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Article

A Systematic Theoretical Analysis of the Impacts of Landslides on Road Networks

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ABSTRACT
Landslides pose a threat to road infrastructure, with consequences for mobility, territorial connectivity, and economic activities. Thus, this study aimed to systematize knowledge regarding the impacts of these processes on road networks, considering their determining factors, socioeconomic consequences, and prevention and mitigation strategies. The research adopted a qualitative approach, based on a literature review and a search for peer-reviewed publications in the CAPES Journal Portal, using the terms "landslides AND roads," covering the period from 1965 to February 13, 2025. The search identified 4,652 documents; of these, the first 30 records were examined, and 20 articles related to the topic were selected for discussion. The analysis indicated that the impacts stem from the interaction between geological and geomorphological characteristics, precipitation, and human interventions, such as slope cutting and changes in drainage. The consequences include damage to infrastructure, isolation of communities, difficulties in accessing essential services, and disruptions to the transport of agricultural inputs and products. The studies also highlighted the contribution of remote sensing, geoprocessing, and susceptibility modeling in identifying critical areas and informing interventions. It is concluded that risk management must integrate slope assessments with the vulnerability and connectivity of transportation networks, guiding preventive maintenance, monitoring, and recovery efforts. This synthesis provides a foundation for research applied to the Brazilian context, particularly in areas affected by the 2024 events in Rio Grande do Sul.
Keywords: Landslides; Road infrastructure; Territorial connectivity; Risk management.

RESUMO
Os movimentos de massa representam uma ameaça à infraestrutura viária, com consequências para a mobilidade, a conectividade territorial e as atividades econômicas. Assim, este estudo teve como objetivo sistematizar o conhecimento sobre os impactos desses processos nas malhas viárias, considerando seus condicionantes, as consequências socioeconômicas e as estratégias de prevenção e mitigação. A pesquisa adotou uma abordagem qualitativa, fundamentada em revisão bibliográfica e busca de publicações revisadas por pares no Portal de Periódicos CAPES, utilizando os termos "landslides AND roads", no período de 1965 a 13 de fevereiro de 2025. A busca identificou 4.652 documentos, dos quais foram examinados os 30 primeiros registros, selecionando-se 20 artigos relacionados ao tema para discussão. A análise indicou que os impactos decorrem da interação entre características geológicas e geomorfológicas, precipitação e intervenções humanas, como cortes de encostas e alterações na drenagem. As consequências abrangem danos à infraestrutura, isolamento de comunidades, dificuldades de acesso a serviços essenciais e prejuízos ao transporte de insumos e produtos agrícolas. Os estudos também destacaram a contribuição do sensoriamento remoto, do geoprocessamento e da modelagem de suscetibilidade para identificar setores críticos e subsidiar intervenções. Conclui-se que a gestão dos riscos deve integrar a avaliação das encostas à vulnerabilidade e à conectividade das redes de transporte, orientando ações de manutenção preventiva, monitoramento e recuperação. A síntese oferece fundamentos para pesquisas aplicadas ao contexto brasileiro, especialmente às áreas afetadas pelos eventos de 2024 no Rio Grande do Sul.
Palavras-chave: Movimentos de massa; Infraestrutura viária; Conectividade territorial; Gestão de riscos.

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Introduction

Road networks play a vital role in sustaining society, and many adverse events can affect the provision of transportation along these networks, especially natural disasters such as floods, landslides, and earthquakes (Bíl *et al*., 2015). Landslides, in particular, can be immensely destructive and restrict the free movement of people and goods when they directly or indirectly affect road networks (Winter *et al*., 2013; Bíl *et al*., 2015; Meneses *et al*., 2019).

The road system is a critical component of transportation infrastructure, playing a fundamental role in connectivity between regions, the distribution of goods, and access to essential services (Vasconcellos, 2014). However, its vulnerability to natural disasters, such as landslides, can result in significant disruptions, affecting not only mobility but also the economy and quality of life of the affected populations.

In the case of Rio Grande do Sul, the road network was severely impacted by landslides resulting from the heavy rains of May 2024. Federal, state, and municipal highways suffered damage such as landslides, erosion, and roadblocks, compromising the movement of people and goods. The analysis of the road system in the context of natural disasters involves identifying critical routes, assessing the resilience of the infrastructure, and planning alternatives to ensure the continuity of transportation flows (Rodrigue *et al*., 2020).

Vulnerability associated with landslides stems from natural phenomena that occur due to a combination of factors such as steep slopes, soil type, vegetation cover, and extreme weather events, such as heavy rainfall (Highland; Bobrowsky, 2008). These events can cause significant damage to infrastructure, especially the road network, which is often built in high-risk areas due to the need to connect regions with steep terrain.

The vulnerability of the road network to landslides is related to factors such as the location of roads, construction quality, and infrastructure maintenance. In the case of Rio Grande do Sul, the southern slope of the Southern Plateau is a region particularly susceptible to these phenomena, due to its rugged terrain and high rainfall. The loss of road connectivity due to landslides and erosion can isolate communities, hinder access to emergency services, and impact economic activities such as agriculture and tourism (Fell *et al*., 2008).

The importance of the road network in the context of natural disasters extends beyond mobility, as it is essential for emergency response logistics, the transport of medical supplies, and post-disaster reconstruction. Therefore, analyzing the vulnerability of road infrastructure to landslides is crucial for planning mitigation measures and for building more resilient roads capable of withstanding extreme events (Petley, 2012).

In addition to geomorphological and climatic factors, the vulnerability of the road network to landslides is also associated with anthropogenic factors, such as inadequate infrastructure planning and unregulated land use (Winter *et al*., 2018). The construction of highways without detailed geotechnical studies can lead to the placement of roads in unstable locations, where erosion and landslides are more frequent.

In this regard, the absence of efficient stormwater drainage systems promotes water accumulation on road embankments, reducing their stability and increasing the risk of failure (Liu *et al*., 2021). Thus, the interaction between natural and human-induced factors plays a decisive role in the susceptibility of roads to natural disasters.

Landslides events affecting road networks are not unique to Rio Grande do Sul. In 2011, for example, the mountainous region of Rio de Janeiro suffered one of Brazil's worst natural disasters, with landslides that buried roads, cutting off entire municipalities and hindering the arrival of rescue teams (Coelho Netto *et al*., 2013).

Similar situations have occurred in countries such as Japan and Colombia, where extreme rainfall triggered landslides that compromised strategic highways and caused significant economic losses (Sidle; Ziegler, 2012). These examples highlight the importance of incorporating geotechnical risk analysis into the planning and maintenance of road infrastructure in regions susceptible to landslides.

To reduce the impacts of landslides on the road network, various strategies can be adopted, including the use of bioengineering techniques for slope stabilization, the implementation of dynamic barriers to contain debris, and the structural reinforcement of slopes in critical areas (Aleotti; Chowdhury, 1999).

Similarly, early warning and monitoring systems based on geotechnical and meteorological sensors can help identify instabilities before landslides occur, enabling preventive actions and the timely closure of roads (Guzzetti *et al*., 2020). Investment in resilient infrastructure and land-use planning based on detailed geotechnical studies is essential to ensure the safety and functionality of highways, especially in regions exposed to natural hazards.

In this regard, the overall objective of this study was to develop a systematic theoretical framework on the impacts of landslides on road networks, a topic that remains largely unexplored in the Brazilian context.

Methodology

The analysis of studies and works that have already been conducted and published allows for the identification of knowledge gaps, the formulation of hypotheses and objectives, and the establishment of theoretical and methodological foundations for new research. Furthermore, it enables the compilation and critical evaluation of existing knowledge on the subject in question (Gall; Gall; Borg, 2013).

Thus, a theoretical analysis was first conducted using bibliographic material—such as books, articles, theses, dissertations, and online resources—related to the subject of the study, in the form of qualitative research. According to Oliveira (2007, p. 37), "qualitative research is a process of reflection and analysis of reality through the use of methods and techniques to gain a detailed understanding of the subject of study within its historical context and/or according to its structure."

In a second phase, the bibliographic method of organization and search was employed, compiling a collection of publications on the topic *"LANDSLIDES AND ROADS"* (without quotation marks) from the historical series of the CAFe network on the CAPES Journals portal (Journal Portal of the Coordination for the Improvement of Higher Education Personnel) from 1965 (since the subject gained greater academic importance starting in that year) through 2025 (as of February 13, 2025)—and only peer-reviewed journals were included. The login was configured using the credentials of authors affiliated with the UFRGS Network.

Thus, the search was limited to 4,652 documents found. Among the top 30 articles with the highest impact in the analyzed database, only 20 were related to the topic of this study; these were discussed in the final section of the next chapter.

Results and Discussion

Landslides are among the most devastating natural disasters in various regions of the world (Habumugisha *et al.*, 2022). The occurrence of these events is associated with multiple factors, including heavy rainfall, earthquakes, volcanic activity, elevation, slope, vegetation cover, soil properties, and human activities such as road construction, building construction, and agricultural practices (Nahayo *et al.*, 2019).

In the historical context of landslides and their social impacts, landslides are phenomena that have accompanied humanity for centuries, with historical records dating back to ancient civilizations. In Europe, for example, landslides in the 19th century caused destruction in Alpine villages, while in Asia, events such as the Kedarnath disaster in India resulted in thousands of deaths and significant economic losses (Petley, 2012).

In Brazil, disasters such as the one in Serra das Araras (RJ) in 1967 and the one in Morro do Bumba (RJ) in 2010 have left their mark on the country's history, highlighting the vulnerability of urban and rural areas to such phenomena (Carvalho *et al.*, 2019). The 2024 mega-event on the southern slope of the Southern Plateau fits into this context, standing out as one of the largest climate-related disasters ever recorded in the region, with impacts that echo those of previous events but on a larger scale due to climate change and increasing human occupation in high-risk areas.

Gariano and Guzzetti (2016) emphasize that it is essential to analyze the various factors that influence slope stability and cause landslides, such as extreme precipitation, snowmelt, temperature variations, earthquakes, and human activities. Similarly, Casagli and Tofani (2025) emphasize that studies on landslides are fundamental to sustainable development, as they aid in risk assessment, disaster mitigation, and the protection of communities, infrastructure, and ecosystems.

These processes can have severe impacts, resulting in loss of life, significant property damage, and costs running into the billions for the recovery of affected areas (Stanley; Kirschbaum, 2017). Given the complexity and destructive potential of landslides, a comprehensive understanding of the triggering factors and the application of effective methods for their prevention and mitigation are essential (Fang *et al.*, 2023).

Zhang *et al.* (2024) emphasize that the analysis and quantification of the landslide deformation process are essential for enabling early warning of these events. Meanwhile, Li *et al.* (2024) propose the use of a cloud-based platform for real-time monitoring, enabling rapid detection of displacement patterns and a more accurate prediction of potential failures.

Furthermore, several studies demonstrate that the intensity and pattern of precipitation events have a direct influence on the magnitude and frequency of landslides (Smith *et al.*, 2023; Emberson *et al.*, 2022; Marc *et al.*, 2018). According to Marc *et al.* (2018), knowledge regarding the relationship between intense storms and the number of landslides expected in certain landscapes remains limited, due to the scarcity of detailed inventories of events triggered by extreme precipitation.

The geographic distribution of landslides also reveals distinct patterns. In a global study, Petley (2012) highlights that these events cause a significantly higher number of casualties than other natural disasters, with the majority of human losses concentrated in Asia, especially along the Himalayan Arc and in China. This

concentration of disasters is directly related to the region's geological and climatic characteristics, as well as to population density in high-risk areas.

In recent years, the use of remote sensing technologies has improved the mapping and detection of landslides. Novellino *et al.* (2024) analyzed more than 700,000 landslides in 52 countries, using satellite imagery to identify flow patterns and ruptures across different landscapes. The study highlights that, starting in 2014, the number of research studies in this field increased significantly due to the availability of data from the Sentinel-1 and Sentinel-2 satellites, enabling more accurate and comprehensive analyses.

In Brazil, and especially in the state of Rio Grande do Sul, extreme weather events have increased the frequency of landslides, floods, and flash floods in both urban and rural areas (Figure 1). In this context, various methods have been developed to map areas susceptible to these processes, including the use of artificial neural networks (ANNs) and machine learning algorithms, such as random forest (Quevedo *et al.*, 2019). The study by Quevedo *et al.* (2019) considered attributes such as elevation, slope, the LS factor (*Slope Length and Steepness Factor*), and valley depth as key determinants for predicting landslides in the state.



Figure 1: Landslide in the municipality of Santa Tereza – RS. Source: Authors (2025).

The World Meteorological Organization (WMO) warns that climate change has intensified extreme events worldwide over the past 50 years, increasing the frequency and severity of natural disasters (Silva *et al.*, 2022). Among these events, floods and landslides in urban and rural areas of Brazil stand out, resulting in significant socioeconomic losses.

In May 2024, the state of Rio Grande do Sul declared a state of public calamity due to the heavy rains that began in April. According to the official classification by the Civil Defense Agency, the impacts were classified as Level III, characterized by extensive damage and losses (Civil Defense Agency, 2007). The weather event included extreme rainfall, flooding, hail, flash floods, landslides, and high-intensity winds. According to Marengo *et al.* (2024), these unprecedented floods affected more than 90% of the state's municipalities (478 of the 497 municipalities in Rio Grande do Sul), resulting in 183 confirmed deaths, 27 missing persons, and more than 2.3 million people affected (Civil Defense, 2024).

, the El Niño-Southern Oscillation (, ENSO) was identified as a key factor in the rainfall variability recorded during the period. During the event, the Taquari, Caí, dos Sinos, and das Antas rivers reached record levels, surpassing historical monitoring records and flooding several cities (Marengo *et al.*, 2024). Collischonn *et al.* (2024) emphasize that the rains of May 2024 far exceeded the extreme precipitation events observed in Brazil between 1961 and 2022, both in terms of volume and geographical extent.

According to Decree 57,626, dated May 21, 2024, 78 municipalities were officially declared to be in a state of public calamity and 340 municipalities in a state of emergency (Rio Grande do Sul, 2024). In addition to the urban impacts, the heavy rains flooded vast agricultural areas, compromising crops and pastures. This scenario directly affected agricultural production, resulting in significant economic losses and impacting the entire supply chain (Bateleur, 2024).

The intensification of natural disasters in recent decades has been widely linked to climate change, which affects precipitation patterns and increases the frequency of extreme weather events (IPCC, 2021). In various

parts of the world, trends toward increased rainfall intensity and variability have been observed, which exacerbates slope instability and contributes to the triggering of landslides (Sudmeier-Rieux *et al*., 2021). In Brazil, studies indicate that rising global temperatures and changes in rainfall patterns have increased the incidence of landslides, especially in mountainous regions and areas with rugged terrain (Almeida *et al.,* 2020).

In addition to climatic factors, geological characteristics play a crucial role in an area's susceptibility to landslides. Clay soils, which are highly susceptible to water saturation, and geological formations with fractures and structural faults increase the likelihood of slope instability (Fernandes; Amaral, 2019). In the case of Rio Grande do Sul, the presence of sedimentary and volcanic rocks on the southern slope of the Southern Plateau contributes to erosion and the occurrence of landslides during periods of heavy rainfall (Rossi; Oliveira, 2022). Thus, the interaction between geological and climatic factors must be considered when assessing vulnerability to these events.

Given the growing incidence of landslides and their social and economic impacts, it is essential to adopt strategies for monitoring and mitigating risks. The use of remote sensing technologies and predictive modeling has proven to be an essential tool in identifying susceptible areas and implementing early warning systems (Gomez; Gutierrez, 2023).

Furthermore, the integration of public policies focused on land-use management and the adaptation of infrastructure to extreme climate scenarios is crucial for reducing the impacts of these events (Reyes; Soares, 2021). Thus, the analysis of landslides must consider both natural processes and human interventions in the environment, with the aim of developing effective strategies to minimize damage.

Risk, Vulnerability, and Hazard

Regarding the concepts used to describe risk, vulnerability, and hazard, many authors have already sought to organize them in a clear and objective manner. The work by Riffel, Guasselli, and Bressani (2016) emphasizes that, although there is no consensus regarding the concepts used by various research and civil defense agencies, it is possible to understand what each one means (Table 1).

Table 1: Concepts organized in the study by Riffel, Guasselli, and Bressani (2016).

Term	***Concept:***
Susceptibility	Susceptibility is the propensity of the terrain for a physical phenomenon and/or process to occur
Vulnerability	Vulnerability is society's ability to cope with and/or withstand a catastrophic event
Hazard	Hazard is a situation with the potential to cause harm
Threat	A threat is a situation that has the potential to cause harm
Risk	Risk is the probability of a harmful event occurring, based on the relationship between susceptibility and hazard. Risk is characterized by the interaction between threat and vulnerability.

Source: Riffel, Guasselli, and Bressani (2016).

Brazil currently relies on its road network to transport agricultural and industrial goods. Municipal, state, and federal highways not only connect cities but also facilitate the transport of goods and access to essential services. According to Bil *et al.* (2015), disruptions on these roads isolate communities, directly affecting sectors such as health and education.

This structural vulnerability of the road network manifests itself in a particularly critical way in specific geomorphological contexts. The construction of road infrastructure on steep slopes, for example, not only poses an engineering challenge but also significantly alters local hydrological dynamics, increasing susceptibility to landslides processes (Winter *et al*., 2013). Such interventions, when not accompanied by adequate mitigation measures, ultimately exacerbate the systemic risks already present in the transportation infrastructure.

The road network also plays a role in the economic impact caused by landslides. A clear example occurred in the EMATER/RS-Ascar administrative region of Caxias do Sul, where the persimmon harvest suffered major losses due to road blockages. Producers were unable to transport their produce, which not only resulted in financial losses but also disrupted the supply to the consumer market (Agrolink, 2024; EMATER, 2024).

This episode demonstrates how the structural fragility of the road system produces cascading effects, simultaneously compromising: (i) the physical integrity of the roads, (ii) the economic viability of production chains, and (iii) the population's access to essential goods.

In the geotechnical context, "hazard" refers to the potential for landslides to occur, regardless of their interaction with human systems (Fell *et al.*, 2008). This probability is intrinsic to natural factors such as geology, geomorphology, and climatic patterns. The National Center for Natural Disaster Monitoring and Alerts (CEMADEN) issued geological risk forecasts for the period from May 4 to 6, 2024, indicating a high probability of landslides in the Central-Western Rio Grande, Central-Eastern Rio Grande, Porto Alegre Metropolitan, Northeastern, and Northwestern Rio Grande mesoregions. These landslides affected both urbanized and natural slopes, in addition to causing road and highway barriers to collapse (CEMADEN, 2024).

Although the landslides had a significant impact on the road network of the Southern Plateau, it is important to note that these events also occurred in both natural and urbanized areas, regardless of direct interaction with human systems (CEMADEN, 2024). Natural slopes, due to soil saturation caused by heavy rains, were susceptible to landslides, resulting in landslides that compromised road infrastructure in the region. During the major disaster in May 2024, for example, rescue teams began searching for 34 people who were trapped in a landslide on the highway along a stretch connecting Veranópolis to Bento Gonçalves (G1, 2024). This type of situation underscores the need for more robust planning to reduce the impacts of natural disasters on mobility and access to essential services.

Risk incorporates the anthropogenic dimension, representing the combination of: (i) the probability of a hazardous event occurring and (ii) the magnitude of its consequences on infrastructure and populations. In the context of highways, this translates into the road network's exposure to damage and disruptions (UNISDR, 2017).

Landslides on highways are influenced by various natural and human-induced factors. From a geological perspective, highways built on tropical residual soils, such as saprolites, or on slopes with fractured lithologies, are more susceptible to landslide (Winter *et al.*, 2013). These conditions make the soil less cohesive and more prone to instability, especially when subjected to extreme weather events. In addition, patterns of intense precipitation, such as those associated with the South Atlantic Convergence Zones (SACZ), act as triggers for landslides, saturating the soil and reducing its bearing capacity.

Anthropogenic factors also play a crucial role in the exposure and vulnerability of highways to landslides. Inadequate slope cuts during road construction can increase the height-to-slope ratio of embankments, making them structurally more unstable (DNIT, 2020). This type of intervention, when carried out without proper geotechnical planning, significantly increases the risk of collapse. Furthermore, the absence of mitigation measures—such as the installation of tensioned retaining walls and deep drainage systems—exacerbates the impacts of landslides, as there are no structures to aid in soil containment or the proper drainage of stormwater (Nery; Reis, 2014).

To minimize the risks associated with these factors, it is essential to adopt efficient and sustainable technical solutions. Preliminary geotechnical studies, the use of appropriate materials in highway construction, and the implementation of effective drainage measures are fundamental to reducing the occurrence of landslides. Furthermore, constant monitoring and public policies aimed at preventing natural disasters are indispensable for ensuring the safety of highway infrastructure and the populations that depend on it.

The risk matrix for highways assesses whether risk can be stratified into three levels, as adapted from Hungr *et al.* (2014). Low-risk highways are those located on plains with stable soils and adequate drainage, where the probability of landslides is low. The medium-risk level includes roads in transitional areas with a history of small landslides, requiring preventive interventions to avoid structural damage. Finally, high risk is associated with highway corridors on steep slopes, which are frequently affected by destabilization processes due to unplanned land use and recurring landslides, requiring rigorous containment measures and constant monitoring.

Thus, understanding the concepts of risk, vulnerability, and hazard is fundamental to formulating strategies for the prevention of and response to natural disasters. Highways are essential infrastructure for the economy and the population's mobility, and their protection must be a priority to minimize impacts and ensure the safety of regions susceptible to landslide.

Remote Sensing and Geoprocessing

Remote sensing is a technology that enables the acquisition of information about the Earth's surface without the need for direct physical contact, using sensors installed on aerial platforms (such as drones and airplanes) or orbital platforms (satellites). This technique has been widely used in environmental, geological,

and infrastructure studies due to its ability to provide data at different spatial, temporal, and spectral scales, covering large areas quickly and efficiently (Jensen, 2009; Novo, 2010).

In the context of natural disasters, such as the landslides that occurred in Rio Grande do Sul in May 2024, remote sensing played a crucial role in monitoring, mapping, and analyzing the impacts. Optical satellite imagery (such as Landsat, Sentinel-2, and CBERS) and radar imagery (such as Sentinel-1) make it possible to identify changes in the Earth's surface, such as landslides, floods, and damage to road infrastructure, even in hard-to-reach areas (Zhou *et al.*, 2018).

The integration of remote sensing data with geographic information systems (GIS) enables the generation of thematic maps, the modeling of susceptibility to landslide, and the assessment of damage to the road network. Techniques such as image classification, time-series analysis, and change detection are frequently used to monitor environmental dynamics and identify critical areas following extreme events (Lu *et al.*, 2016).

In the specific case of the major disaster in Rio Grande do Sul, remote sensing was used to map the extent of landslide, assess damage to roads and highways, and monitor the recovery of affected areas. The combination of multitemporal and multispectral data enabled a comprehensive analysis of the impacts, providing a basis for planning mitigation measures and for the reconstruction of road infrastructure.

Geoprocessing is a set of computational techniques and tools used to collect, store, process, and analyze georeferenced data, enabling the generation of spatial information for decision-making (Câmara; Davis, 2001). These techniques are fundamental to the study of environmental and socioeconomic phenomena, such as landslide, as they allow for the integration of data from various sources (remote sensing, thematic maps, databases) into a geographic information system (GIS).

In the context of the major disaster that occurred in Rio Grande do Sul in 2024, geoprocessing was essential for mapping the extent of damage to the road network, identifying critical areas, and planning recovery efforts (Figure 2). Tools such as spatial analysis, digital terrain modeling (DTM), and the overlay of thematic layers made it possible to assess the interaction between natural factors (such as slope, soil type, and vegetation cover) and road infrastructure, providing insights into the impacts of landslide (Burrough *et al.,* 2015).



Figure 2: Landslides striking a road and a residence in a rural area during the 2024 mega-event. Source: Image courtesy of IGEO – UFRGS (2024).

In recent years, technological advances in the field of remote sensing have enabled significant improvements in the detection and monitoring of natural disasters. The growing availability of high-resolution satellites, combined with the use of sensors mounted on drones, allows for a more detailed, real-time analysis of the environmental and infrastructural impacts caused by extreme events (Tucker *et al.,* 2018). The use of multispectral and hyperspectral imagery has been fundamental for characterizing areas affected by landslides, allowing for the differentiation between exposed surfaces, vegetation, and unstable soil (Li *et al.*, 2020).

International cases demonstrate the importance of remote sensing in disaster response. In Japan, for example, following the 2011 earthquake and tsunami, satellite imagery was widely used to map the affected

areas and assist in reconstruction planning (Gamba; Marchese, 2019). Similarly, following the 2015 earthquake in Nepal, remote sensing technologies were employed to identify earthquake-induced landslides and to monitor the recovery of the impacted areas (Kargel *et al.*, 2016). These examples underscore the potential of remote sensing as an essential tool for risk management and rapid disaster response.

In addition to monitoring the impacts of past events, geoprocessing plays a crucial role in the predictive modeling of areas susceptible to landslides and in the creation of early warning systems. Models based on spatial analysis and machine learning have been developed to estimate the probability of landslide, integrating variables such as slope, precipitation, soil type, and land use (Paulo *et al.*, 2022). In the case of Rio Grande do Sul, the application of geographic information systems to identify risk areas and simulate future scenarios can contribute to the formulation of more effective public policies for reducing the vulnerability of road infrastructure and mitigating damage caused by extreme events.

Case Studies

Among the top 30 articles with the greatest impact in the analyzed database, only 20 were related to the topic of this study, which will be discussed below.

Thus, Berlin and Anand (2014) present an emerging technology for Intelligent Transportation Systems, proposing a Risk Routing Protocol to disseminate information about fixed hazards on roads, such as roadblocks, fallen trees, rocks on the road, snow accumulation, landslides, maintenance work, and other obstacles to vehicles approaching a hazardous location. The authors emphasize the importance of developing protocols and methodologies to disseminate information about road safety and hazards using vehicle-to-vehicle communication.

Meneses, Pereira, and Reis (2019) analyzed the influence of land-use and land-cover data with different properties on the landslide-prone areas of the road network in a river basin in Portugal. The study identified locations with the highest spatial probability of landslides that directly affect roads.

Sharma *et al.* (1991) emphasized that extensive sediment control measures are necessary to improve the safety and efficiency of many hydroelectric projects, and that the main sources of sediment are ravine erosion, stream bank erosion, landslides, road construction, and glacial erosion.

Postance *et al.* (2017) conducted a study on landslide risks in Scotland's road network. The results indicated that at least 152 road segments are susceptible to landslides, which could cause indirect economic losses exceeding £35,000 (Pounds Sterling) for each day of closure. Furthermore, previous estimates for historical landslide events may have significantly underestimated socioeconomic losses.

Landslide susceptibility maps are widely used for various purposes, such as mitigating the effects of landslide, decision-making, and planning. Thus, Eker and Aydin (2014) found that road-related landslides are common in forested areas in Turkey because the roads are located in mountainous regions with steep slopes; in this regard, in addition to their impact on forests, landslides can cause damage to roadbeds, which requires immediate maintenance.

Haigh and Rawat (2011) studied the landslides and floods that struck the Himalayan district of Almora (Uttarakhand) during the late monsoon season of 2010. The phenomenon affected thousands of kilometers of roads, and the damage totaled more than $125 million. Therefore, the height of the road cut, the incision of the channel that eroded the road cut, and, especially, the slope gradient were found to be significant factors.

Landslides and rockfalls are the most common and dangerous natural hazards to linear transportation infrastructure in mountainous regions, as noted by Laimer (2017). The author provides an inventory of landslide that affected the Austrian Federal Railways network between 2005 and 2015, and an analysis of the 106 events in the historical series showed that anthropogenically induced events (71.7%) outnumbered naturally induced ones (28.3%). Human activities related to the construction of transportation infrastructure account for more than half of all causes of landslides (Laimer, 2017).

Yu *et al.* (2022) applied a *machine learning* methodology to an area slated for the construction of a road/highway in Wanzhou, China. The data-driven approach was used to generate regional landslide susceptibility maps. Therefore, landslide susceptibility mapping can provide valuable information to local governments for landslide prevention and mitigation.

A study conducted in Nepal found that more than 40% of recently triggered landslides crossed a road, and 84% of them are located within 40 meters of it. Roads are therefore influencing slope stability by cutting into the slope and concentrating surface water, thereby altering hydrological patterns, which are destabilizing the upper sections (Vuillez *et al.* 2018).

The article by Liu *et al.* (2022) presents a probabilistic analysis of landslide risk along a regional highway, with risk considered as a function of geographic data and road vulnerability. The results showed that the

probability of the regional highway reaching a specific damage state varies with time interval, landslide scale, and spatial location.

Landslides cause severe damage to the road network in the affected area, both in terms of direct costs (partial or complete destruction of a road or roadblocks) and indirect costs (traffic restrictions or closure of a specific area), as emphasized by Bordoni *et al.* (2018). In this regard, Bordoni *et al.* (2018) conducted a study in a watershed in northeastern Oltrepò Pavese (northern Italy), where several surface landslides have affected roads in recent years. The results demonstrate the effectiveness of the developed methodology in assessing susceptible roads, providing infrastructure managers with information on the criticality of different road characteristics, thereby allowing attention and financial resources to be directed toward the most critical assets, where structural and non-structural mitigation measures could be implemented.

Meanwhile, Bozhinova-Haapanen (2016) reports that Bulgaria is a country with a rugged terrain and conditions conducive to the occurrence of various types of landslides.

Therefore, the expansion of road networks in mountain ranges in developing countries has significantly increased the risk of landslides and sedimentation, and has created vulnerabilities for residents and water resources (Sidle; Ghestem.; Stokes, 2014). A more sustainable approach to road development is needed, based on an analysis of susceptibility to landslides and how the thresholds for triggering mechanisms would be modified by the road's location and different construction techniques (Sidle; Ghestem.; Stokes, 2014).

Zhou *et al.* (2024) investigated the risk to road networks posed by landslides in six counties adjacent to Sichuan Province and Yunnan Province, both in China, taking into account landslide susceptibility and road vulnerability. The total length of the analyzed road network was 4,631.63 km. Heavy rainfall in the study area is concentrated in June, July, and August, with up to 100 mm per day. During storm events, landslides are frequently reactivated. Consequently, the distribution of high-, medium-, and low-risk areas accounted for 14.23%, 3.08%, and 82.69% of the total study area, respectively.

In Morocco, landslides pose recurring challenges for highway projects due to factors such as lithology, climate, fault structures, and high altitudes. Therefore, developing landslide susceptibility maps is crucial for anticipating and taking appropriate measures (Youssef *et al.*, 2023). Since National Highway No. 9, particularly in the Tizi N'tichka region of the High Atlas, faces significant landslide problems, the authors Youssef *et al.* (2023) compiled a susceptibility map, enabling proactive measures to mitigate the impacts of landslides on road infrastructure.

Jalooli *et al.* (2014) emphasize that landslides are a serious geological disaster that has a severe impact on road safety, traffic flow efficiency, and environmental preservation. Therefore, the authors developed a landslide detection technique based on (i) motion detection and (ii) cross-motion methods. These are applied during a detection phase to identify the extent to which landslides affect road capacity, taking vehicle dimensions into account.

The article by Pecoraro *et al.* (2023) presents a procedure for assessing, at the municipal level, the risk level (or level of attention required) for road sections exposed to existing or potential slow landslides. The procedure analyzed by the authors can be applied to support studies of road networks in large areas, with the aim of prioritizing risk mitigation measures and identifying road sections that require further investigation.

Taylor (2012) analyzed a logistic regression model designed to assess the likelihood of landslides using nine factors and 359 samples; thus, the greater the expected loss, the greater the length of road exposed to landslides.

Methodologies based on high-resolution imagery acquired from unmanned aerial vehicles (UAVs) were used to analyze a landslide that affected several roads and access routes to a highway in Spain (Cardenal *et al.*, 2019). In this regard, lightweight equipment is well suited for updating and monitoring landslides and, therefore, for predicting or analyzing hazards and risks (Cardenal *et al.*, 2019).

Chau *et al.* (2004) established a risk zoning map for Hong Kong Island using historical data; based on frequency-volume analysis for Hong Kong Island, it was estimated that the return period for a landslide of 26,000 $m^3$is approximately 3.12 years. Populated areas and roads in Hong Kong pose the greatest risk. Therefore, it is necessary to use GIS technology to integrate various layers of geological, geomorphological, population, climatic, and precipitation data to generate risk maps.

Based on all these examples, it can be concluded that geological hazards along highways represent a prevalent concern in the field of engineering, posing a threat that impacts the safety of many people (Liu *et al.*, 2022). Thus, highways, as linear infrastructure, inevitably traverse various geomorphological units, encountering a wide range of complex geological and topographic conditions, while remaining vulnerable to various natural disasters (Liu *et al.*, 2022).

Final Considerations

The literature review made it possible to systematize the main factors associated with landslide and to understand their repercussions on road networks, linking physical, socioeconomic, and land-use management aspects. The studies analyzed indicate that the occurrence and impacts of these processes involve the interaction between geological and geomorphological conditions, precipitation, land use and land cover, and human interventions. Thus, understanding the vulnerability of roads requires an integrated approach that considers the characteristics of slopes, the conditions under which infrastructure is built, and its importance for the organization of regional traffic flows.

A recurring theme in the reviewed literature is the dual role of roads in the dynamics of landslide: while they are exposed to these processes, their construction and maintenance can alter slope stability. Slope cutting, removal of vegetation cover, and changes in water flow paths can contribute to instability when not accompanied by solutions appropriate to local conditions. However, the influence of these factors varies depending on the environmental context and the characteristics of the interventions, which reinforces the need for specific assessments and precludes the adoption of explanations based exclusively on slope gradient or rainfall intensity.

The identified impacts go beyond the physical destruction of roads and the immediate costs of clearing and reconstruction. The disruption of road segments can compromise the movement of people and goods, hinder access to health services and emergency response efforts, increase travel times, and isolate communities. In rural areas, these disruptions also hinder the delivery of inputs and the shipment of produce, with consequences for producers, agribusinesses, and consumer markets. Thus, the extent of the damage depends both on the magnitude of the event and on the function performed by the affected section of road, as well as on the availability of alternative routes.

This finding highlights the importance of analyzing infrastructure as an interdependent network. A spatially localized blockage can have consequences in areas far from the incident, especially when it affects strategic corridors or locations served by few connections. Therefore, the prioritization of interventions must take into account the susceptibility of slopes, the exposure and vulnerability of roads, and their relevance to territorial connectivity. The joint consideration of these elements provides a more consistent basis for allocating resources, identifying critical sections, and planning responses capable of reducing the effects of disruptions.

The literature reviewed also highlights the contribution of remote sensing, geoprocessing, and susceptibility models to the identification of potentially unstable areas and the monitoring of surface changes. These tools make it possible to integrate information on topography, land cover, precipitation, and the location of events, thereby supporting infrastructure planning and management. Their application, however, must be accompanied by an assessment of data quality and resolution, validation of results, and—depending on the study's purpose—field investigations. In this way, cartographic products and models can inform decisions without replacing the geotechnical analysis required for local interventions.

In the Brazilian context, and particularly in Rio Grande do Sul, the events of 2024 underscore the importance of incorporating risk management into the planning, maintenance, and reconstruction of road networks. The evidence discussed supports the need to coordinate structural measures—such as drainage improvements and slope stabilization—with monitoring, preventive maintenance, risk communication, and the planning of alternative routes. The selection of these measures should take into account the conditions of each road segment and the protection of populations that depend on the infrastructure, aiming to reduce the likelihood of further disruptions and facilitate the restoration of essential services.

As a limitation, this study presents a qualitative synthesis constrained by the search strategy and the set of selected publications; it does not constitute an exhaustive survey of the scientific literature on the topic. Furthermore, the diversity of scales, methods, and contexts among the studies examined limits direct comparisons and the transfer of their results to other regions. The conclusions, therefore, provide a basis for interpreting the impacts and formulating new research questions, but they do not allow for quantifying the risk of specific segments or establishing causal relationships for the events recorded in Rio Grande do Sul.

As a follow-up, it is recommended to conduct research that integrates georeferenced inventories of landslide, slope characteristics, road maintenance conditions, and connectivity indicators. Studies on the duration of road closures, the costs of travel via alternative routes, and the losses associated with the interruption of productive activities and services are also relevant. The main contribution of this review is to bring together elements that link the analysis of geomorphological processes to an understanding of their territorial consequences. This integration can strengthen prevention and recovery decisions, guiding the construction of safer transportation networks capable of maintaining or restoring their functions in the face of adverse events.

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