Susceptibility mapping for shallow landslides in Tierras Altas, Chiriqui, Panama: An integration of geophysical measurements

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ABSTRACT

The Tierras Altas region in Chiriqui, Panama presents a high agricultural activity susceptible to extreme climatic events, especially precipitation and surface runoff due to its high moisture retention capacity soils. A mountainous region with heavy winter rainfall and dry summers, part of the Chiriqui volcanic arc, and the point of triple convergence of the Coco, Nazca, and Panama microplate, also makes it a seismic threat zone. Historically, the Tierras Altas district has been susceptible to landslides, floods, and erosion-related phenomena. Through site characterization and the survey of ground dynamics, the research aims to build the input data of geological parameters and analyze dynamic properties through geophysical measurements of surface accelerations, allowing the characterization of the region and the coupling of the soil with climatic and seismic triggers. The results focus on geospatial maps and georeferenced datasets. The preliminary results were obtained through a GIS-based methodology that mapped the physical and dynamic properties of soils, identified high susceptibility zones, and analyzed how the measured dynamic data adjusted the Vs30 model.

Keywords: geological data, geophysical prospecting, mapping, soil degradation.

1. Introduction

The objective of this study is to comprehensively analyze landslide susceptibility in the Tierras Altas district, region of Panama; by incorporating geological data, land cover, slope, and acceleration measurements. The susceptibility analysis aims to identify areas most prone to landslides, triggering factors, and the associated impact degree (Pinyol, 2017).

The impact of a series of landslides can be mitigated through identification, monitoring, and prevention based on major triggers. This impact can range from material damage and human losses to economic consequences such as transportation network blockage.

Mountainous areas are particularly susceptible to these events due to the presence of four key triggering elements: precipitation, seismicity, weathering, and relief. Tectonic movements, among others, and a decrease in shear resistance due to factors such as reduced material strength or changes in its structure (Yanrong, 2019), (Schilirò, 2019).

Seeking to understand landslide susceptibility this study focuses on characterizing geological parameters through data collection. Simultaneously, we delve into the analysis of soil dynamic properties using geophysical data; and generate geospatial maps that visually represent the identified susceptibility by applying the AHP method to prioritize factors based on their relevance. Also, integrating local data to refine the Vs30 model, enhancing its accuracy for a more precise representation of the region's unique characteristics.

2. Site description

Tierras Altas is a mountainous region that belongs to the Chiriqui mountain range. The area is characterized by steep slopes, valleys, and elevations ranging between 2,000 and 3,500 meters above sea level, and its geology is mostly of volcanic origin (Ministerio de Ambiente, 2019). The predominant soils belong to the Andosol type, composed of organic material and pyroclastic clays, characterized by their exceptional water retention capacity and low bulk density, making them highly susceptible to erosion (Ministerio de Ambiente, 2019).

The identified geological formation in the area is the Barú Formation (OPS-Ba), which dates back to the Pleistocene Quaternary period. This formation mainly consists of a sandy matrix with the presence of andesites, tuffs, and volcanic sediments. The Cañazas hydrogeological group (TM-SAVi) from the Tertiary Miocene period is also present in the area and contains basalts of fissural origin, andesites, breccias, and tuffs, as well as abundant pyroclastic deposits (ETESA, 1999).

The study area, Fig. 1, has experienced significant climatic changes in recent years, with an increase in precipitation critical events and temperature; increasing landslide frequency and creating high-susceptibility areas. According to the Third National Communication on Climate Change, an increase in precipitation and the occurrence of extreme events are expected to happen more frequently in the Western Pacific region (Ministerio de Ambiente, 2019).

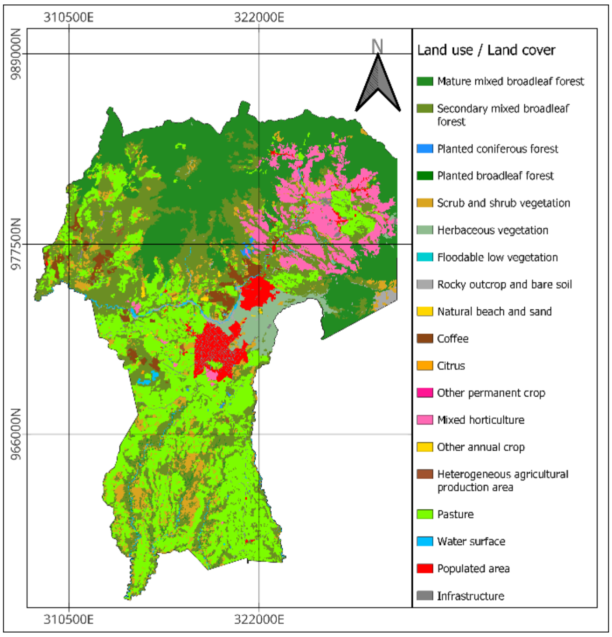

Figure 1. Land use / Land cover (LULC) map.

2.1. Seismic activity in Tierras Altas

The study site is prone to significant and periodic seismic activity, mostly originating from right lateral transverse faults from the Nazca and Cocos plates, and the Chirigui volcanic arc (Hopp, 2014).

Shallow earthquakes, and seismic swarms with magnitudes less than 6.0 on the moment magnitude (Mw) scale are common. These events can reach intensities of up to VIII on the modified Mercalli (MM) scale at short distances from the epicenter (Vasquez et al., 2021).

The relationship between seismic activity and landslides is crucial for risk assessment and implementation of mitigation measures. Continuous monitoring of seismic activity in the region can help predict and prepare for possible landslide-triggering events, allowing a rapid and effective response to protect the population and infrastructure.

3. Susceptibility mapping for underdeveloped countries

Many developing countries are subject to a wide range of natural disasters, whose frequency and diversity distinguish the region. Although these countries may have lower material losses due to their economic limitations, human losses are usually significantly higher than in developed nations.

In the region, hazards can be divided into two main groups, threats associated with the location, which may be more pronounced in mountainous areas (Gupta, 1999). Secondly, rapid urban development and the accelerated exploitation of natural resources, resulting in deforestation, soil degradation, water, and air pollution, as well as the loss of biodiversity; threaten both, the environmental balance, and the quality of life of the inhabitants (Aristizábal, 2006).

Both categories of threats overlap and simultaneously affect the same area. Tierras Altas is prone to landslides and accelerated urban development compromising soil and vegetation stability. Addressing these threats in a comprehensive and planned manner is crucial for the sustainability and well-being of communities.

Previous research has shown high susceptibility zones by implementing dynamic soil properties based on elevation data from the USGS (Castillo et al., 2023). Acceleration measurements were used to microzone a nearby district. These measurements are now used as input for Tierras Altas, that has been confirmed as a high landslide susceptibility area. (Caballero, Castillo, Castrellón, Pérez, et al., 2023).

4. Methodology

The landslide susceptibility analysis for the defined study area (Fig. 2) used a multi-stage methodology. Field data collection was conducted using ETNA and IGU-16HR sensors to validate the Vs30 map. The compilation and analysis of maps utilizing diverse cartographic sources to understand critical geotechnical factors. And the application of the AHP method on key factors and prioritize the most significant ones, establishing a robust base for mitigation strategies.

4.1. Fieldwork

The process involved the compilation of diverse cartographic datasets, including surface accelerations measured using ETNA triaxial sensors. Additionally, ReMi data was acquired with IGU-16HR sensors.

Evaluating datasets and repositories is important to understand geotechnical factors and their impact on landslide susceptibility, particularly when there are limitations in local resources and data generation. As emphasized by (Sui et al., 2013), cartographic datasets and GIS play a key role in integrating spatial information for a comprehensive understanding of geotechnical phenomena.

This GIS data compilation is a geotechnical analysis base for the Tierras Altas region, the compiled map data is displayed in “Table 1”. It helps identify critical landslide factors. The incorporation of diverse spatial data sources enhances the representation of the geotechnical complexity of the study area, aligning with the perspective of (Haklay, 2013).

4.1.1. Acceleration measurements

Surface accelerations were measured using ETNA Altus series triaxial sensors, following the guidelines established by SESAME (European Commission – Research General Directorate Project No. EVG1-CT-2000-00026, 2004). The measurements were conducted at various locations across the Tierras Altas district, focusing on main streets crucial for inter-town communication, as well as in the urban zone of the Volcan province due to its high population density, making both, particular concern cases regarding landslide risk.

Specifically, a total of 4 measurements were taken at important targets close to the highway or residential areas, such as Renacimiento, 11 within Cerro Punta, and 21 in the urban zone of Volcan, Fig 2.

Adhering to the SESAME guidelines, sensors were strategically placed in low-traffic areas, maintaining a safe distance from both natural and artificial structures.

Measurements were avoided during rain or windy conditions to prevent interference, and sites with potentially high noise sources were also avoided. For sensor placement firm ground was considered, and locations with ditches or slopes were deliberately avoided.

The measurements, with an approximate duration of 20 minutes, provided a significant amount of data for analysis, and the sampling frequency was set at 100 Hz. This information is essential for understanding the data quality and the time resolution of the measurements.

Table 1. Data compilation

	Source Institution	**Data format**	**Pixel size** (m)	**Reference citation**	**Additional information**
Panama political-administrative limits	Smithsonian Institution	Vector	-	(Solano, 2024)	-
Panama geology	Smithsonian Institution	Vector	-	(Solano, 2021)	-
Land elevations (DEM)	NASA SRTM	Raster	30 x 30	(Düster, 2021)	QGIS SRTM-downloader, in meters
Panama land use/land cover (LULC)	SINIA	Raster	10 x 10	(Ministerio de Ambiente, 2021)	-
Streets and waterways OSM data	OpenStreetMap	Vector	-	(Trimaille, 2023)	QGIS QuickOSM
30 meters shear-wave velocity	USGS Vs30 Models and data	Raster	924 x 924	(U.S. Geological Survey, 2019)	In m/s
SoildGrids maps	SoilGrids	Raster	0.002 x 0.002	(ISRIC — World Soil Information, 2020)	Coarse fragments (cm3/dm3), and (g/kg), silt (g/kg), clay content (g/kg)

It's important to highlight that the collected sensor data was analyzed to determine the site's natural frequency, providing valuable insights into the dynamic properties of the ground in the Tierras Altas region, particularly considering its characteristic sandy soils (Caballero, Castillo, Castrellón, & Rodríguez, 2023).

4.1.2. ReMi data

Refracted Microtremor (ReMi) measurements were acquired using geophones integrated into IGU-16HR sensors, following the ReMi methodology. A total of 10 measurements were conducted in the Tierras Altas district, strategically chosen to coincide with locations near the ETNA measurements, one in Renacimiento, 5 via and within Cerro Punta, and the remaining 4 in Volcán, which are represented as yellow in Fig 2.

For this method, 10 sensors were linearly positioned with a 10-meter separation between each, covering a 100-meter distance for approximately 30 minutes for data collection, employing a sampling frequency of 100 Hz.

To enhance data precision sensors were installed perpendicular to the street to ensure sequential reflection of waves from nearby vehicles across each sensor.

Throughout the ReMi data collection, meticulous consideration of environmental factors involved situating sensors away from disturbances, including traffic and constant noise sources, and optimizing their alignment respecting the street layout to enhance the reliability of the obtained results.

4.2. Data analysis

The geotechnical analysis involved a comprehensive exploration of various data sources to characterize landslide susceptibility. The study involved two main processes. The first one was the maps assessment, which required processing in QGIS to provide a detailed representation of the study area. The second one was dynamic data analysis, which involved cross-validation by measuring with ETNA and IGU-16HR sensors and analyzing using Python scripts.

In addition, the frequency validation stage enhanced the comparison of the correlation between Vs30 models and field data, making the results more reliable from different data sources.

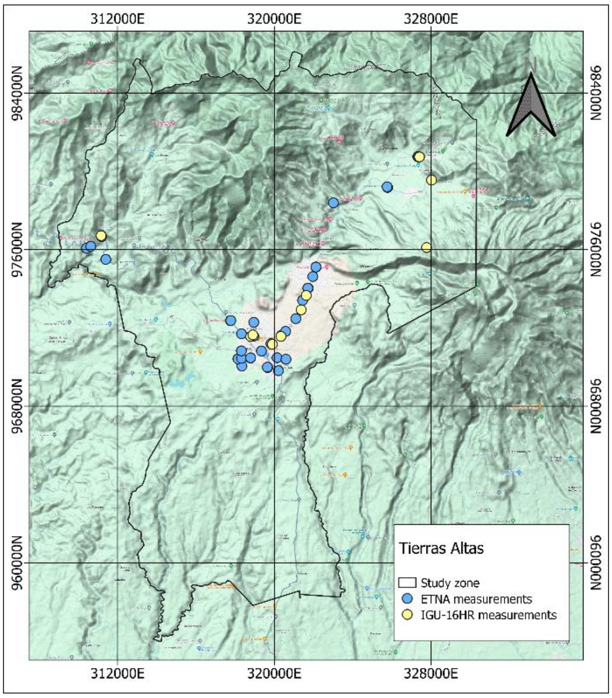

Figure 2. Study zone and sensor measurements.

4.2.1. Maps analysis

The collected data, as a whole group, provides a comprehensive understanding of geotechnical factors that may directly impact landslide susceptibility.

The map analysis using the open-source software QGIS, aimed to process and prepare the maps for susceptibility analysis. To ensure uniformity among rasters, the resolution was standardized using the DEM in Fig. 3 as a reference. The OSM and faults data are represented in Fig. 4.

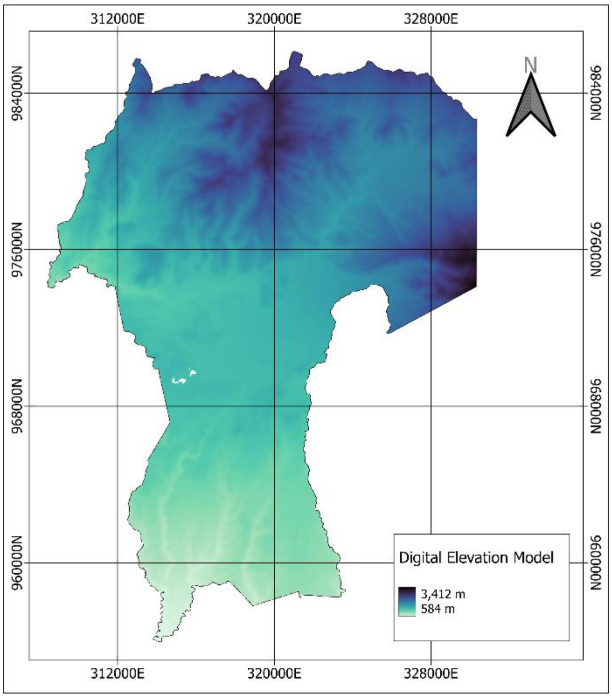

Figure 3. Digital Elevation Model (DEM) map.

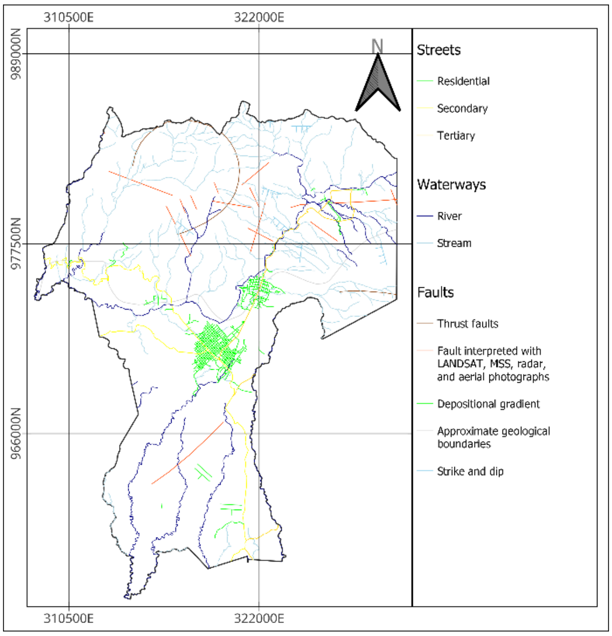

Figure 4. OpenStreetMap data (OSM).

For the SoilGrids maps, layers corresponding to coarse fragments, sand, silt, and clay content were downloaded for three depth ranges: 15-30 m, 30-60 m, and 60-100 m. Subsequently, by calculating the average within each depth range, the data was converted into percentages, and categorized into two main groups: coarse and fine fractions.

For the field measurements from the ETNA and IGU-16HR sensors, frequency and Vs30 values were obtained respectively. The ETNA and IGU-16HR layers were classified according to soil type to cross-verify the results. This process ensures an accurate representation of the geotechnical complexity of the study area, which is crucial for the subsequent stages of the investigation.

4.2.2. Dynamic data analysis

The dynamic data analysis involved processing information from both the ETNA and IGU-16HR sensors to gain insights into the soil's dynamic properties. This dual-method approach allowed for a comprehensive understanding of the site's dynamic response, contributing significantly to our overall investigation.

For the ETNA sensors, data was acquired, capturing measurements along the x, y, and z axes. The analysis was conducted using a Python code specifically tailored for surface acceleration analysis, following the Nakamura method or Horizontal-Vertical Spectral Ratio (HVSR). This approach entails examining surface waveforms to identify predominant frequencies and extracting the soil's natural frequency. The Research Group developed the Python code to:

- incorporated a Hamming filter applied to the acceleration signals before the Fourier transform, which is utilized to obtain frequency spectra.
- a weighting method is employed to smooth these spectra, representing the frequencies clearer.
- the code includes compliance verification, assessing whether the analysis results adhere to the criteria established by SESAME. These criteria encompass parameters such as amplitude, fundamental frequency, and standard deviation.
- graphs are generated, illustrating the frequency spectra, and categorizing the outcome based on the achieved error.
- dynamically adjusts the window size and bandwidth to enhance the reliability of the results.
- undergoes iterations with adaptive adjustments if SESAME criteria are not met, exploring different combinations until compliance is achieved.

Concerning the IGU-16HR sensors, data was obtained and subsequently exported in a miniseed format. The ReMi involves studying travel times of waves among different sensors, providing valuable insights into Vs30 values, and offering information about shear velocity in near-surface layers:

- enables the set-up of an acceptable standard deviation.
- generates frequency spectra for each specified time window.
- calculates shear wave velocity for a depth of 30 meters (Vs30), based on the sensor's travel times.
- Analyze and visualize results through graphs displaying frequency spectra, angles, wave velocities, and other pertinent parameters.
- utilizes linear regression to estimate wave velocity.
- evaluate results from predefined criteria, including acceptable deviations.
- generates graphs illustrating the relationship between wave velocity and wavelength.

Both analysis processes were fundamental to understanding the dynamic properties of Tierras Altas. The combination of data from both sensors provided a comprehensive understanding of the site's seismic response.

4.2.3. Dynamic data validation

To validate the data obtained from the sensors, and to utilize Vs30 models in areas lacking dynamic data, a thorough dynamic data validation process was undertaken. The primary objectives were to compare the Vs30 sample derived from the Vs30 USGS map with the sites where measurements were taken, enabling a comparison between model and field Vs30 data.

Additionally, Vs30 values were compared with frequencies obtained. Both the Vs30 values and frequencies were translated into soil types for a meaningful comparison. The NEHRP systems (FEMA, 2020) were applied to Vs30 values, consolidating the A and B, C and D, and E and F categories. For frequencies, a conversion into periods was performed, and the data was categorized into Type 1, Type 2, and Type 3 for critical periods of 0.4, 0.6, and 0.8 respectively, following the Japanese regulations (Earthquake Resistant Design Method for Buildings, 2019).

The correlation between these datasets contributes to a more robust understanding of the soil dynamic properties and enhances the reliability of our overall findings. Adhering to existing classification systems, and regulatory norms ensures a standardized and comprehensive evaluation of the compiled data.

4.3. Susceptibility analysis

The susceptibility analysis constitutes a crucial component for understanding and mitigating the landslide risk. This process implies an integral evaluation of the diverse factors that contribute to the probability of landslide occurrence. This integrated focus not only prioritizes relevant factors with AHP but also validates the results by considering real landslides, ensuring a solid base for effective decision-making in land-use and mitigation strategies.

4.3.1. AHP method (Analytic Hierarchy Process)

To determine the hierarchy of importance for each layer in the susceptibility mapping, we used the AHP (Analytic Hierarchy Process) method. We assigned a numeric scale ranging from 1 to 9 to evaluate the layers.

Criteria are assessed based on their importance in the decision matrix in “Table 2”, where each pair of criteria is compared to establish their relative priorities. The layers considered for comparison include the A - LULC, B – distance to faults, C – distance to waterways, D – distance to streets, E - Vs30, F - slopes, and the G - ratio of the coarse to fine soil fractions.

Table 2. Decision matrix

	A	B	C	D	E	F	G
A	**1**						
B	1/5	**1**					
C	1/5	1/2	**1**				
D	1/7	1/3	1/2	**1**			
E	1/3	2	3	3	**1**		
F	3	7	5	5	5	**1**	
G	1/3	5	5	5	3	1/3	**1**

The input data undergoes weighting, and its consistency is evaluated. A consistency index below 10% is deemed acceptable, ensuring the precision of calculations. This approach provides a robust base for decision-making by prioritizing relevant layers in the susceptibility analysis, thereby enhancing the reliability of the results.

4.3.2. Susceptibility mapping

For the susceptibility mapping process, we utilized a methodology based on the Analytic Hierarchy Process (AHP) to prioritize each layer and assign respective weights. The landslide susceptibility map is generated by calculating the susceptibility index, which is achieved through the summation of the product of each variable's classification and its corresponding weight.

After performing calculations in QGIS, the susceptibility index was determined with “Eq. (1)”, and a susceptibility map was obtained. Subsequently, a visual analysis of the map is conducted to identify susceptible zones. To validate the results, these zones are compared with previous landslide locations, providing a practical assessment of the maps' accuracy.

$$LSI = \sum_{i=1}^{n} RI \times WI \quad (1)$$

This method incorporates both AHP prioritization and actual landslide occurrence to increase the reliability of the susceptibility map. By visually analyzing the data, we can identify areas with a high likelihood of landslides, which is useful for land-use planning and developing strategies to mitigate the risks.

5. Results

The results obtained in this geotechnical mapping study for Tierras Altas provide insights into the factors influencing landslide susceptibility. Utilizing QGIS, we generated informative maps, such as the slope map, derived from the DEM, which effectively distinguishes between gentle and steep terrains.

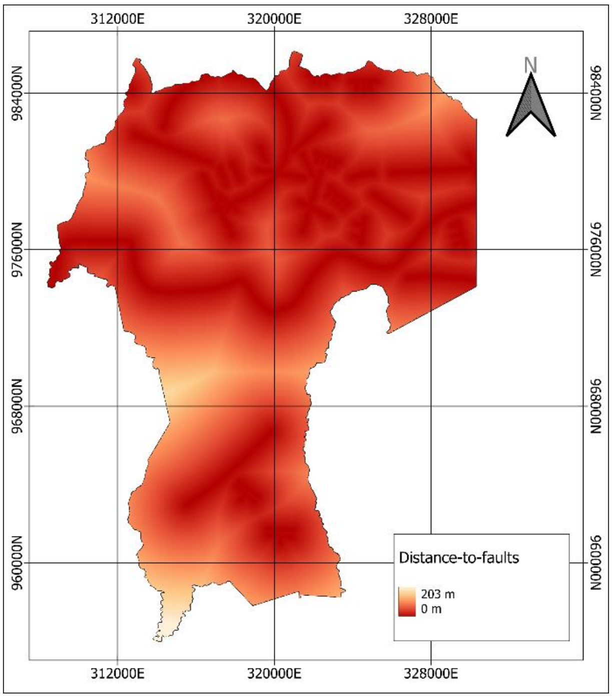

Figure 5. Distance to faults map.

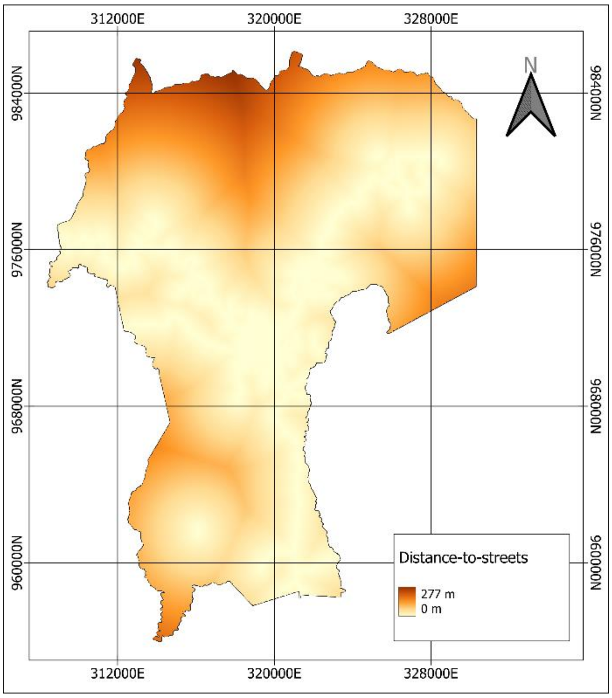

Figure 6. Distance to streets map.

Seismic measurements offered information on soil dynamics for the refinement of Vs30. The susceptibility analysis, employing AHP, yielded the susceptibility map, highlighting areas with elevated landslide occurrence probabilities. This approach ensures reliable representation, essential for informed risk planning.

5.1. Geotechnical maps

The results obtained from the geotechnical maps contribute to our understanding of the factors influencing landslide susceptibility. Using the raster proximity tool in QGIS we generated the distance-to-faults, distance-to-streets, and distance-to-waterways maps, which were employed in the AHP method, as illustrated in Fig. 5, Fig. 6, and Fig. 7 respectively.

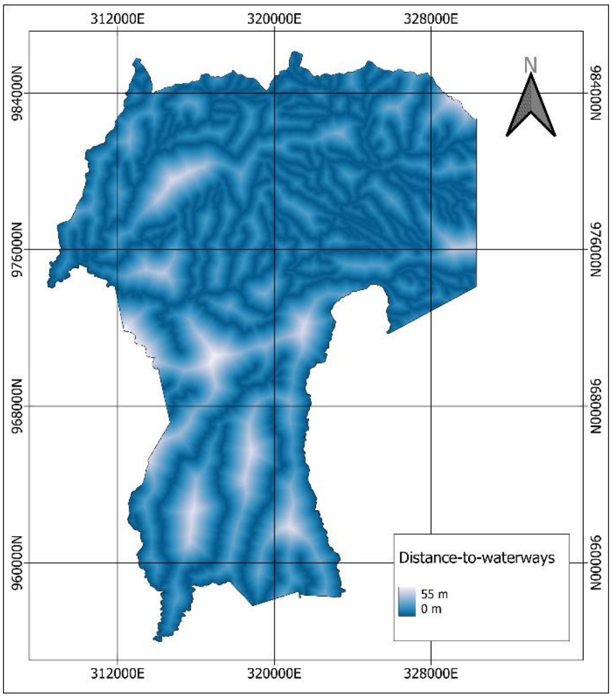

Figure 7. Distance to waterways map.

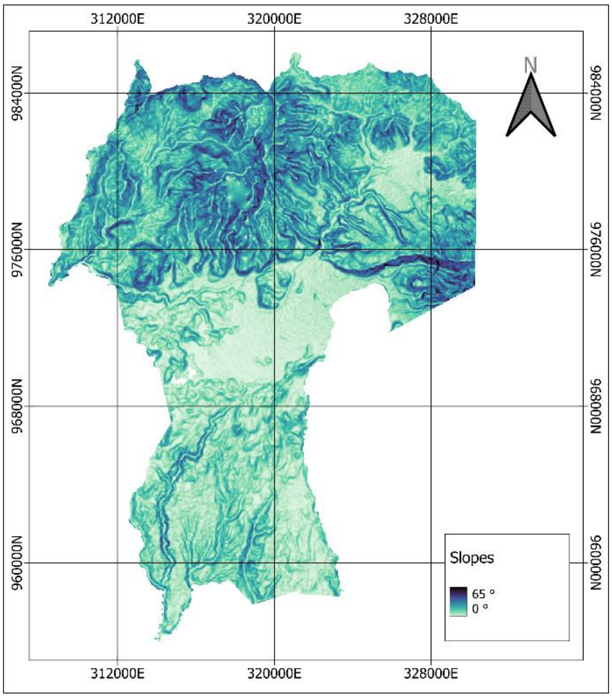

Figure 8. Slopes map.

Additionally, the final map derived from SoilGrids rasters illustrates in Fig. 9 the ratio between coarse and fine fractions. This map highlights areas with a higher proportion of coarse fragments, indicating zones of elevated risk. These findings offer valuable insights into geotechnical variation within the region.

5.2. Site frequencies and Vs30

The seismic measurements and analysis of dynamic data have provided a comprehensive understanding of the dynamic characteristics of the soil in Tierras Altas. We utilized ETNA triaxial sensors to determine the natural frequency of the ground, and IGU-16HR sensors enabled measurements for Vs30, which is another crucial dynamic parameter.

To ensure the accuracy of the measured data, a cross-validation process was conducted. The field results for Vs30 were utilized to refine the USGS Vs30 values specific to the study area, incorporating a correction factor. This factor was established based on the VS30 values obtained from measurements in an elevation range of 1210 to 1665 meters.

It's important to note that the adjustment factor was selectively applied within this altimetry range, as additional data is required to ensure reliable adjustments for elevations below and above the specified limits. Consequently, while the field/raster comparison might suggest a decrease in adjustments for higher elevations, the current dataset lacks sufficient information to validate such adjustments in practice.

The adjusted results for the Vs30 USGS map showcased in Fig. 10, were refined by integrating seismic sensors data. These corrections significantly enhance the accuracy of the Vs30 values, providing a more precise representation. The adjustment factor for this elevation range was 1.20 calculated as the average of the factors for all measured sites with altimetry below 1900 meters.

Figure 9. Coarse to fine soil fraction ratio map.

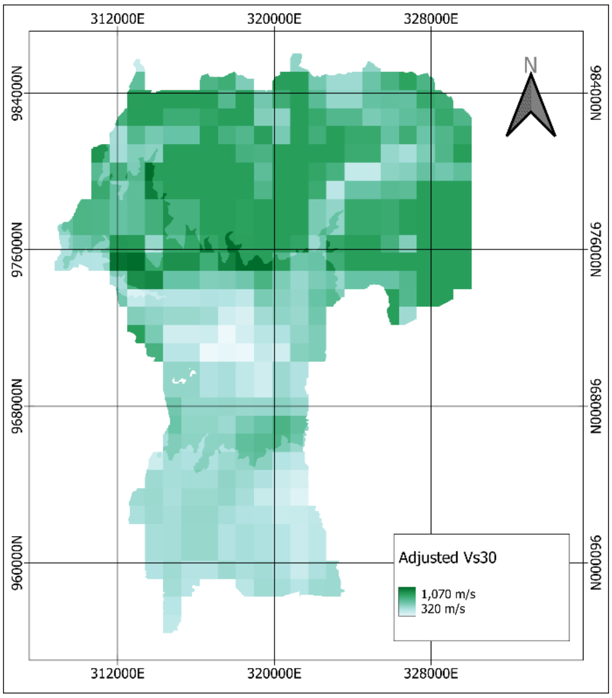

Figure 10. Adjusted Vs30 map.

5.3. Susceptibility map

The results of the susceptibility analysis provide a detailed insight into areas with a higher probability of experiencing landslides in Tierras Altas. To determine the importance hierarchy for each layer in susceptibility mapping, the AHP method was employed, assigning weights to the criteria: LULC, slopes, distance-to-faults, distance-to-waterways, distance-to-streets, Vs30, and coarse-to-fine fractions ratio.

“Table 3” summarizes the priorities assigned for each criterion, established for calculating the susceptibility index with the equation. These weights were applied through the raster calculator in QGIS to generate the susceptibility map in Fig. 11, where areas with higher values show a higher chance of landslide occurrence. Additionally, coherence in comparisons between layers was ensured, with a minimum consistency ratio of 6.5% during the AHP process, supporting the reliability of the assigned priorities.

Table 3. Criteria priorities

	Priority (%)	**Rank**	+/- (%)
LULC	24.5	2	11.0
distance-to-faults	5.5	5	2.1
distance-to-waterways	4.3	6	1.7
distance-to-streets	3.2	7	1.7
Vs30	8.4	4	2.2
slopes	37.1	1	17.7
coarse to fine fractions	17.0	3	6.4

This integrated approach, considering layer prioritization through AHP, enhances the reliability of the susceptibility map. These results are essential for land use planning and the development of risk mitigation strategies for Tierras Altas.

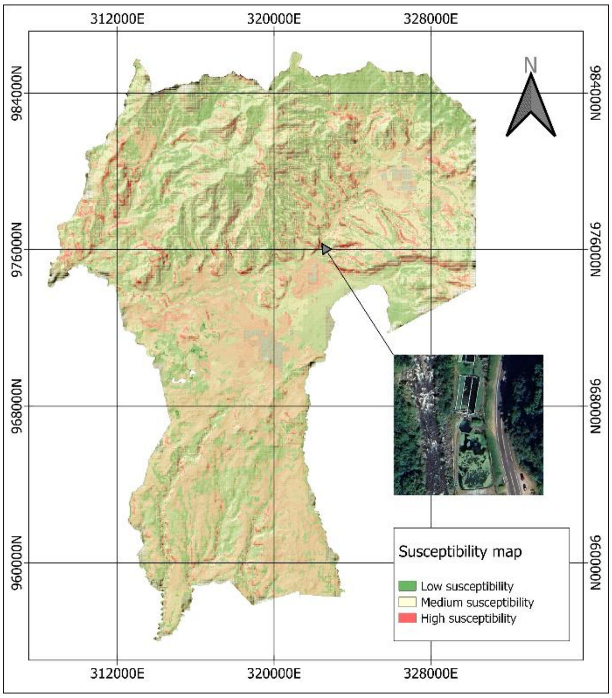

Figure 11. Susceptibility map.

6. Conclusions

Hierarchical criteria allowed the identification of the most influential variables in the geotechnical mapping.

The integration of global data, such as the Vs30 model from USGS, with local measurements, showcases the importance of adjusting global models to site-specific conditions. The correction of Vs30 with local data significantly improves the model's precision, emphasizing the need to consider the site's unique characteristics.

The generation of detailed maps, including slope and coarse-to-fine fraction maps, provided precise insights into geotechnical parameters, serving as valuable tools for identifying critical areas, risks associated with urban developments in landslide-prone areas, emphasize how natural resource exploitation can significantly increase the region's vulnerability. This study lays the groundwork for future similar investigations in mountainous regions.

To ensure sustainable development and resilience in the face of environmental challenges, future research could delve deeper into specific aspects of landslide susceptibility, considering the socio-economic impacts on local communities and exploring global adaptations of our methodologies. The methodologies employed and the findings presented here serve as a reference point for researchers and practitioners, fostering the continuity of research in this vital field.

To successfully apply the presented susceptibility maps practically, it's highly suggested to develop an exhaustive landslide inventory for validation. This step, although not yet undertaken by local authorities, would ensure the reliability for future investigations.

Acknowledgments

The authors express their gratitude for the invaluable support from members and collaborators of the Geotechnical Engineering Research Group (GIIG) and the Seismic Engineering Research Group (GIIS) at the Technological University of Panama – Chiriqui Regional Center. Their valuable assistance in sensor measurements and the development of the analysis codes have significantly contributed to this research. We also extend our thanks to the university and the personnel of the center for the resources throughout the investigation.

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