v. 4, n. 17, 2024

Journal of
Engineering
Research

MULTITEMPORAL MONITORING OF LAND USE AND LANDSLIDE RISK IN NORTHWEST GUATEMALA

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Abstract: Advances in remote sensing technology have made it possible to model the Earth's surface with a high degree of precision, providing high-resolution spatial data through geographic information systems (GIS). These GIS allow monitoring multi-temporal changes in land cover and use derived from growing urban expansion. In the study area of the El Incienso ravine, located northwest of Guatemala City, its climatic conditions and rugged topography make it susceptible to mass removal phenomena. This research uses remote sensing techniques based on multispectral satellite images to analyze the spatio-temporal evolution of these phenomena, whether anthropogenic or natural, and establish critical thresholds that allow early warning systems to be implemented for informed risk management. Quantitative interpretation through thematic cartography derived by applying the Mora-Vahrson hazard assessment methodology allows the generation of an updated inventory of areas susceptible to landslides. This provides the geotechnics professional with robust technical input to evaluate the quality and reliability of the information, optimizing the allocation of economic resources and human capital. Multi-temporal analysis makes it possible to generate dynamic digital cartography that can be continuously updated, significantly increasing the predictive and response capacity to these risk phenomena.

Keywords: spectral, slope, multitemporal, reflectance, sensors, remote sensing.

INTRODUCTION

The study of the evolutionary dynamics of landforms requires a combination of field work and remote analysis. Although in situ recognition is essential, the contributions of remote sensing allow detailed interpretation of areas of complex topography directly from the office, complementing and optimizing field efforts.

Advances in remote sensing technology have radically transformed this discipline. Modern high-resolution sensors capture exceptional quality multispectral and multitemporal data on atmospheric and terrestrial conditions. This abundance of quantified geophysical data allows natural hazards to be modeled and monitored with unprecedented precision. Multi-temporal analysis of satellite images reveals the dynamic patterns of the terrain, facilitating the reconstruction of past evolution and the prediction of possible future scenarios.

This synoptic and integrative vision of the previously inaccessible terrestrial environment has made remote sensing an indispensable tool for modern researchers. By combining remote and ground-based data, geoscientists can now understand the complex natural processes that shape our planet with an unprecedented level of detail. This new scientific perspective significantly improves our ability to study and manage natural phenomena more effectively.

BACKGROUND

In recent years, Guatemala has experienced a worrying increase in landslides, attributed primarily to human activities. According to Cardona (1996), an expert in risk management, the country lacks the necessary preparation to deal with these events effectively. However, it is noted that, if there were no anthropogenic intervention, the occurrence of such phenomena would be limited to natural causes, such as meteorological and geological cycles (Taloor et al., 2024).

Earth science experts use various methodologies to develop landslide susceptibility maps (Vázquez et al., 2021), with the overlay approach being one of the most common. Although these maps are usually based on a subjective weighing of relevant factors, they are highly precise and useful. Remote sensing is commonly used to collect the necessary data.

Traditionally, the development of these maps has depended on high-resolution images, which has limited their applicability. However, studies have shown that high resolution is not always required to develop landslide susceptibility maps. In a comparative study conducted in California (Weirich & Blesius, 2007), it was found that the results obtained from medium-resolution satellite images, such as SPOT, were practically identical to those obtained with high-resolution images, suggesting its feasibility as an alternative.

Furthermore, additional research has delved into the geological and seismic characteristics of the study area, highlighting the complexity in the preparation of thematic maps for the detection of risk areas (Tobías, 1993; Olivares, 2004). It is emphasized that it is crucial to recognize the causes and effects of natural disasters, as well as implement effective mitigation measures (Cardona, 1996; Ferrando, 2003).

Remote sensing technologies, such as satellite imagery and drones, have significantly improved the assessment and prevention of landslide-prone areas (Frederiksen et al., 2024). Remote sensing has also contributed to generating cartography to evaluate the susceptibility of slopes, allowing us to distinguish between multiple images and classify soils using specific algorithms (Swain & Davis, 1978).

It is crucial to constantly update accurate and efficient spatial information to evaluate urban growth and develop engineering projects in risk areas (Touge et al., 2023). The combination of specialized computational models and field reconnaissance is essential to classify satellite images and determine changes in land use.

Satellite images play a fundamental role in landslide detection and prediction, as well as disaster response and environmental monitoring (Trevisiol et al., 2024). However, manually identifying relevant features in these images can be tedious and impractical. That is why deep learning, especially convolutional neural networks (CNN), offers a promising solution to automate this process and improve the accuracy in satellite image classification (Vidhya et al., 2024).

This significant advance will strengthen the ability to detect and predict landslides, as well as improve disaster response and environmental monitoring initiatives. By using appropriate methodologies for their processing and integrating them into digital tools, a more precise and efficient evaluation of natural risks is ensured (Ayala-García & Dall'Erba, 2022). This will not only facilitate better urban planning and land management, but will also promote environmental preservation. Ultimately, this technological integration offers an advanced and effective solution to address the challenges associated with landslides and natural risk management (Román & Castillo, 2017).

STUDY DEVELOPMENT

Digital images obtained from Landsat remote sensors have been essential to identify landslide-prone areas, which has resulted in an optimization of the costs associated with their monitoring (LATAM Satelital, 2016). In the field study, a survey was carried out in the northwest of the El Incienso ravine to evaluate and collect soil samples from the slopes. This analysis highlighted the presence of a growing metropolis with inadequate infrastructure on slopes, where the Negro River acts as a collector of sewage and solid waste that flows into the Motagua River, fed by tributaries that directly affect the inclined slopes.

For supervised classification, we evaluated parameters such as ecological stability, changes in vegetation cover and cyclical ecological alterations (Lambin, 1997) using ENVI software. The results, processed and converted to vector format, facilitate the interpretation of digital cartography in geographic information models. An area of four square kilometers was selected for the study field, located in the northwest of Guatemala City.

Due to the strong incidence of construction in areas with irregular topography in recent years, a vulnerability to mass soil movement events was identified due to poor urban planning.

Considering previous works related to this topic, we propose a series of methods that will contribute to the knowledge and use of digital elevation models, establishing geoforms of interest and generating a susceptibility map using the Mora-Vahrson parameters. This comprehensive approach will allow a better understanding of landslides and their relationship with urban planning, providing effective tools to mitigate the associated risks.

Satellite-based change detection is essential to address multi-objective scenarios. This study provides a comprehensive analysis of its applications and methodologies, focusing on the challenges and advances in identifying changes in urban areas using multi-temporal remote sensing data (Farooq & Manocha, 2024; Weirich & Blesius, 2007). Advances in remote sensing technology have led to numerous applications, including urban growth monitoring, disaster response, and monitoring land cover changes. Additionally, the study explores real-time change detection applications, emphasizing areas such as land use, environmental changes, urban sprawl, and disaster assessments.

Deep learning approaches have emerged as crucial tools, outperforming traditional techniques and demonstrating effectiveness on various types of remote sensing data. Furthermore, the study considers unconventional change detection techniques, particularly those based on artificial intelligence, highlighting the promising results of deep learning algorithms in evaluating images with different timestamps. The ultimate goal is to provide a comprehensive understanding of change detection methods to meet the growing demand for remote sensing (Zeng et al., 2023).

METHODOLOGY

The research focuses on identifying areas vulnerable to landslides on the slope of the El Incienso ravine, a result of urban expansion and changes in land use during the last decade. An evaluation of the representative parameters of the Earth's crust will be carried out through laboratory tests, classifying them according to the AASHTO M-145 standard to determine their geomechanical characteristics. In addition, satellite images obtained through remote sensing, specifically from the Alos Palsar sensor, will be used to analyze the morphology and changes in the Earth's surface.

The study will be carried out in an area of four square kilometers northwest of Guatemala City, where construction on terrain with irregular topography has experienced notable recent growth. The methodology includes the formulation of the problem, an exploratory phase, data collection using the Alos Palsar sensor, field and office work, as well as the presentation and interpretation of results through the preparation of digital maps.

The evaluation of the El Incienso ravine will be supported by satellite images, geological maps from the National Geographic Institute and multi-temporal analysis.

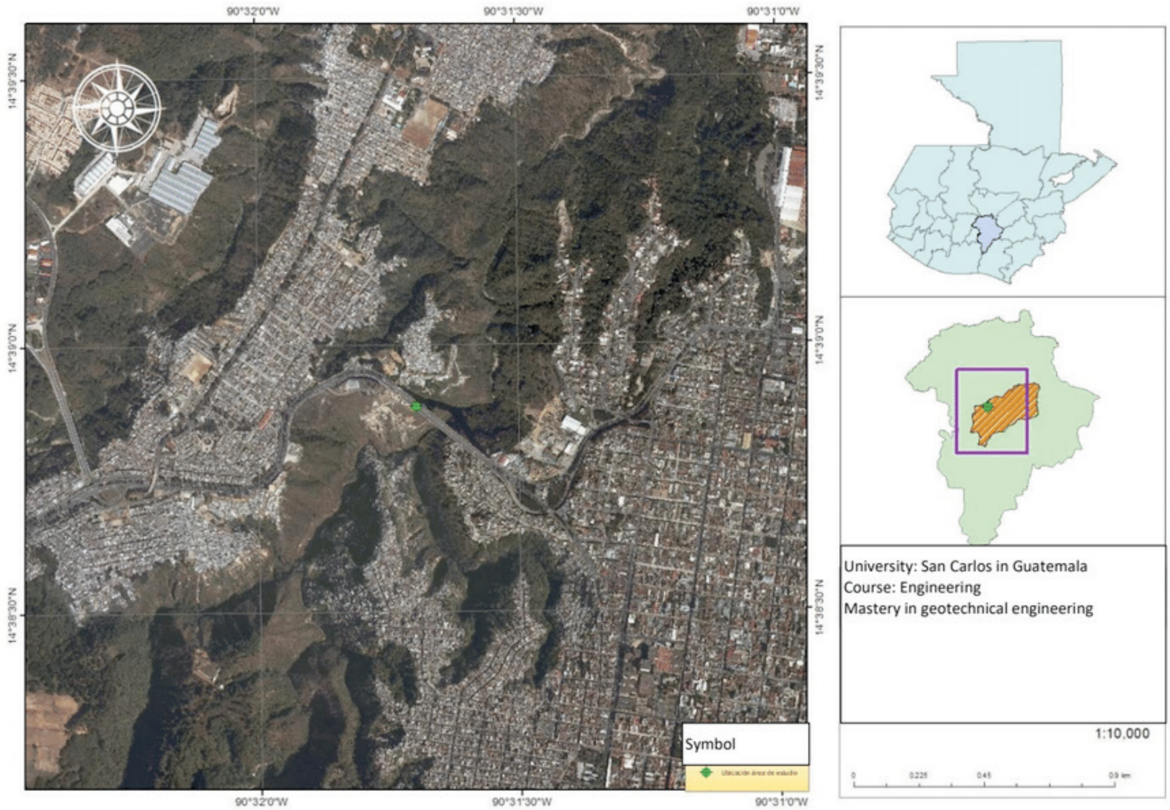

Figure 1: Location of the ravine. El Incienso, in Guatemala City.

Source: own elaboration. h

Geomorphological zones and slopes will be identified, and the soil granulometry will be analyzed. For image processing, geographic information systems programs will be used. ENVI will be used for image analysis, allowing pixels to be evaluated through supervised classification, while ArcGIS will facilitate vector processing and map generation. Mora Vahrson's methodology will be used to classify the landslide susceptibility map, complementing the analysis.

Technological advances will be integrated into the training of future geotechnical engineers and related professionals, developing specific algorithms and using the panchromatic band to obtain a spatial resolution of fifteen meters. This methodology will allow the categorization of areas susceptible to mass movements, offering advantages in terms of spectral and temporal resolution. This detailed and specific methodological approach to the study problem guarantees a comprehensive understanding of the risk conditions in the El Incienso ravine.

RESULTS OBTAINED

The results that established the baseline for a detailed scale of 1:13,000 in the El Incienso ravine sector were based on a meticulous analysis of the perimeter of Guatemala City. It was considered that part of the urban expansion entered into areas that were not suitable for the construction of infrastructure, especially if the structural criteria established by the country's regulations were not met. This geotechnical analysis provided crucial information to identify risk areas and make informed decisions about urban development in the region.

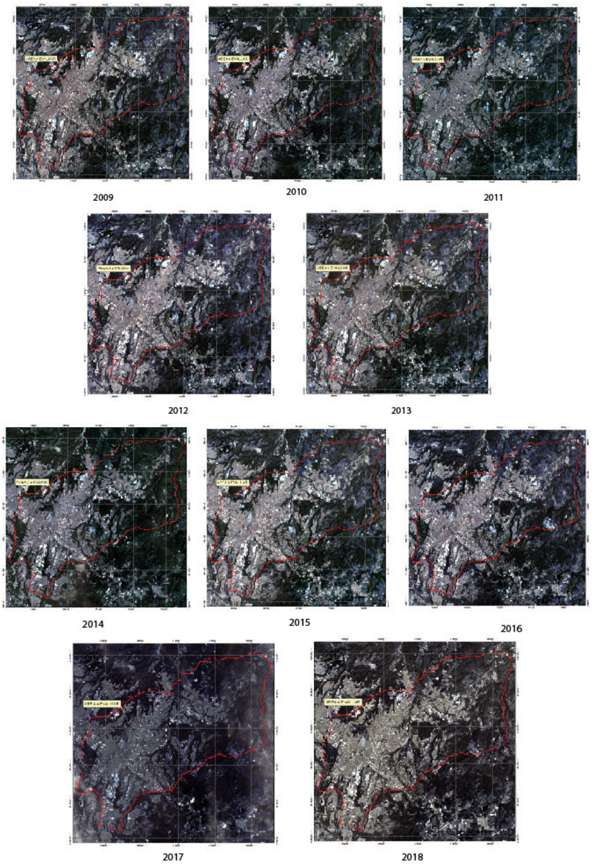

Figure 2: Multi-temporal analysis for a period of ten years.

Source: own elaboration, adapted for multi-temporal analysis using Landsat satellites.

Figure 3 shows the slope map that visualizes the area of influence of the project. It is essential to carry out a correct classification of the slopes, since this directly impacts the precision and effectiveness of the terrain analysis and the identification of areas vulnerable to landslides.

For an area of 1 km², the classification carried out for a period of ten years is presented below, based on the multi-temporal analysis of satellite images. This classification includes the identification and delimitation of various categories present in the images, such as clouds, forests and vegetation, bodies of water, soil and urban areas.

The analysis allowed us to observe significant changes in land cover and urban expansion during the last decade. Areas with increased vegetation were identified, as well as areas where urbanization has advanced significantly. Water bodies were monitored to detect variations in their extent, while the presence of clouds was appropriately managed to minimize their impact on the accuracy of the analysis.

Through the multi-temporal classification in Figure 4, areas could be categorized based on their susceptibility to mass movements, offering a clear perspective on changes in land use and their implications. These results are fundamental for the planning and management of the territory, providing a solid basis for future interventions and risk mitigation strategies.

The increase in eroded soil and the decrease in forests in the delimited area of influence underline the need to implement mitigation measures to control erosion. Figure 5 shows the landslide susceptibility map, validated through a multi-temporal analysis of land change and use obtained from satellite images.

For the susceptibility analysis, an intersection with the soil classification was carried out, identifying the geological and precipitation factors that trigger landslides. This information was represented using a digital elevation model with a pixel resolution of twelve meters, complemented by data from the ALOS PALSAR remote sensor (EARTHDATA, 2019).

DISCUSSION OF RESULTS

When performing supervised classification, it is crucial to generate a confusion matrix for each image analyzed. In the case of our study, where five classes are considered, the Kappa coefficient is a fundamental indicator that reflects the precision and quality of the samples selected in the analyses. It is important to note that this value must be greater than 0.90, since the interpretation of pixel values can

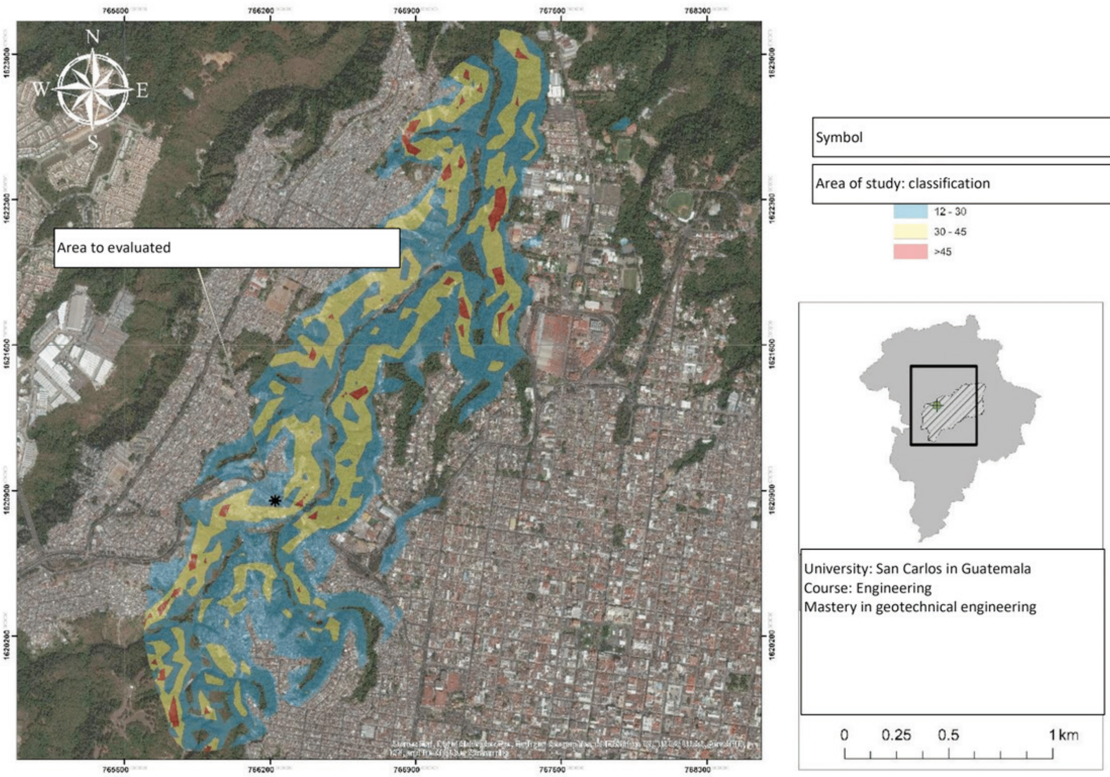

Figure 3: Map of slopes and area of influence for the case study.

Source: own elaboration.

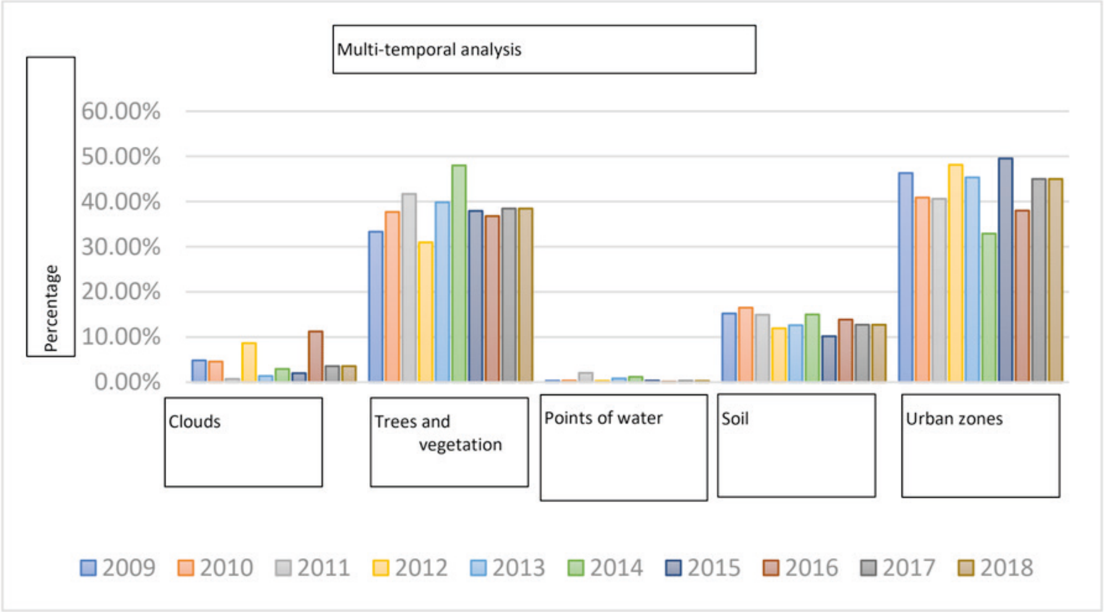

Figure 4: Multitemporal analysis of land use and change for a period of ten years.

Source: own elaboration, adapted with available ENVI 5.3 digital information (Harris Geospatial, 2015).

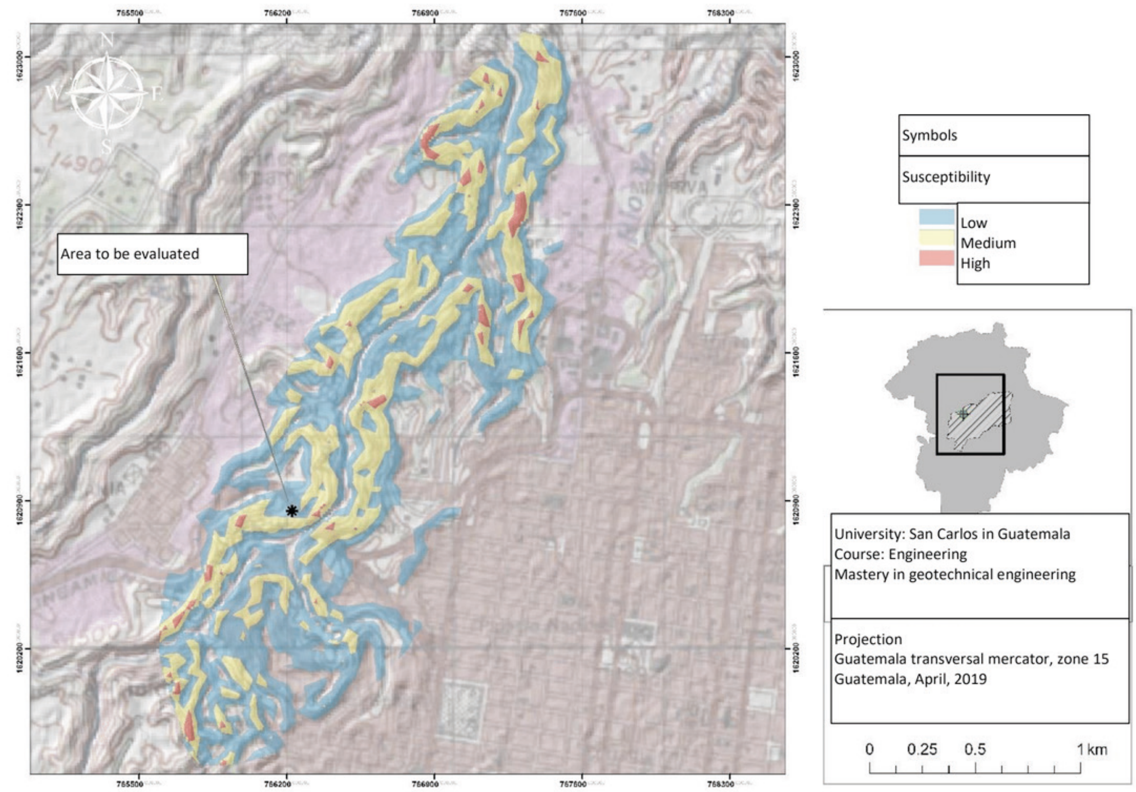

Figure 5: Map of susceptibility to mass movement in the ravine. The Incense.

Source: own elaboration.

be unintuitive for those who are entering the field of digital image geoprocessing. A value below this threshold could lead to incorrect categorization in the first results obtained.

To determine the degree of susceptibility, five values were evaluated that represent the combination of passive factors and latent actions that can trigger landslide events. Following the Mora-Vahrson methodology, it is essential to consider the seismic activation values and superimpose them on the cartographic sheet. This allows an inventory of the classification of construction conditions in areas adjacent to slopes, which provides effective control of territorial planning and helps to identify areas prone to landslides. (Mora Chinchilla, Chaves Gamboa, & Vásquez Fernández, 2015)

CONCLUSIONS

Importance of Multitemporal Analysis for Risk Assessment: The correct evaluation of the classification through multi-temporal analysis is crucial to understand the evolution of landslide risk. In this study, the susceptibility map indicates a medium susceptibility, suggesting the need for continuous monitoring and strict control over new buildings. It is essential to be alert to possible changes in ground conditions and take preventive measures to avoid exacerbating the risk.

Comprehensive Risk Management in Hillside Areas: Given the average susceptibility identified on the map, comprehensive risk management is required in hillside areas. This involves not only controlling new construction, but also implementing appropriate stormwater management measures. It is crucial to direct water discharges towards areas where they will not cause erosion, thus mitigating the risk of landslides induced by soil erosion.

Need for Continuous Monitoring and Sustainable Urban Planning: Risk assessment must not be a static process, especially in areas with medium landslide susceptibility. Continuous terrain monitoring and sustainable urban planning that actively considers natural risks are required. This will guarantee safe and sustainable urban development, minimizing the vulnerability of the population and infrastructure to catastrophic events.

RECOMMENDATIONS

Implementation of Continuous Monitoring Systems: It is recommended to establish continuous monitoring systems that use remote sensing technologies to actively monitor areas identified as having medium susceptibility to landslides. These systems can use high-resolution satellite images and drones equipped with specialized sensors to obtain updated data on the evolution of the terrain and changes in environmental conditions. This will allow a proactive response to any significant change in landslide risk.

Development of Advanced Predictive Models: It is suggested to develop advanced predictive models that integrate multi-temporal remote sensing data with detailed geological and geotechnical information. These models can use spatial data analysis and machine learning techniques to identify emerging patterns and predict the evolution of landslide risk over time. Furthermore, the incorporation of real-time data and constant feedback will improve the accuracy and reliability of the models, allowing for more effective planning of preventive and response measures.

Promotion of Sustainable Urban Planning Practices: t is essential to promote sustainable urban planning practices that incorporate geotechnical and landslide risk considerations from the initial stages of urban design and development. This includes the implementation of regulations and standards that restrict construction in areas with high susceptibility to landslides and encourage the use of risk mitigation technologies, such as adequate storm drainage systems and soil stabilization techniques. Likewise, work must be done to raise awareness and train the actors involved in urban decision-making to guarantee comprehensive and sustainable management of the territory.

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