


Figure 15. Location of the Tunja – Páez roadway in the department of Boyacá
Source: Taken from [70]

4.2. Adaptation Measures

Due to climate change and climate variability, a series of measures have been proposed in order to mitigate the impacts of mass removal processes within Colombia. This entails updating the design criteria of new projects while adapting existing ones. This also ensures that risk is prioritized while investing in infrastructure that is resilient to adverse weather factors [71].

The adaptation of road infrastructure and projects related to the containment and drainage of slopes should increase the resilience of infrastructure. To achieve this type of response, the World Road Association proposes the development and selection of responses and adaptation strategies within its methodology, which are made up of three stages as shown in Figure 16 [72].

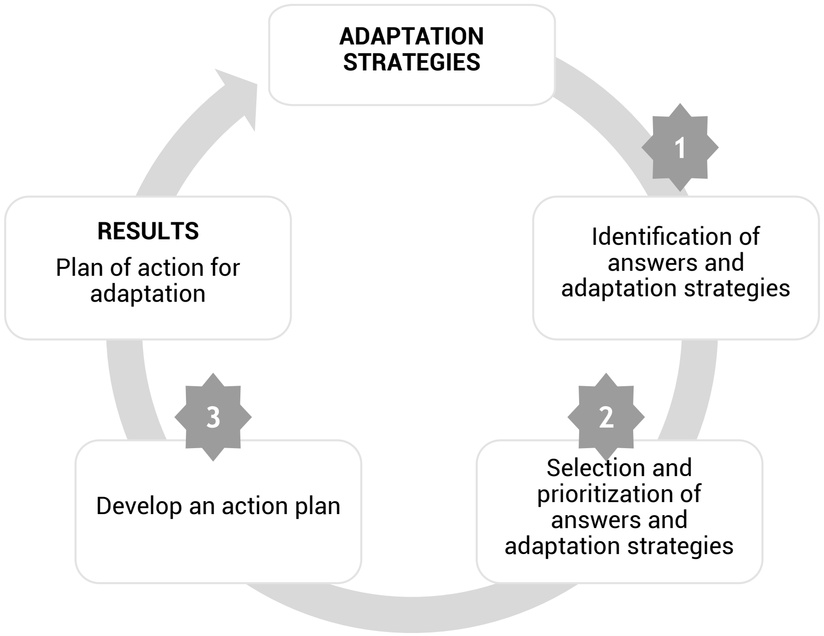


Figure 16. Impact of climactic variability on highway infrastructure
Source: Taken from [72, p. 36]

The aim of these strategies is to evaluate and prioritize the risks to which the country is exposed and design adaptation strategies that allow for the identification of responses and development of emergency plans. These plans help guide the pertinent authorities to adopt measures to respond to damage in the best way possible and allow their implementation through action plans [72, p. 10]

The impact generated by climate variability on transport infrastructure (incorporating elements such as slopes, drainage systems, structures, and pavements) [73] affects both society and its transportation dynamics. Figure 17 below demonstrates the incidence of climatic variables in these elements and the resulting damages.

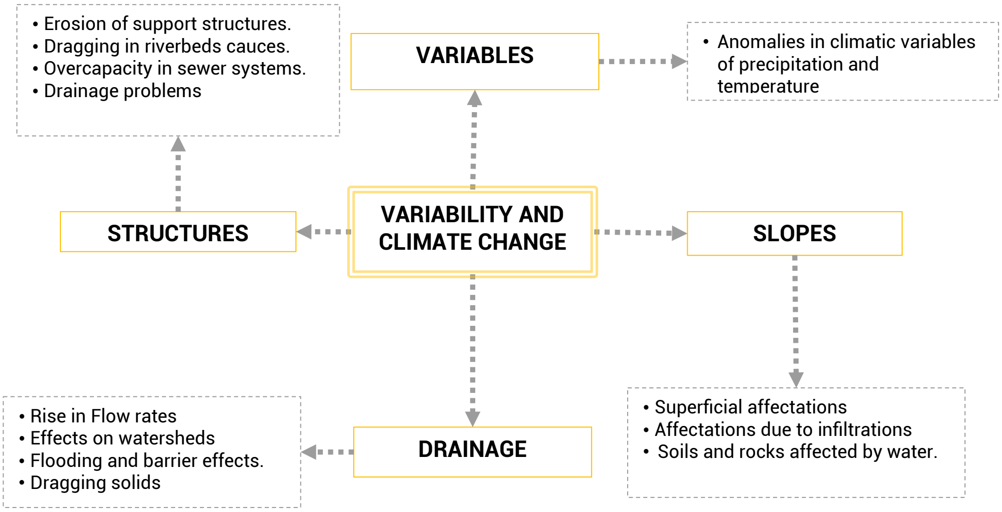
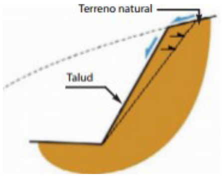
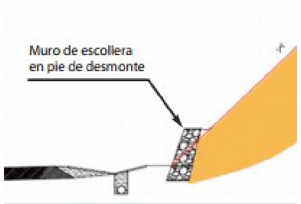
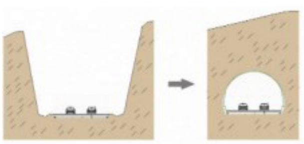
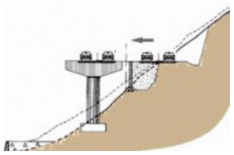
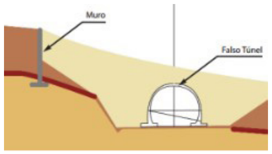


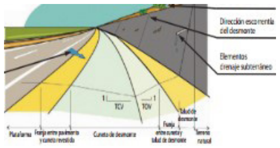
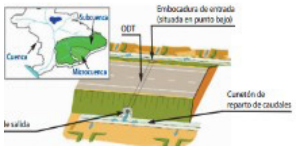
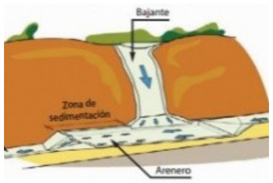
Figure 17. Development and selection of answers and strategies of adaptation
Source: Taken from [73, p. 75]

The effects mentioned above are evidence of the absence of mitigation and adaptation measures for the elements associated with road infrastructure. It is essential to specify the effects caused by the instability of slopes in road projects, especially as the result of using inappropriate materials (high degree of saturation and low quality among others) during the design phase. This does not allow the road infrastructure to respond to the adverse effects of weather. Given this scenario, rapid response methods should be proposed and implemented that prevent or mitigate the damages that may be caused, such as those proposed below in Table 6 [73, p. 76].

Table 6. Adaptation Measures for Instability Problems

PROBLEM	CORRECTIVE ACTION	POSITIVES AND NEGATIVES	CONTROL
Alteration of the slope due to climatic action and verticality 	Slope reduction and surface stability through praderization	Lower maintenance cost. Improved traffic in the area due to the reduction of road cuts. Increase in costs of excavation and transport of material.	Review condition of plants, need for pruning, and general cleaning.
Deterioration of footings at high altitude cuts due to water 	Retaining walls with cut footings to reinforce the base of the slope.	Facilitates water drainage and prevents undercutting at the base of the slope. Containment of small drags due to falling soil and rocks. Avoid landslides on the road. Increased costs compared to other measures that do not involve the retaining wall. Probability of occurrence of slope mismatches.	Review and registration of affected wall with respect to the entire wall (in length)
Land fracture and slope stability problems due to large slopes. 	Construction of tunnels to replace cuttings (for slopes with heights of >40 meters)	There is no slope instability in the future. There is no impact due to surface runoff. Solution for areas with steep and mountainous terrain. Rigorous design of the road layout. Difficulty in construction processes.	Are not contemplated
Abuse of high-rise cutting solutions 	Movement of the axis of the road towards the filling area to avoid cuts in areas with geological instability.	Reduces slope instability because cuts are avoided. Harmonization of infrastructure with the environment, environmental impact is reduced. Reduction of excavation material and transport to dumps. Increased costs in cross section designs.	Longitudinal cracks in the pavement. Review in periods of heavy intensity rains.
High risk of slope instability 	Construction of false tunnel	Slope stabilization. There are no effects on the environment. Use of cutting material. Increase in costs of the project. Routine maintenance of drainage works.	Review of the vertical settlement with respect to the height of the slope.

continue

PROBLEM	CORRECTIVE ACTION	POSITIVES AND NEGATIVES	CONTROL
Alteration of the slopes of the roads by climatic agents  	Surface protection of slopes using sprayed concrete.	Prevents erosion on the slope and reduces the risk of material falling onto the road. It allows high inclinations in the slope. Reduction of material costs Increase in costs in the construction process regarding footings, concrete, and drainage. Maintenance in the drainage system.	Drain damage review with the ratio of number of drains damaged to total drains. Annual review or in periods of intense rainfall.
Lack of consideration for the presence of basins in the design phase  	Improvement in the characterization of basins, expanding the detail at the micro-basin level.	Improvement in the transversal drainage of the road. Avoid the discharge of flows to the road. Increase in the costs of the hydrological study for the project	Review of the hydraulic operation of pipes and water catchment areas. Annual review or in periods of intense rainfall.
Problems in drainage systems in the crown of the slope due to the presence of sediments  	Construction of weirs to dissipate the energy of the water	Improved transport of water from the crown to the foot of the slope. It helps control the sedimented material product of the hydraulic transport. Control of the hydraulic capacity of the drainage system. Increase in construction costs. Complexity in the construction process.	Verification of the operation of the drainage system. Annual review or in periods of intense rainfall.

Source: Created from [73, pp. 87-100)

5. Conclusions

The review of different scientific and academic publications has allowed for a condensation of results on the relationship between precipitation and temperature, seismic activities, and mass removal processes.This review utilizes reports, guides, and manuals published over the last decade worldwide and nationally and is supported by institutions such as the Intergovernmental Group of Experts on Climate Change (IPCC). The published information seeks to address climate variability, climate change, and roadway infrastructure to strengthen actions that must be implemented to mitigate hydroclimatic triggers of mass movements in Colombia.

Climatic anomalies of precipitation and temperature registered since the middle of the 20^{th} century, allow research methodologies using probabilistic models to estimate the occurrence of disasters in future scenarios. Within this approach, the logistic regression method and the Poisson distribution method stand out, providing the ability to predict the behavior of climate variability in different temporal scenarios.

The independent variables incorporated in the development of the probabilistic models correspond to the annual mean temperature and the intensity, duration, and frequency of rainfall. Studies showed that the cause that generates mass movements corresponds to accumulated rainfall that occurs between 3 and 15 days prior to the mass removal event and greater than 2 000 mm/year.

Seismic activity is considered to be another trigger for mass movements and a strong relationship has been established between the minimum magnitude required for mass removal. Additionally, a horizontal acceleration of 0.2g raises the probability of a landslide to be greater than 90% for the case of dry soils and 100% in saturated soils.

With the predictions indicated in the studies, it has been observed that the road infrastructure in Colombia is neither designed for nor built to face the effects of the climatic anomalies presented. This is primarily due to the lack of inclusion of these variations in the design phase of the road construction projects and the hydraulic elements associated with it. It could be suggested that a resizing of the hydraulic capacity of slope drainage projects is required in order to prevent and mitigate impacts in Colombia due to flooding and mass removal processes that may occur.

In the case study corresponding to the Tunja-Páez road corridor, a high degree of exposure to latent threats has been observed due to geotechnical problems in the area. Around 70% of this corridor is considered threatened between the municipalities that make up the corridor. It is necessary to recognize the lack of economic investment for the development and implementation of mitigation measures and adaptation measures that would make infrastructure resilient to extreme climatic events.

The adaptation strategies are considered engineering solutions that guarantee the correct operation of the infrastructure projects related to the stability and containment of slopes. This allows for the ability to maintain security and adequate transportation between cities and departments while maintaining structural integrity through extreme climatic events that may trigger natural disasters.

6. Acknowledgment

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