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Sustainable Management of Landslides in Ecuador: Leveraging Geophysical Surveys for Effective Risk Reduction

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Abstract: The present work explores the use of geophysical surveys as valuable tools for the study and sustainable management of landslides, with a particular focus on Ecuador. As an Andean country, Ecuador's geomorphology and geology are dominated by volcano-sedimentary materials and processes, which confers a high susceptibility to landslides. In the last few years, a number of landslide events (such as those at La Josefina, Alausí, and Chunchi) have given rise to disasters with significant material damage and loss of life. Climatic events, affected by climate change, earthquakes, and human activity, are the main landslide triggers. Geophysical surveys, like seismic refraction, electrical resistivity tomography (ERT), and ground-penetrating radar (GPR), are easy and low-cost techniques that provide valuable and critical subsurface data. They can help define the failure surface, delimit the mobilized materials, describe the internal structure, and identify the hydrological and geotechnical parameters that complement any direct survey (like boreholes and laboratory tests). As a result, they can be used in assessing landslide susceptibility and integrated into early warning systems, mapping, and zoning. Some case examples of large landslide events in Ecuador (historical and recent) are analyzed, showing how geophysical surveys can be a valuable tool to monitor landslides, mitigate their effects, and/or develop solutions. Combined or isolated geophysical techniques foster sustainable management, improve hazard characterization, help protect the most vulnerable regions, promote community awareness for greater safety and resilience against landslides, and support governmental actions and policies.

Keywords: landslide hazards; geophysics; sustainability; effective risk management; Ecuador

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1. Introduction

The sustainable management of landslides involves implementing strategies and practices that aim at reducing the risk and impact of landslides while looking for environmentally responsible, economically viable, and socially equitable solutions [1]. This approach focuses on reaching long-term solutions to strengthen community resilience, including infrastructures and preserving natural ecosystems. Sustainable management seeks to balance hazard mitigation with resource preservation and promote safe land use practices according to the Sustainable Development Goals (SDGs) [2].

Ecuador is a country in South America affected by climate change, such as El Niño (warm and rainy) or La Niña (cold, dry, and with eastwardly wind) events. The Andean Cordillera (which reaches heights of up to 4000 m above sea level) divides it into three parts: coastal, mountainous, and Amazonian. These provide exposure to severe conditions (rural locations with limited communication roads, stepped territory with small agricultural communities, indigenous population with limited acquisition power, and the frequent climatological and geological events that beat them) that increase the population's vulnerability. Recent natural disasters, which include flooding, volcanic-related events, and massive landslides (for example, in Chimborazo province), have been a source of destruction, including loss of life. Thus, adopting sustainable management approaches is crucial, and there is a need to perform extended studies to improve knowledge about the natural hazards that will prevent this impact and permit mitigation of the effects. In this context, geophysical surveys could provide valuable information and ensure the safety of the population, maintenance of infrastructure, and environmental preservation [3–8].

Ecuador's surficial geomorphology and geology are dominated by eruptive volcanic episodes from 25 M years ago through to the present. Hence, these sediments, including ash and tuff, are thickest over ancient rocks and the basement. Soil landslides are common hazards, and the surficial geology is the main factor that controls slope stability analysis. Landslides have increased in recent years in both frequency and severity all along the Andean Cordillera [9,10] and also in Ecuador, where climate change with the increase in rainfall acts as a trigger for such events [11].

Understanding the factors involved in slope stability is vital to identifying potential areas prone to landslides. Both spatial and temporal dimensions must be analyzed to assess the susceptibility to landslides and deep knowledge of potential causes and factors involved in landslides is required. The vulnerability in Andean countries is also increasing due to the size of the population, land use (deforestation), and urbanization, the last two poorly controlled by states. All these issues drive a progressive risk increase [1,10,11].

The Ecuadorian government has been actively working to address the impact of landslides on its territory. This is part of their broader strategy to promote sustainable development and ensure the safety and well-being of the population, as outlined in the *Plan Nacional para el Buen Vivir 2017–2021* [12] and subsequent planning initiatives as a further tool to promote sustainable development. Some of these activities are pursuing an integrated approach to risk reduction by focusing on sustainability and resilience, such as by updating building codes (with the new 2024 release of the Ecuadorian construction norms), renovating baseline information on zoning hazard areas, and developing methodological guidelines for land use planning. Ecuador has a decentralized system of organization where the provincial, canton, and parish GAD (Decentralized Autonomous Government, in Spanish abbreviation) manage and are responsible for risk reduction and their definition in each territory. This is intended to develop a local capacity integrated with local policies and strategies. However, technical capacity needs to be improved and strengthened with specialized technicians. There is also a need to increase seismic vulnerability analysis, reduce structural losses, and preserve lives, including a regulatory and policy framework, technical and engineering solutions, and community education and involvement.

The present work focuses on applying geophysical surveys from the point of view of sustainable management strategies that need the application of easy and low-cost techniques. These techniques, including the application and resolution of models or their use in monitoring, can address issues such as defining the surface rupture, the mass volume mobilized, and the geological characteristics of the materials involved in landslides. Some case examples of large landslide events in Ecuador (historical and recent) are analyzed to show how geophysical surveys can help provide information quickly and are valuable tools for mitigation and developing solutions. Thus, this work explores and analyzes the role of geophysical surveys in the sustainable and effective management of landslide problems in Ecuador, contributing to their knowledge and analysis.

2. Understanding the Landslide Problem in Ecuador

Ecuador has mountainous regions in both flanks of the Andean Cordillera as well as topographical features that confer particular conditions. The presence and development of tropical soils, mostly from recent volcanic eruptions and neo-tectonic activity, contribute to modeling different landscapes prone to landslides [13–15].

Over the last few decades, Ecuador has suffered significant landslide events, such as those reported in La Josefina, Azuay province (1993); Chunchi, Chimborazo province (2021); Gulag-Marianza and La Cría (Figure 1), Azuay province (2022); and most recently, Alausí, Chimborazo province (2023). The impact and effects of these landslides were not limited to rural areas as they also affected urban regions like El Tejado (Quito), in Pichincha province, with two events in 2022 and 2024 [16], and the Rio Verde event, Tugurahua province (2024), where debris and mud flow events were also experienced.

Figure 1. A view to the North (upper right corner arrow) of the 2023 La Cría landslide (Nabón canton, Azuay province, Ecuador). This involved slow-motion, large-scale, complex movement with a crown and scarps that ran backward against the La Cría community's location. Arrows indicate the movement direction of the landslide, limited to the South by the La Cría River (modified from [17]).

Landslides are an important and dangerous hazard in Ecuador. According to the Desinventar-Sendai database (www.desinventar.org, accessed on 20 August 2024), the phenomena responsible for the most deaths in Ecuador during the period 1970–2019 were landslides, which directly killed more than 1642 people by landslide mass movement (with a tendency line increasing across the years, see Figure 2), caused 1481 people to be injured and/or missing, affected 10,307 houses (destroyed or damaged), and damaged 1420 km of roads. As an example, from the first of December 2023 to the first days of May 2024, 647 landslide events were reported, 5 of which resulted in loss of life (ten people died), and 2 mudflow events, in which two people were reported as dead (https://www.gestionderiesgos.gob.ec/informes-de-situacion-epoca-lluviosa-2022-2023/, accessed on 21 September 2024).

However, the natural environmental contribution to landslide hazards is not alone. Human factors, such as uncontrolled land use and invasion of hazard-prone areas, such as the stepped flanks of mountains, flood river areas, and filled rivers, also play a significant role.

All in all, significant factors that contribute to landslides in Ecuador include:

- Heavy rainfall: The country experiences two seasons, one of which has intense, fast, and prolonged rainy periods, which increases soil saturation.
- Seismic activity: Ecuador is located along the Pacific Ring of Fire, an area prone to earthquakes, which are one common trigger of landslides [18].
- Volcanic activity: The so-called Volcano Avenue (named by A. Humbolt in the XIX century) is characterized by the presence of active volcanoes and recent soft sediments from their eruptions.

- Deforestation and land use: Inappropriate or uncontrolled land use and deforestation practices exacerbate soil nudity and, consequently, the erosion of slopes.

According to Auflič et al. [19], landslides are more prominent in earth slide types (>50%) with a medium to large size, with deep to very deep failure surfaces (between 5 to 20 m and more than 20 m). Slow motion is reported as the trigger in more than 65% of cases, and rainfall is reported in the same proportion. Human activity is reported in 10% of cases, and infrastructural facilities and residential houses are affected in 75% of cases. Even though these figures were gathered from European landslides, such characteristics can be applied to Ecuadorian landslides, adding the tectonic characteristics of the country, which is affected by several earthquakes every year [20].

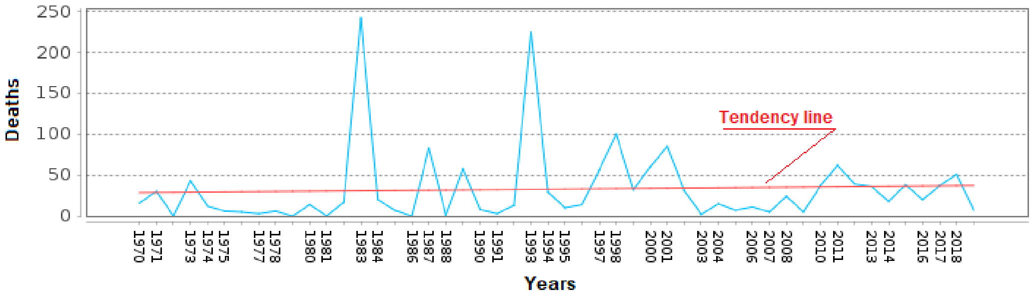

Figure 2. Deaths per year between 1970 and 2019 in Ecuador. Values are contained in the Desinventar database. A tendency line is depicted, uprising through the years (modified from www.desinventar.org, accessed on 20 August 2024).

3. Geophysical Surveys in Sustainable Management Approaches for Landslide Risk Reduction

Landslide complexities in Ecuador make it necessary to adopt an approach using different methods to conduct proper landslide management. Conducting landslide risk reduction and mitigation in a sustainable way involves using early warning systems, planning and regulating land use, maintaining ecosystems, engaging communities, and engineering interventions through infrastructure construction [1,21].

Apart from community and ecosystem approaches, geophysical surveys play a key role in landslide management, as they can be used in the area definition, delimitation, and investigation of landslide characteristics. Geophysical surveys can be a fundamental component of early warning systems, identifying and monitoring areas prone to slide or suffer some kind of movement (even in rock slopes). In land use planning, although based on and supported by surficial and shallow information, in-depth information obtained from geophysical surveys may help define and limit high-risk areas. For infrastructure design, such as slope stabilization, drainage definition, or geological hazard mitigation procedures, where knowledge about geological materials and geotechnical parameters is vital, geophysical surveys complement borehole investigation and laboratory tests while easily covering and providing information on a greater geographical area with low costs.

3.1. Geophysical Surveys as an Investigation Tool

Geophysical surveys can be used as a complementary source of information together with other investigations and monitoring surveys. They are not limited to a single method but involve diverse methods [22]. These include seismic, electric, and electromagnetic (EM) methods using different techniques: refraction, passive, or reflection (seismic surveys); electrical resistivity and chargeability measures from vertical electrical soundings (VES) and 2D and 3D electrical tomography (ERT); and ground-penetrating radar (GPR) or time-domain (TDEM) in the EM method [8]. Using a single approach or a combination of techniques allows detailed information about the subsurface structure of the terrain to be gathered. This is essential for identifying potential landslide hazard areas and developing effective risk reduction strategies.

The advantages of using geophysical surveys when compared with traditional or mechanical methods (boreholes) for landslide studies in risk reduction include [3]:

- They can provide non-invasive information about the stratigraphy (internal structure of material as layers) and physical properties of ground subsurface geological materials. This helps to better understand landslide mechanisms and identify potential failure surfaces.
- They can be applied over two, three, and even four (over time) dimensions using a variety of methods (seismic, electrical, and electromagnetically—EM) to map the subsurface. This helps to better understand and more comprehensively characterize landslide areas compared to traditional geological and engineering mapping methods, which are more limited tools.
- They cover larger areas and volumes than traditional investigations (which are local and point-based, i.e., one-dimensional surveys). This enables them to explore great areas affected by hazards, conduct a widespread investigation, or perform a regional-scale landslide assessment.

However, integrating multiple investigation techniques (geophysical and non-geophysical ones) is essential when developing a proper landslide study and management strategy [3,22] since geophysical surveys also suffer some limitations. These include:

- Indirect nature of the measuring, as they recall data about physical properties that can be correlated to geotechnical parameters or other material characteristics. Careful data acquisition and interpretation are needed, and although applying several methods or techniques is highly recommended to lessen this issue, direct geological and geotechnical measurements are often needed to calibrate and validate models [3].
- The non-uniqueness of solutions in modelization can be challenging if relying solely on geophysical surveys, as it can produce problematic solutions due to the infinite models obtained from a dataset.
- Geophysical methods show a typical decreasing resolution with depth due to absorption and/or distortion on the main field. Integration with other direct data techniques and/or geophysical methods is therefore needed.
- Overestimation of the reliability and quality of the results can lead to misinterpretations or bad use of the final models by practitioners.

Based on the authors' experience and the literature [3,5,23,24], Table 1 shows the suitability of different techniques used in geophysical surveys to study landslides in rocks and soils (abbreviations used include the following: SP: Spontaneous Potential, IP: Induced Polarization, FDEM: Frequency Domain EM, SASW: Spectral Analysis of Surface Waves, MASW: Multichannel Analysis of Surface Waves, ReMi: Refraction Microtremor, HVSR: Horizontal to Vertical Spectral ratio, and SPAC: Spatial Autocorrelation). The primary techniques listed in the first column include artificial field methods and natural field methods, such as gravity and magnetic methods, which have limited application to landslide investigations. The reflection seismic technique has also limitations in terms of its cost (it is too expensive for small areas or geotechnical investigation budgets) and the size and depth of landslides (it is not adequate for shallow ones). However, reflection offers good results when high-definition reflection seismics are applied.

Rockfall landslide typologies (including toppling) are complex systems for establishing the survey campaign, including direct surveys such as boreholes, due to the possibility of discontinuous landslides, i.e., the fall of isolated rocks and blocks. Therefore, depending on the ground and objectives to be defined, some geophysical techniques could be appropriately applied to their definition.

The applicability of each geophysical technique depends on the measured parameter, the basis of each method, and the correlation with geotechnical or geological parameters. The applicability of a method or technique is affected by what is being measured and its characteristics. Size, depth, impedance contrast, and surrounding materials are the most important characteristics that generate good modeling after data processing [8].

Table 1. Geophysical methods and their application to landslides (based on Bell et al. [23]).

METHOD	TECHNIQUE	LANDSLIDES TYPOLOGIES			
		ROCK SLIDES	SOIL SLIDES	QUICK CLAY LANDSLIDES	ROCK FALLS
SEISMIC	Reflection	Adequate	In big ones	Depends on size (big)	Depends
	Refraction	Adequate	Good results	Adequate to good results	Depends
	Passive *	Adequate	Good results	No references	Adequate
ELECTRIC	VES	Poor results	Good results	Adequate to good results	No suitable
	ERT	Good results	Good results	Good results	Depends
	SP	Poor results	Adequate	Poor results	No suitable
	IP	No suitable	Usable	Adequate	No suitable
EM	TDEM	Poor results	Adequate	Poor results	No suitable
	FDEM	Poor results	Adequate	Adequate	No suitable
	GPR	Shallow results	Poor results	No suitable	Depends
GRAVITY	Micro **	Poor results	Poor results	Depend on size	Depends
MAGNETIC	Profile ***	No suitable	Depends	Depends	No suitable

* This includes those whose measures are related to the shear wave velocity, such as SASW, MASW, ReMi, HVSR, and SPAC. ** Microgravimetry *** Depends on the magnetic susceptibility of the soil.

Table 2 gives a comprehensive guide to the related geotechnical parameters, identification of failure surface, and hydrogeological parameters for each technique, as shown in Table 1. That provides a general idea of those investigating techniques, aiding in understanding and applying each method. Geotechnical parameters can be found through seismic surveys based on the elastic waves analyzed. Electrical and EM methods cannot provide geotechnical parameters but help define geological structures (better than seismic refraction), stratigraphy, moisture, and hydrologic conditions (humidity and aquifer presence, including phreatic levels and flows).

Table 2. Parameters obtained when using geophysical methods applied to landslides.

METHOD	TECHNIQUE	RELATED TO LANDSLIDE PARAMETERS		
		GEOTECHNICAL	FAILURE SURFACE	HYDROGEOLOGY
SEISMIC	Reflection	Non-related	Internal structure	No data available
	Refraction	Elastic-related	Impedance contrast	Phreatic level
	Passive *	Elastic moduli	Impedance contrast	No data available
ELECTRIC	VES	Non-related	Impedance contrast	Aquifer, %humidity
	ERT	Non-related	Impedance contrast	Aquifer, %humidity
	SP	Non-related	No data available	Aquifer flow
	IP	Non-related	Clayed material	Clay/Saturation
EM	TDEM	Non-related	Impedance contrast	Aquifer, %humidity
	FDEM	Non-related	Impedance contrast	Aquifer, %humidity
	GPR	Non-related	Up to ~5 m depth	Phreatic level
GRAVITY	Micro **	Non-related	Density contrast	No data
MAGNETIC	Profile ***	Non-related	Non-related	Non-related

* This includes those whose measures are related to the shear wave velocity, such as SASW, MASW, ReMi, HVSR, and SPAC ** Microgravimetry *** Depends on the magnetic susceptibility of the soil.

When failure surface definition is sought, seismic techniques can establish that surface depending on sonic impedance contrast. However, a contrast value of up to 2 is required to have good results between geological material layers that separate the mobilized part of the landslide from the fixed one [8]. Electrical methods also help to define failure surfaces by electrical impedance contrast. In this case, the presence of high water content (close to or saturated) or clays could be an exceptional support for identifying it. Particularly, the induced polarization potential from the IP technique enables the separation of water-saturated materials from clayed ones by analyzing the chargeability potential (water can never be charged).

Electrical and EM methods are in fact the most valuable methods for hydrogeology investigations. They can give information about the presence of aquifer layers (phreatic or piezometric) and the percentage of moisture (with previous parametrization of resistivities). The usefulness of SP in subterranean flows and IP in the discrimination of clay materials from saturated sands is remarkable.

Conversely, natural field methods, i.e., gravity and magnetic approaches, have limited application to landslides. This is due to the need for high contrast in measured parameters (variations of potential fields gravimetric and magnetic) as well as the presence of magnetic permeability. For example, very dense grids must use the magnetic method to obtain useful and accurate results.

3.2. Geophysical Surveys in Landslide Early Warning Systems (LEWSs)

Geophysical surveys can be used with other investigation techniques (like remote sensing, monitoring, direct surveys, and topographical data) to provide valuable Landslide Early Warning System (LEWS) inputs [3]. A LEWS can be considered a procedure focusing on vulnerability reduction by measuring different geological, geotechnical, hydrological, and/or geophysical parameters. LEWSs can be divided into regional/territorial (great to medium scale) and local (small scale) types [25], depending on the slope-scale set. However, both are related to the increasing moisture and precipitation trigger measures.

While geophysical surveys can investigate broad areas, slope-scale applications are more suitable. Surface monitoring by topographical or satellite measures offers a shallow view of the movements, while geophysical surveys can produce internal and deeper information about the structure and parameter variations.

Electrical surveys such as tomography or seismic data acquisition (2D or 3D imaging) can detect changes in parameters such as moisture, porosity, compaction, and internal structure. A good correlation with geotechnical parameters obtained from traditional borehole investigations is needed to achieve satisfactory accuracy in these determinations. This correlation process involves comparing the geophysical data with the physical properties of the soil and rock samples obtained from the borehole investigations, thereby enhancing the reliability of the LEWS. However, these techniques are currently underused, mainly due to the economic or technical processes needed to install, analyze, and implement a LEWSs [25].

A promising geophysical technique in LEWSs uses ambient noise correlation, a seismic passive technique. This technique has robust processing (stable signal affected by only great changes), improves the time resolution to less than a day (giving the option to implement warnings before the rupture happens), and enables a better understanding of environmental fluctuations related to humidity or topographical changes [26].

3.3. Engineering Assessing Landslide Risk Reduction

Landslide Risk Reduction (LRR) consists of Exposure Reduction (ER), which is considered a form of management, and Hazard Reduction (HR), which is applied as mitigation. The former comprises educational approaches, geographical warnings, and responses to disaster events. The latter focuses on engineering elements at risk, remediating hazards, and removing elements at risk [27].

Landslide investigations must consider different approaches and multi-method information compilation techniques to achieve LRR. While surface characteristics are typically defined from field morphology mapping [28], recently using Unmanned Aerial Vehicles (UAV) and LiDAR (light detection and ranging) topography [5], geotechnical investigations and geophysical surveys are used in the definition of the inner structures, material characteristics, and hydrogeological conditions [29–31].

The factors influencing LRR in tropical countries must be understood because they are essential inputs, particularly in changing climatic conditions. These factors, including the absolute physical exposure of people to landslides and landslide-prone areas, the population size, and the country's Human Development Index (HDI), are significantly impacted by climate change. The difficult access conditions to landslide areas (vegetation and slopes), the lack of geotechnical knowledge, and the insufficient temporal information (due to reduced state budgets) can be addressed using geophysics (land and airborne methods), UAV equipment, or LiDAR [32].

Table 3 aims to summarize the assessment methods used to manage and analyze landslide risk events in soil and rock from an engineering point of view. Modelization methods implied a qualitative risk assessment where different risk grades (to assets or human safety) could be defined based on hazards and consequences. They use the Safety Factor (SF) or failure and slide displacement velocity as the main parameters. These methods imply general data observations, which could be obtained from direct surveys (boreholes and laboratory tests) and geophysical surveys as complementary information. Stress–strain methods (such as the finite element method, FEM) can be used as a quantitative risk assessment method through the definition of strains, displacements, and weak zones related to rupture, and can also be performed using the same type of data. In contrast, statistical methods need a detailed database, including other additional parameters, such as a reliability index, probability of failure, and system reliability, being, together with FEM methods, applicable to both soil and rock landslide types [1].

Table 3. Assessment methods to manage and analyze landslide risk events (based on Flentje and Chowdhury [1]).

METHOD	TECHNIQUE	MATERIAL		RISK ASSESSMENT METHODS		
		ROCK	SOIL	PARAMETER	TYPE	OBSERVATIONS
MODELIZATION	Limit equilibrium	-	X	Factor of safety	Qualitative	Based on hazards and consequences
	Rock falls	X	-	Failure and dispersion	Qualitative	Monitoring variables
	Runout flows	-	X	Reach and velocity	Qualitative	Rainfall and displacements in surface or subsurface
STRESS–STRAIN	FEM	X	X	Strain, displacements	Quantitative	Intersection of hazard, vulnerability, and exposure
STATISTIC	Probabilistic	X	X	Observational	Semi-quantitative	Need an extensive database

In material columns (-) means no applicable or not valid and (X) means is suitable or useful.

4. Analyzed Landslide Case Studies in Ecuador

Several case studies of landslides and different approaches to using geophysical surveys can be drawn from Ecuador. Five of the most relevant areas with a sustainable management focus are sequentially analyzed below (Figure 3), systematically comparing the types of geophysical surveys and their application to landslides.

For each case study, Table 4 lists the Ecuadorian province where the landslide occurred along with the year, size, damage and injuries inflicted, and geotechnical investigations performed. It is interesting to note that the first case study analyzed, La Josefina, which occurred in 1993, is a case where no in-depth studies were conducted due to its size and the urgent need to demolish the natural dam that led to the collapse of the surrounding area. The other four case studies have geophysical surveys but no direct investigations, such as boreholes.

Table 4. The most significant landslides in Ecuador reviewed (see Figure 2 for location).

Landslide Name (Province)	Size	Injuries and Damages	Investigation Applied	Geophysics
La Josefina (Azuay), 1993	Big	Properties and lives	Mapping and geophysics	VES [1]
Pujilí (Cotopaxi), 2018	Medium	Road and properties	Geophysics and mapping	Seismic [2]
Guarumales (Azuay), 2019	Small/Local	Access road damage	Geophysics	Seismic and electrical [3]
Chunchi (Chimborazo), 2021	Medium	Property and lives	Geomorphic mapping	ERT
Alausí (Chimborazo), 2023	Medium/Big	Lives and properties	Geophysics	Electrical and seismic [4]

[1]—Investigation post-landslide over the dam; [2]—HVSR and MASW; [3]—HVSR, refraction, MASW, and VES; [4]—ERT (mostly), refraction, and MASW.

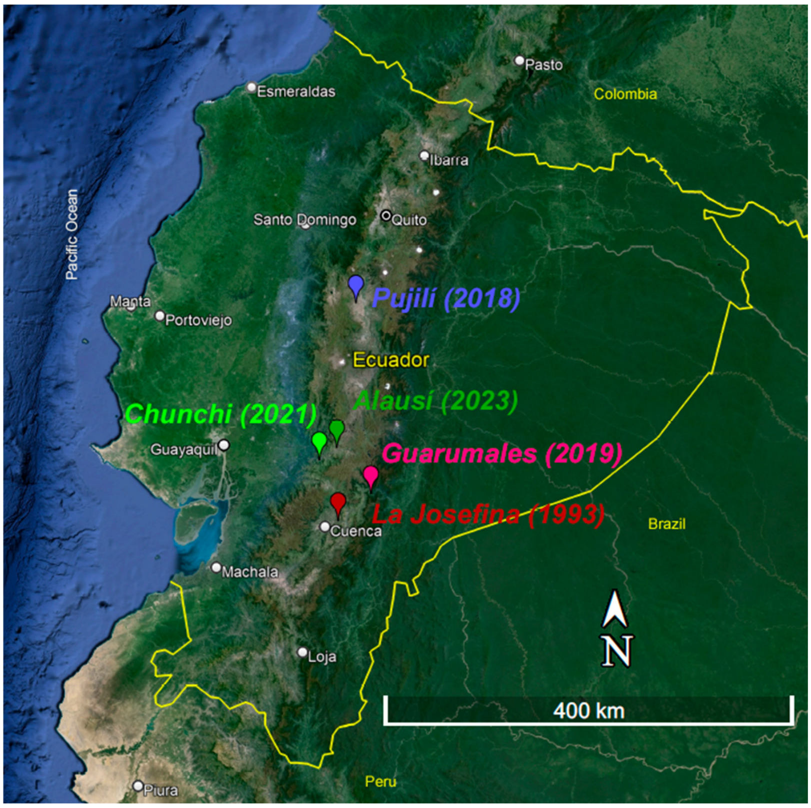

Figure 3. Analyzed locations of landslides in Ecuador (marks, the year it happened, and denominations indicated in different colors). As can be seen, all of them are located along the Andean Cordillera from the center to the South (modified from Google Earth (www.google.com/earth, 2024, accessed on 25 September 2024)).

4.1. The La Josefina Case (Azuay Province)

The La Josefina landslide is an example of how rainfall and anthropic combination have triggered a macro-landslide where the effect and consequences of the lack of investigation ended in catastrophic damage [33,34]. In 1991, three years before the landslide, several studies warned about the possibility of a landslide in the zone, but no studies, mitigation, or previous decisions were applied before the damage occurred [34,35]. The Tamuga mountainside collapsed in March 1993, creating a natural dam on the Paute River (Figure 4).

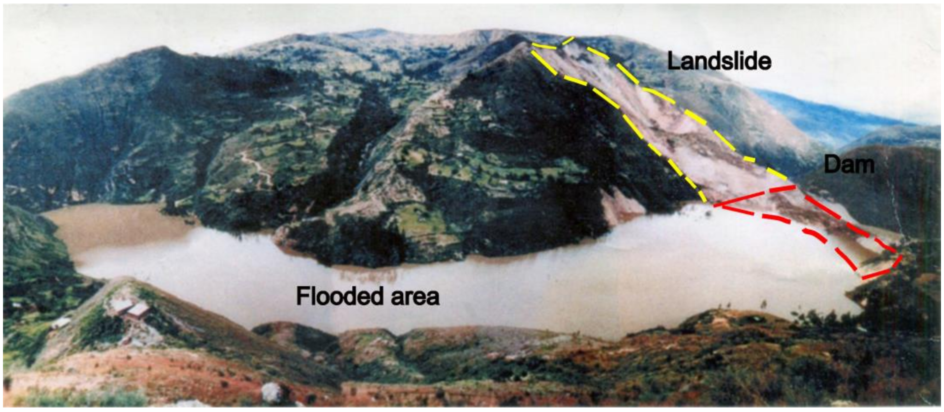

Figure 4. La Josefina landslide and its natural dam. In yellow is the landslide area; in red, the natural dam which formed upstream of the flooded area some days after the landslide was produced (modified from a municipality old picture: https://gualaceo.gob.ec/desastre-de-la-josefina/, accessed on 24 August 2024).

The urgent need to reduce the height of the material blocking the river course (the level of the flooded areas increased quickly and threatened major cities) led to the removal of the fallen sediments by the digging of an artificial spillway. The INECEL government institution performed 12 VES (and probably seismic refraction profiles, not confirmed) over the natural dam to analyze the characteristics of materials (Figure 5), but the obtained results were scarcely used, and some people considered them to be unreliable [36].

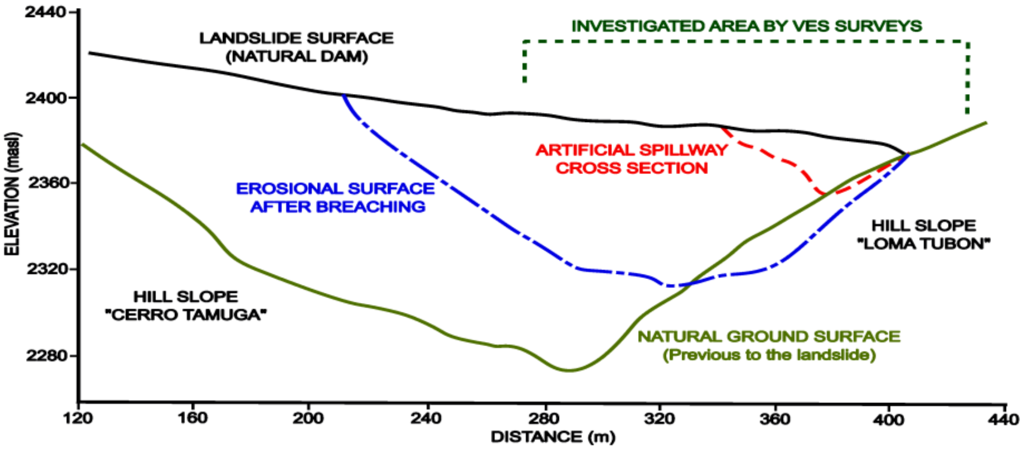

Figure 5. The Paute River valley's cross-section shows the height of the natural dam after the La Josefina landslide. The artificial spillway and the erosional surface sections after the failure are shown. Also, we indicate where the 12 VES were applied to study how the flooded water could be freed (modified from Plaza et al. [35]).

In the 1990s, geophysical surveys remained not well-developed in the country, so interpretations may not have reached the necessary accuracy [36]. Nevertheless, this is a good example of a case where the use of geophysical surveys could have provided valuable knowledge on the initial area that later slid (the landslide had two phases: the upper area moved downhill, and then the mobilized material pushed the rest of the material through the river valley), as well as two years before the event when warnings signals initiated.

Even though the landslide's size made it unstoppable, such evidence might have been used as premonitory advice and to prepare for the disaster (by issuing alerts, initiating evacuations, and establishing ready-to-act processes). As Schneider [37] indicates, there was a limitation in the linkage between hazard mitigation, community planning, and emergency management which made it impossible to successfully implement hazard mitigation strategies.

4.2. The Chunchi Case (Chimborazo Province)

In the La Armenia sector (Chunchi canton), a mass movement affecting an area of 115.35 hectares with a volume of approximately 30 million cubic meters occurred in 2021. This would later temporally dam the Picay River in the Guataxi sector, generating a flow of debris that partially destroyed the village of Chanchan (Figure 6).

Initial observations indicate that the mass movement comprised three large-magnitude landslides: two rotational slides and one mass-flow type that moved along a fault wedge [38]. The instability of the ground was mainly conditioned by the geological characteristics of the sector, where poorly consolidated soils (in the area of an old landslide) and residual soils (soil weathering) are observed. In addition, hydrogeological characteristics, i.e., the presence of groundwater, the steep slopes on the margins of the basin with marks of water erosion, the rains of 12 February 2021 (11 to 19 mm), and agricultural activities in the area, created a continuous process of the soil mass sliding [38].

In previous field trips and investigations, the National Risk and Emergency Management Service (SNGRE) evidenced the need for mitigation actions and defined the risk areas to proceed with prevention processes. Such delimitation of the slide area and the characteristics of the materials involved in the soon-to-happen landslide were performed from the application of electrical tomography surveys. In the area, six ERT profiles were performed by IIGE and SNGRE institutions (Figure 7 shows two examples) and they put in evidence the high water content, reaching the saturation at deep levels. This saturation corresponds with an aquifer with low mobility in the water (aquiclude) and faults (F1 and F2 in Figure 7) inside the body of the mobilized materials as part of the compartmentation of the landslide [38].

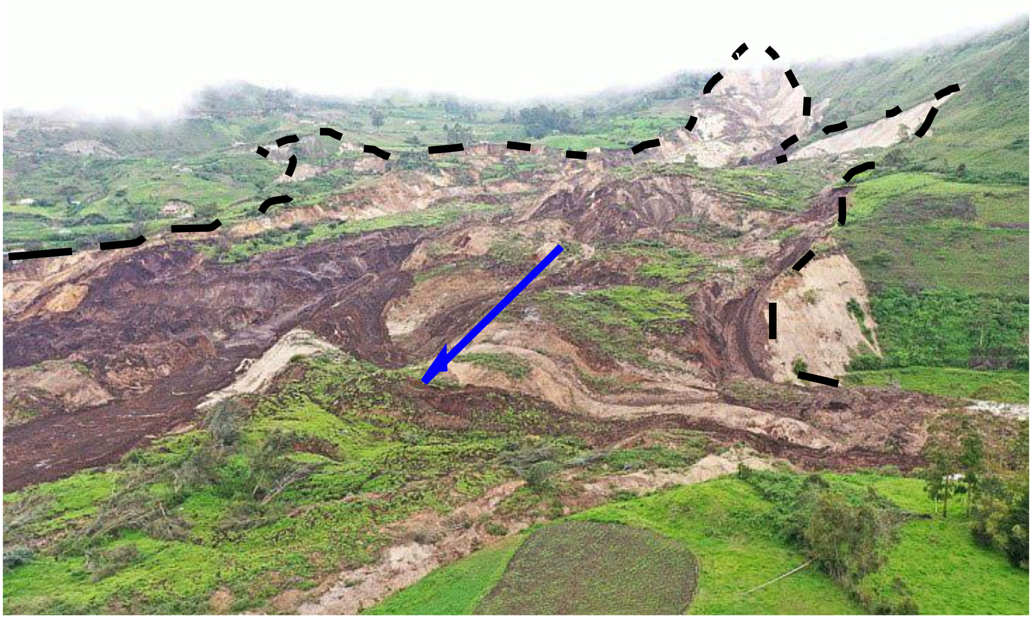

Figure 6. A general view of the Chunchi landslide (La Armenia sector). The direction (blue arrow) and delimitation of the landslide's head and the affected area are indicated as a black dashed line (modified from https://municipiochunchi.gob.ec/wp-content/uploads/2024/05/01-1.jpg, accessed on 21 September 2024).

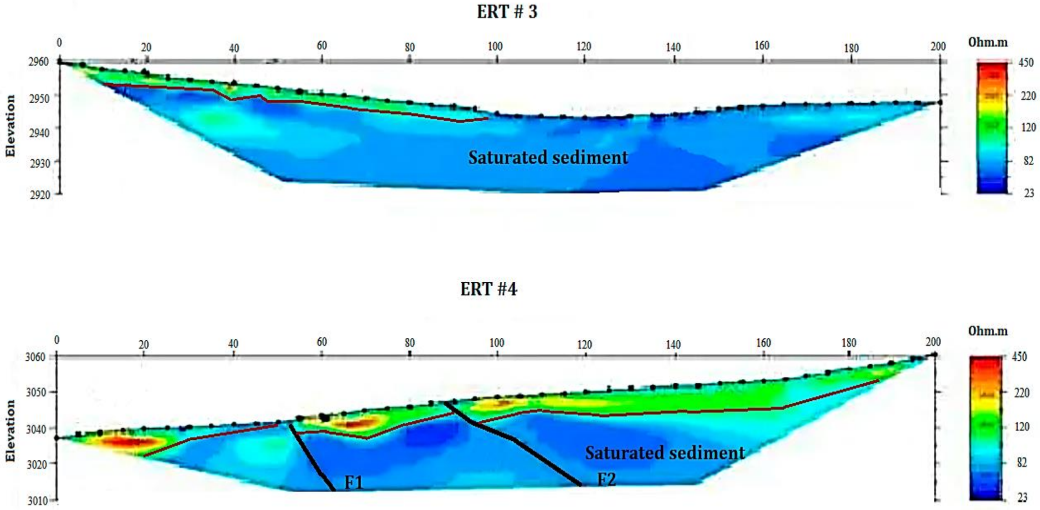

Figure 7. ERT geophysical interpretation of #3 and #4 resistivity profiles applied over the Chunchi landslide. Dotted lines show the electrode positions, and red lines delimit the shallow sediments, unsaturated, from saturated sediments. It also indicated faults that were obtained in the geophysical interpretation (F1 and F2) (modified from SNGRE [38]).

The ERT geophysical technique applied here is a source of information, including the stratigraphy and 2D or even 3D geometric distribution of materials, water content, saturation state, and geological structures (faults and discontinuities). This kind of information can also be used to define the landslide failure surface if the depth of the data reaches it [39].

4.3. The Alausí Case (Chimborazo Province)

The Alausí landslide is one of Ecuador's most recent and still-active sliding mass movements. On the evening of 23 March 2023, a landslide 380 m wide and 780 m long (with more than 125 thousand cubic meters of soil) affected the Alausí village (Chimborazo province). According to official reports from the SNGR [40], the landslide has buried more than 161 homes, leaving 65 people dead, 10 missing, 44 injured, and more than 800 affected [41] (see Figure 8).

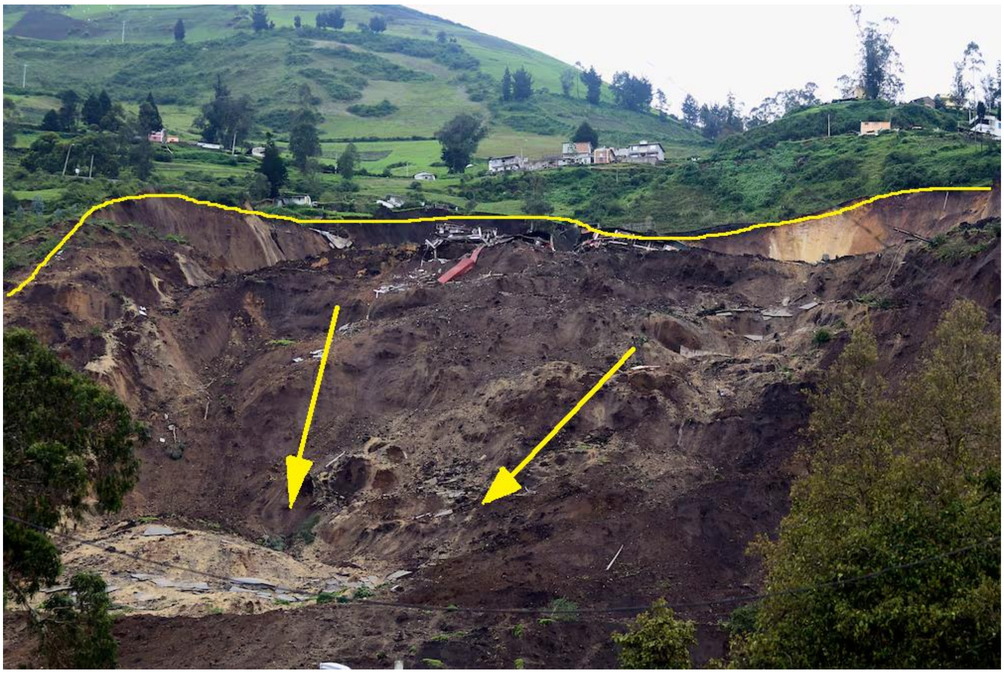

Figure 8. A view from the West of the 2023 Alausí landslide, one of the biggest and most mortiferous landslides in the last years in Ecuador (yellow line indicates the landslide head and arrows the movement) (modified from https://www.eluniverso.com/noticias/ecuador/quito-deslizamientos-inundaciones-epoca-lluviosa-ecuador-nota/, accessed on 2 July 2024).

Several months before the event happened, some cracks were observed in the area, particularly on the national road E-35. The rainy days and the possible interaction of an earthquake five days before the landslide were the most probable causes of the ground failure [41–44].

The investigation of the landslide area before and after the event was performed by the Geological and Energy Research Institute (IIGE) and SNGRE [44]. Two electric tomography profiles were applied before the failure, and six more were applied afterward. The MASW seismic technique was also used to separate the mobilized material from the static one (Figure 9A). The geophysical results provided information about the sediment layer deposited (up to 45 m thick) and the characteristics of the soil resistivity of the bottom along the longitudinal ERT-1 profile (Figure 9A). A reinterpretation of the geophysical data is made in the present work by the authors (Figure 9B), also delineating the altered layer of soil (in situ saprolite) and the probable presence of a fault with saturation.

The surroundings of the landslide continue to be unstable. A FIGEMPA Faculty of the Universidad Central del Ecuador team is still working on analyzing new prone-to-slide areas based on topographical measures and geological data [42].

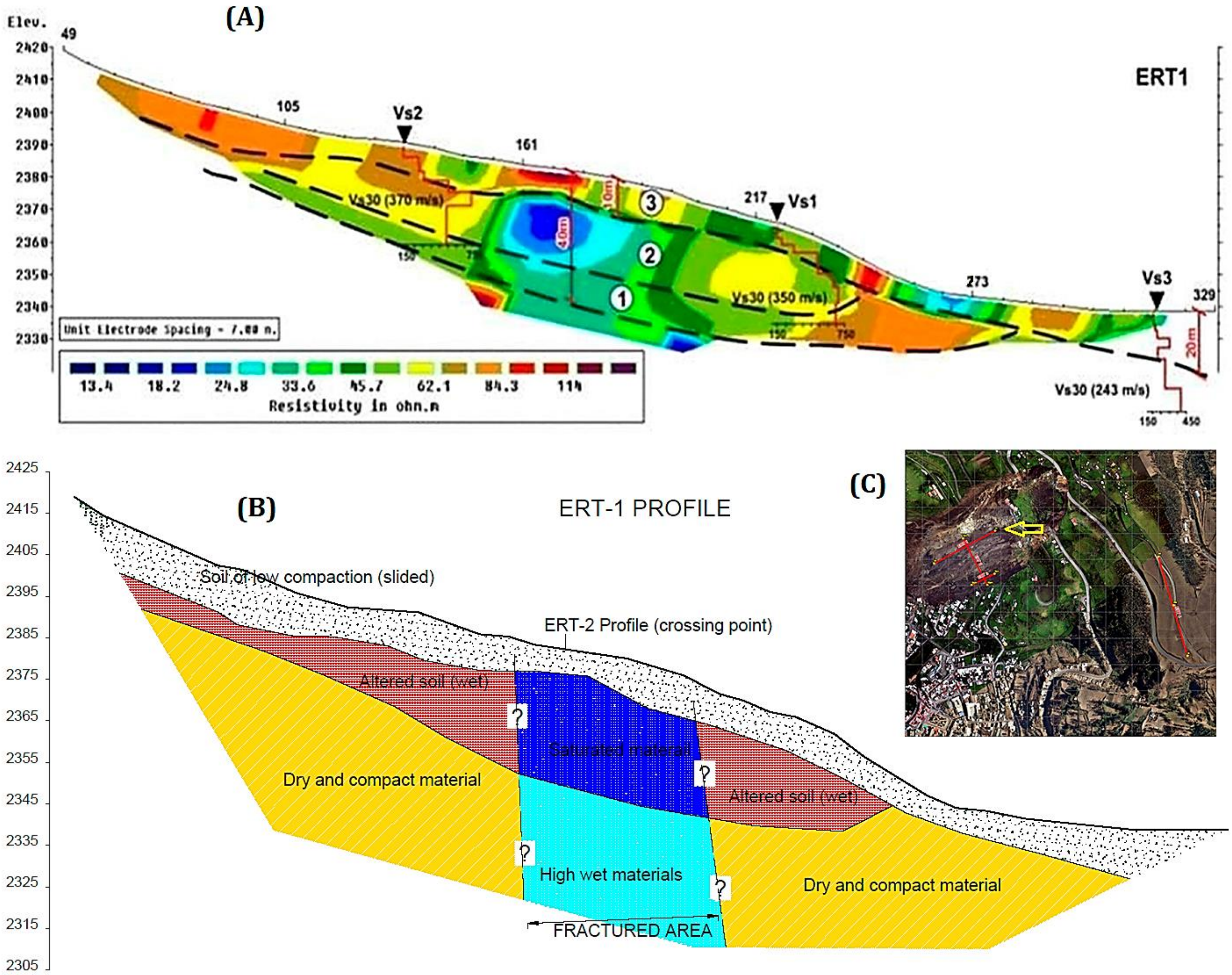

Figure 9. ERT-1 profile performed along the longitudinal section of the Alausí landslide: (**A**) original interpretation of resistivity geophysical data included in the SNGRE (2023) inform, where MASW survey results are superimposed in the section (Vs. 1 to Vs. 3 positions marked by inverted black triangles) V_{s30} values are indicated at every surveyed point, and numbers indicated the defined geophysical levels; (**B**) new geological interpretation made in the present work of the previous ERT profile to clarify the geophysical results (vertical scale doubled); (**C**) location of this profile (red line pointed by a yellow arrow) on an aerial view of the 2023 Alausí landslide where three more profiles location are indicated (red lines) ((**A**,**C**) pictures were modified from SNGRE and IIGE [44]).

4.4. The Guarumales Case (Azuay Province)

The area around the Guarumales village (Azuay province) has experienced various landslides affecting infrastructure, such as roads and hydroelectric dams. These landslides were triggered by the rainy climate with increasing time precipitations on a steeped mountain flank environment with more than 40° inclination [15].

One of the landslides at Guarumales was investigated by the authors, who applied a combination of geophysical techniques, particularly seismic and electric methods [22]. Even though the landslide study was small, it had a transcendental value because the affected road was the only way to access a hydroelectrical machine building.

After an initial release of materials and an urgent remediation action (Figure 10A), the landslide continued its movement, and a detailed investigation was necessary. The work focused on defining the landslide failure surface, a challenging task due to its continuous movement and the loose and falling stones. Only geophysical surveys were used for this purpose. Figure 10B shows the obtained longitudinal geologic section along the maximum slope of the landslide. By performing the VES test, the delimitation of the rocky basement (thickness of sediments) and water saturation conditions was achieved, while seismic refraction and MASW techniques enabled the establishment of V_p and vs. seismic velocity values, and an HVSR single station passive seismic survey (Figure 11) was able to delimitate and set the failure surface [22].

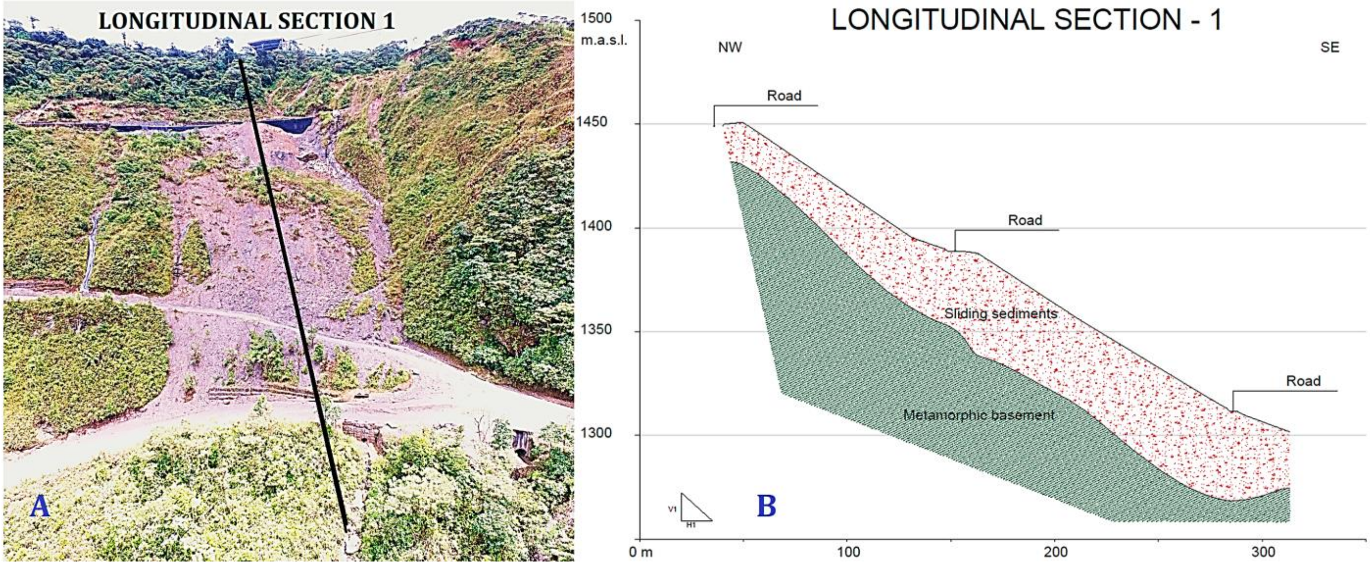

Figure 10. The Guarumales landslide analyzed: (**A**) frontal view with longitudinal section indicated; (**B**) geological interpretation of the longitudinal section, showing the thickness of sliding sediments over the metamorphic basement (modified from Alonso-Pandavenes et al. [22]).

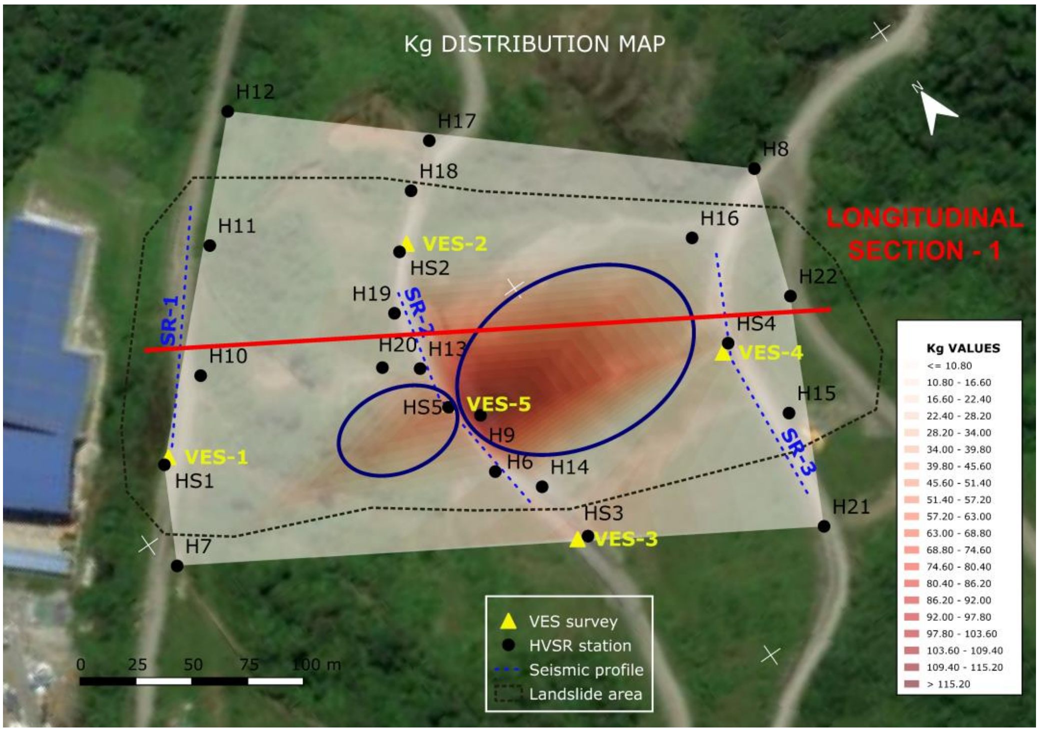

Figure 11. K_g vulnerability index [45] distribution map in the Guarumales landslide. The dark blue ellipses at the center of the landslide indicated two areas prone to movement (white crosses indicated the coordinate system). The position of the longitudinal section shown in Figure 9 is displayed in red (modified from Alonso-Pandavenes et al. [22]).

This methodology, which has never been applied before in Ecuador, implied the empirical correlation between sediment thickness and ground natural frequency (f_o) to define a formulation that can be extended all around the investigated area. In this situation, it is only necessary to obtain the f_o value from the HVSR tests. This geophysical technique is easy, quick, and economical. Measures obtained by this technique can be also used in time series analysis as a monitoring process, where the robustness of HVSR signals might better indicate previous movement than precipitation analysis [26].

Moreover, the HVSR K_g vulnerability index defined by Nakamura [45] (relation between the A_o amplification and the f_0 natural frequency) was validated as a valuable tool in the determination of prone-to-landslide areas (Figure 11) in the determination of ground shear strain areas. Identifying two zones with the highest values (up to 30) where the movement continued and needed new mitigation actions was possible [22].

4.5. The Pujilí Case (Cotopaxi Province)

The Pujilí canton and surrounding areas are prone to landslide events, with more than 40 potential zones suffering a mass movement. The Cangahua Formation, a recent volcanic sedimentary hard soil, overlays a Paleozoic basement in this area. These types of materials are easily weathered at shallow levels, leading to a high susceptibility to slide [46].

Near Cachi Alto village, over a small landslide located inside a big one (Figure 12), partially stable, the authors performed an investigation using natural vibration of the ground measured by HVSR surveys as a first technique [47]. More than 80 single stations were performed to delimitate the mobilized materials from the static ones. The soft sediment thickness was computed from the ground natural frequency (f_o) and the sediment's shear-wave velocity, averaged over the whole sedimentary soft material above the static materials considered as the basement, by applying the formulation shown in Nakamura [45]. The shear-wave velocity was obtained using the MASW seismic technique, which can be applied to every measured HVSR point (Figure 13A). In this case study, the failure surface was obtained from three methodologies based on the geophysical surveys performed. The differences between them were established as minimum values (Figure 13B).

Figure 13A shows a complementary analysis of the directivity of HVSR signals. This enables the establishment of the direction of the movement of every block in the landslide and also sets the internal cracks that section the mobilized mass (the blue arrows in Figure 13A). The statistical analysis of those directivities in the frequency of appearance gives the direction and sense of the motion (rose diagram in Figure 13A) and also defines new areas that are prone to slide by applying the same K_g parameter that was used in the previous case study [47].

Figure 12. A panoramic lateral view of the Pujilí landslide taken from the right flank shows the scarp failure at the center of the picture (movement from left to right, arrow). In the bottom-right corner of the picture, the HVSR geophysical equipment is placed for survey.

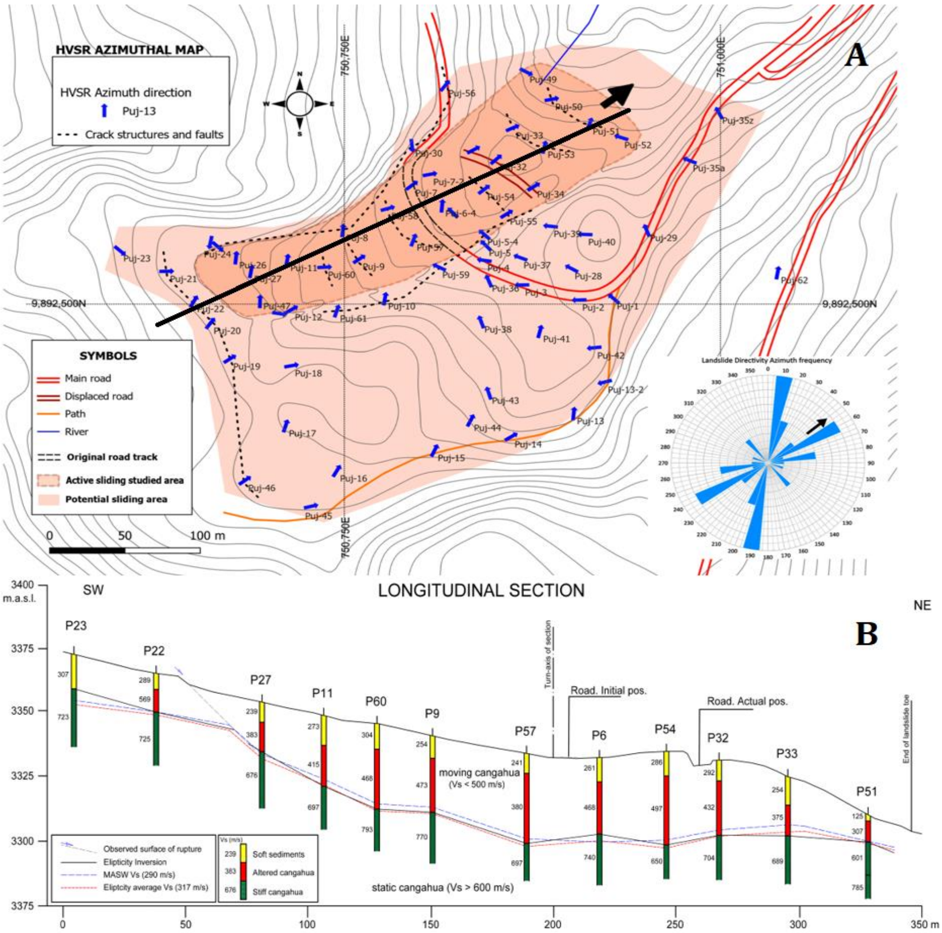

Figure 13. Pujilí landslide analysis: (**A**) azimuthal sense of the directivity analysis of HVSR surveys (blue arrows) and rose diagram of direction frequency values; (**B**) interpreted longitudinal section over the black line in (**A**) with failure surfaces interpretation (black arrows show the movement direction) (modified from Alonso-Pandavenes et al. [47]).

5. Discussion

The surficial geology of Ecuador is dominated by volcano-sedimentary sediments from recent geomorphological events (eruptions, erosion, and fluvial processes). These materials can develop a great soft thickness overburden that is prone to weathering and which alters their geotechnical properties. In addition, the two climate seasons (rainy and drought), exacerbated by global climate change, have modified the static stability of these geological materials in the topography of high steep slopes [13,15,46].

The use of integrated techniques involving geophysical surveys has been demonstrated to accurately define the failure surface. In the Loja basin, a multi-method approach using geotechnical and mineralogical parameters and rain time series identified smectites and their expansivity as conditional factors in mobilization. These delineate the low-rate slide materials with the support of ERT profiles [48]. The Pujilí landslide [47] is another example of the use of basic geotechnical parameters supporting and constraining geophysical modeling. In that case, seismic active and passive techniques were combined to set the failure surface using three different approaches.

In difficult-to-access locations with geology where geophysical investigation can be challenging to apply, area uprising techniques such as Differential Interferometry Synthetic Aperture Radar (DInSAR) are helpful tools for performing analysis of real-time series and applying a LEWS to preserve infrastructures and lives [49]. This type of monitoring can be also implemented by other geophysical techniques or used for the identification of sliding-prone areas using the vulnerability index (K_g) as an indication of hazardous areas [22].

In the last few years, investigations and studies in different cases developed in Ecuador were conducted using other approaches related to geophysical measures, although these were noted and considered here. These new techniques are related to telemetry, i.e., taking measurements from space or over the Earth's surface, and involve the use of:

- Remotely Piloted Aircraft Systems (RPAS): Photogrammetric techniques were applied to study and characterize landslides in Ecuador to characterize and analyze landslide evolution in intramountain areas [50,51].
- Unmanned Aerial Vehicle—Structure from Motion (UAV-SFM): 4D mapping was used to study and monitor landslides in Ecuador and also to monitor landslides in steep terraced agricultural areas, providing valuable insights for early warning systems [52,53].
- Geographic Information Systems (GISs) and Remote Sensing: Both technologies have been integrated to identify micro-scale landforms of landslides and monitor landslide dynamics [50].

Integrating those techniques and their data with other geospatial and environmental data, especially complemented by detailed studies such as boreholes and surface-applied geophysical surveys, enables practitioners to gain a more comprehensive understanding of landslide dynamics. Thus, a more effective risk management strategy is expected to be developed in the future [29].

To address the sustainable management of landslides in Ecuador, an approach that adopts and incorporates strategies from long and short-term planning is necessary. The last lines of investigation must incorporate the new approaches in LEWSs and monitoring through geophysical technique applications, which can produce valuable information in maintenance or mitigation strategies. These inputs must be used as tools to translate land use planning to improve infrastructure and building conditions in considering the risks and hazards affecting these zones. This will result in the development and growth of communities and the expansion of cities.

In addition, local communities must be involved in these actions and activities. Installing monitoring or recurrent measures in controlling landslide risk areas is an important way to engage local communities with government activities, incorporate them into education processes (schools, colleges, and people), and share knowledge of how to live with disaster events.

Resilience is fundamental for social sustainability and enabling communities to cope with disasters. It is related to technical knowledge, which comes from geotechnical studies and geophysical data as primary sources of information and investigation. This also permits communities to adapt and plan for changing conditions.

The Andean Cordillera that crosses Ecuador is experiencing an increasing number of landslides that demand deep engagement from scientific and policy approaches. The design and implementation of policies and mitigation strategies need specific local adaptations but face a complicated situation where political cycles, institutional gaps, and informal land use affect the correct application. Moreover, the uncertainty of a changing climate (considered globally but especially intense locally) means that local adaptation capacity needs to be increased [54].

6. Conclusions

The most recent landslides that affected the Ecuadorian territory and their losses (including lives) pose a significant threat to be faced by the government. Adopting new sustainable management approaches, where geophysical surveys are a fundamental tool for investigating and mitigating their impact, is one way to reduce risk and increase resilience in the next few years.

Including various geophysical techniques in combination with the aerial and/or terrestrial methods in implementing LEWSs, or using them to strengthen the foundations of infrastructure and buildings, is a novel and useful application.

Advanced technologies such as RPAS photogrammetric products, UAV-Structure from Motion (SfM) 4D mapping, GIS, and remote sensing can provide valuable insights and support effective risk management strategies. These aerial methods must be confirmed and specified accurately by applying terrestrial techniques such as direct borehole studies and geophysical surveys.

Technical, social, and economic considerations must be integrated into the approach to the sustainable management of landslides. By leveraging geophysical surveys, the reduction in risk and the impact of the landslides can be achieved, including community engagement, infrastructure development, monitoring and maintenance, and the economic and environmental considerations of communities. At the same time, natural ecosystems are preserved and social sustainability is promoted. Thus, Ecuador can reduce the landslide risk and increase the safety and well-being of its population through geophysical surveys.

Sustainable landslide management in Ecuador must be addressed by a multifaceted approach that combines improving models and achieving greater accuracy with land use strategies and mitigation processes. This can be achieved by applying traditional geophysical techniques (ERT, refraction seismic, VES, or GPR) with emerging ones (DInSAR, HVSR, or RPAS-based) as sources of knowledge that complement the direct data (boreholes and laboratory tests) or allow continuous monitoring of moving masses. Most of these techniques, whether combined or isolated, have been implemented in landslide investigations in Ecuador, evidencing that they can improve hazard characterization, lead to mitigation solutions, and promote community awareness for greater safety and resilience when facing these natural events.

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References

1. Flentje, P.; Chowdhury, R. Resilience and Sustainability in the Management of Landslides. *Proc. Inst. Civ. Eng.—Eng. Sustain.* **2018**, *171*, 3–14. [CrossRef]
2. Azadi, H.; Petrescu, D.C.; Petrescu-Mag, R.M.; Ozunu, A. Special Issue: Environmental Risk Mitigation for Sustainable Land Use Development. *Land Use Policy* **2020**, *95*, 104488. [CrossRef]
3. Jongmans, D.; Garambois, S. Geophysical Investigation of Landslides: A Review. *Bull. Société Géologique Fr.* **2007**, *178*, 101–112. [CrossRef]
4. Pazzi, V.; Morelli, S.; Fanti, R. A Review of the Advantages and Limitations of Geophysical Investigations in Landslide Studies. *Int. J. Geophys.* **2019**, *2019*, 2983087. [CrossRef]
5. Hussain, Y.; Schlögel, R.; Innocenti, A.; Hamza, O.; Iannucci, R.; Martino, S.; Havenith, H.-B. Review on the Geophysical and UAV-Based Methods Applied to Landslides. *Remote Sens.* **2022**, *14*, 4564. [CrossRef]
6. Alonso-Pandavenes, O.; Torres, G.; Torrijo, F.J.; Garzón-Roca, J. Basement Tectonic Structure and Sediment Thickness of a Valley Defined Using HVSR Geophysical Investigation, Azuela Valley, Ecuador. *Bull. Eng. Geol. Environ.* **2022**, *81*, 210. [CrossRef]
7. Alonso-Pandavenes, O.; Andrade-Mendoza, C.; Torrijo-Echarri, F.J. La Investigación Geofísica En Los Estudios de Balsas de Relaves: Su Aplicación e Inclusión En El ACUERDO Nro. MERNNR-MERNNR-2020-0043-AM de La República de Ecuador. *Figempa* **2023**, *16*, 39–57. [CrossRef]

8. Alonso Pandavenes, O. Técnicas de sísmica pasiva HVSR aplicadas a la geotecnia. Aplicación al estudio de Movimientos en Masa en la Planificación Territorial e Infraestructura Civil en Ecuador. Ph.D. Thesis, Universitat Politècnica de València. Escuela Técnica Superior de Ingenieros de Caminos, Canales y Puertos, Valencia, Spain, 2024.
9. Blodgett, T.A.; Blizard, C.; Isacks, B.L. Andean Landslide Hazards. In *Geomorphological Hazards in High Mountain Areas*; Kalvoda, J., Rosenfeld, C.L., Eds.; The GeoJournal Library; Springer: Dordrecht, The Netherlands, 1998; Volume 46, pp. 211–227, ISBN 978-94-010-6200-8.
10. Delgado, F.; Zerathe, S.; Schwartz, S.; Mathieux, B.; Benavente, C. Inventory of Large Landslides along the Central Western Andes (ca. 15°–20° S): Landslide Distribution Patterns and Insights on Controlling Factors. *J. South Am. Earth Sci.* **2022**, *116*, 103824. [CrossRef]
11. Cobos-Mora, S.L.; Rodriguez-Galiano, V.; Lima, A. Analysis of Landslide Explicative Factors and Susceptibility Mapping in an Andean Context: The Case of Azuay Province (Ecuador). *Heliyon* **2023**, *9*, e20170. [CrossRef]
12. SENPLADES Plan Nacional para el Buen Vivir 2017–2021. 2017. Available online: https://www.gobiernoelectronico.gob.ec/wp-content/uploads/downloads/2017/09/Plan-Nacional-para-el-Buen-Vivir-2017-2021.pdf (accessed on 22 September 2024).
13. Aspden, J.A.; Litherland, M. The Geology and Mesozoic Collisional History of the Cordillera Real, Ecuador. *Tectonophysics* **1992**, *205*, 187–204. [CrossRef]
14. Coltorti, M.; Ollier, C.D. Geomorphic and Tectonic Evolution of the Ecuadorian Andes. *Geomorphology* **2000**, *32*, 1–19. [CrossRef]
15. Urgilez Vinueza, A.; Robles, J.; Bakker, M.; Guzman, P.; Bogaard, T. Characterization and Hydrological Analysis of the Guarumales Deep-Seated Landslide in the Tropical Ecuadorian Andes. *Geosciences* **2020**, *10*, 267. [CrossRef]
16. Troncoso, L.; Torrijo, F.J.; Ibadango, E.; Pilatasig, L.; Alonso-Pandavenes, O.; Mateus, A.; Solano, S.; Cañar, R.; Rondal, N.; Viteri, F. Analysis of the Impact Area of the 2022 El Tejado Ravine Mudflow (Quito, Ecuador) from the Sedimentological and the Published Multimedia Documents Approach. *GeoHazards* **2024**, *5*, 596–620. [CrossRef]
17. Álvarez Encalada, S.I. Análisis del macro deslizamiento suscitado en la comunidad La Cría del cantón Santa Isabel, provincia de Azuay. Master's Thesis, Pontificia Universidad Católica del Ecuador, Portoviejo, Manabí, Ecuador, 2024.
18. Román-Herrera, J.C.; Rodríguez-Peces, M.J.; Garzón-Roca, J. Comparison between Machine Learning and Physical Mo-dels Applied to the Evaluation of Co-Seismic Landslide Hazard. *Appl. Sci.* **2023**, *13*, 8285. [CrossRef]
19. Auflič, M.J.; Herrera, G.; Mateos, R.M.; Poyiadji, E.; Quental, L.; Severine, B.; Peternel, T.; Podolszki, L.; Calcaterra, S.; Kociu, A.; et al. Landslide Monitoring Techniques in the Geological Surveys of Europe. *Landslides* **2023**, *20*, 951–965. [CrossRef]
20. Tibaldi, A.; Ferrari, L.; Pasquarè, G. Landslides Triggered by Earthquakes and Their Relations with Faults and Mountain Slope Geometry: An Example from Ecuador. *Geomorphology* **1995**, *11*, 215–226. [CrossRef]
21. Anderson, M.G.; Holcombe, L. Sustainable Landslide Risk Reduction in Poorer Countries. *Proc. Inst. Civ. Eng.—Eng. Sustain.* **2006**, *159*, 23–30. [CrossRef]
22. Alonso-Pandavenes, O.; Torrijo, F.J.; Garzón-Roca, J.; Gracia, A. Early Investigation of a Landslide Sliding Surface by HVSR and VES Geophysical Techniques Combined, a Case Study in Guarumales (Ecuador). *Appl. Sci.* **2023**, *13*, 1023. [CrossRef]
23. Bell, R.; Kruse, J.-E.; Garcia, A.; Glade, T.; Hördt, A. Subsurface Investigations of Landslides Using Geophysical Methods: Geoelectrical Applications in the Swabian Alb (Germany). *Geogr. Helv.* **2006**, *61*, 201–208. [CrossRef]
24. León Gómez, A.M.; Tijera Carrión, A.; Ruiz Bravo, R. Utilización de Técnicas Geofísicas En La Identificación de Deslizamientos de Ladera. *CEDEX Ing. Civ.* **2014**, *175*, 39–51.
25. Whiteley, J.S.; Watlet, A.; Kendall, J.M.; Chambers, J.E. Brief Communication: The Role of Geophysical Imaging in Local Landslide Early Warning Systems. *Nat. Hazards Earth Syst. Sci.* **2021**, *21*, 3863–3871. [CrossRef]
26. Le Breton, M.; Bontemps, N.; Guillemot, A.; Baillet, L.; Larose, É. Landslide Monitoring Using Seismic Ambient Noise Correlation: Challenges and Applications. *Earth-Sci. Rev.* **2021**, *216*, 103518. [CrossRef]
27. Winter, M.G. A Strategic Approach to Landslide Risk Reduction. *Int. J. Landslide Environ.* **2014**, *2*, 14–23.
28. Travelletti, J.; Malet, J.-P. Characterization of the 3D Geometry of Flow-like Landslides: A Methodology Based on the Integration of Heterogeneous Multi-Source Data. *Eng. Geol.* **2012**, *128*, 30–48. [CrossRef]
29. Lissak, C.; Bartsch, A.; De Michele, M.; Gomez, C.; Maquaire, O.; Raucoules, D.; Roulland, T. Remote Sensing for Assessing Landslides and Associated Hazards. *Surv Geophys* **2020**, *41*, 1391–1435. [CrossRef]
30. Fressard, M.; Maquaire, O.; Thiery, Y.; Davidson, R.; Lissak, C. Multi-Method Characterisation of an Active Landslide: Case Study in the Pays d'Auge Plateau (Normandy, France). *Geomorphology* **2016**, *270*, 22–39. [CrossRef]
31. Cance, A.; Thiery, Y.; Fressard, M.; Vandromme, R.; Maquire, O.; Reid, M.E.; Mergili, M. Influence of complex slope hydrogeology on landslide susceptibility assessment: The case of the Pays d'Auge (Normandy, France). In Proceedings of the Journées Aléas Gravitaires, Besançon, France, 24 October 2017; p. 1.
32. Thiery, Y.; Kaonga, H.; Mtumbuka, H.; Terrier, M.; Rohmer, J. Landslide Hazard Assessment and Mapping at National Scale for Malawi. *J. Afr. Earth Sci.* **2024**, *212*, 105187. [CrossRef]
33. Zevallos, O. Lecciones del Deslizamiento "La Josefina"—Ecuador. In Proceedings of the Sistema Nacional para la prevención y atención de desastres de Colombia, Cartagena de Indias, Colombia, 21–24 March 1994; Volume A-09, p. 14.
34. Harden, C. Sediment Movement and Catastrophic Events: The 1993 Rockslide at La Josefina, Ecuador. *Phys. Geogr.* **2001**, *22*, 305–320. [CrossRef]

35. Plaza, G.; Zevallos, O.; Cadier, É. La Josefina Landslide Dam and Its Catastrophic Breaching in the Andean Region of Ecuador. In *Natural and Artificial Rockslide Dams*; Evans, S.G., Hermanns, R.L., Strom, A., Scarascia-Mugnozza, G., Eds.; Lecture Notes in Earth Sciences; Springer: Berlin/Heidelberg, Germany, 2011; Volume 133, pp. 389–406, ISBN 978-3-642-04763-3.
36. Plaza, G.; Zevallos, O. La Josefina: Lecciones aprendidas en Ecuador. *Desastres Soc.* **1994**, *3*, 17.
37. Schneider, R.O. Hazard Mitigation and Sustainable Community Development. *Disaster Prev. Manag. Int. J.* **2002**, *11*, 141–147. [CrossRef]
38. SNGRE. *Análisis de nuevas grietas. Cantón Chunchi. Informe Técnico No SNGRE-IASR-08-2021-036*; Servicio Nacional de Gestión de Riesgos y Emergencias: Quito, Ecuador, 2021.
39. Perrone, A.; Lapenna, V.; Piscitelli, S. Electrical Resistivity Tomography Technique for Landslide Investigation: A Review. *Earth-Sci. Rev.* **2014**, *135*, 65–82. [CrossRef]
40. SNGRE Deslizamiento Casual-Alausí. *Informe de Situación No 98 (7/11/2023)*; Servicio Nacional de Gestion de Riesgos y Emergencias: Quito, Ecuador, 2023; p. 7. Available online: https://www.gestionderiesgos.gob.ec/wp-content/uploads/2023/11/SITREP-Nro.-98-Deslizamiento-Alausi-31102023-15h00-revf.pdf (accessed on 22 September 2024).
41. Veloz-Cherrez, D.; Ojeda, M.; Moreno, D.; Del Pozo, J. Susceptibility to Translational Landslides in Ecuador Caused by Changes in Electrical Permittivity of Andepts Soils Using Software-Defined Radar for Detection. *Earth* **2024**, *5*, 670–689. [CrossRef]
42. Pilatasig, L.; Ibadango, E.; Troncoso, L.; Mateus, A.; Alulema, R.; Alonso Pandavenes, O. *Evaluación del deslizamiento Casual Nuevo Alausí y su Zona de Influencia*; FIGEMPA—Universidad Central del Ecuador: Quito, Ecuador, 2023; p. 25.
43. IG-EPN. *Observaciones sobre el deslizamiento del 26 de marzo del 2023 en Alausí (Provincia de Chimborazo)*; Instituto Geofísico de la Escuela Politécnica Nacional: Quito, Ecuador, 2023; p. 22.
44. SNGRE; IIGE Instituto de Investigación Geológico y Energético. *Estudio Geológico-Geofísico para generación de datos para estabilidad del deslizamiento de Alausí 26.03.32023*; SNGRE-IIGE: Quito, Ecuador, 2023; p. 46.
45. Nakamura, Y. A Method for Dynamic Characteristics Estimation of Subsurface Using Microtremor on the Ground Surface. *Q. Rep. Railw. Tech. Res.* **1989**, *30*, 25–33.
46. Pilatasig, L.; Bustillos, J.; Jácome, F.; Mariño, D. Evaluación de la Actividad de los Movimientos en Masa de Cachi Alto-Pujilí, Ecuador Mediante Monitoreo Instrumental de Bajo Costo. *Rev. Politécnica* **2022**, *49*, 19–30. [CrossRef]
47. Alonso-Pandavenes, O.; Bernal, D.; Torrijo, F.J.; Garzón-Roca, J. A Comparative Analysis for Defining the Sliding Surface and Internal Structure in an Active Landslide Using the HVSR Passive Geophysical Technique in Pujilí (Cotopaxi), Ecuador. *Land* **2023**, *12*, 961. [CrossRef]
48. Soto, J.; Galve, J.P.; Palenzuela, J.A.; Azañón, J.M.; Tamay, J.; Irigaray, C. A Multi-Method Approach for the Characterization of Landslides in an Intramontane Basin in the Andes (Loja, Ecuador). *Landslides* **2017**, *14*, 1929–1947. [CrossRef]
49. Miele, P.; Di Napoli, M.; Guerriero, L.; Ramondini, M.; Sellers, C.; Annibali Corona, M.; Di Martire, D. Landslide Awareness System (LAwS) to Increase the Resilience and Safety of Transport Infrastructure: The Case Study of Pan-American Highway (Cuenca–Ecuador). *Remote Sens.* **2021**, *13*, 1564. [CrossRef]
50. Zárate, B.A.; El Hamdouni, R.; Fernández, T. GNSS and RPAS Integration Techniques for Studying Landslide Dynamics: Application to the Areas of Victoria and Colinas Lojanas, (Loja, Ecuador). *Remote Sens.* **2021**, *13*, 3496. [CrossRef]
51. Zárate, B.A.; El Hamdouni, R.; Fernández Del Castillo, T. Characterization and Analysis of Landslide Evolution in Intramountain Areas in Loja (Ecuador) Using RPAS Photogrammetric Products. *Remote Sens.* **2023**, *15*, 3860. [CrossRef]
52. Mauri, L.; Straffelini, E.; Cucchiaro, S.; Tarolli, P. UAV-SfM 4D Mapping of Landslides Activated in a Steep Terraced Agricultural Area. *J. Agric. Eng.* **2021**, *52*. [CrossRef]
53. Mauri, L.; Cucchiaro, S.; Grigolato, S.; Dalla Fontana, G.; Tarolli, P. Evaluating the Interaction between Snowmelt Runoff and Road in the Occurrence of Hillslope Instabilities Affecting a Landslide-Prone Mountain Basin: A Multi-Modeling Approach. *J. Hydrol.* **2022**, *612*, 128200. [CrossRef]
54. Puente-Sotomayor, F.; Egas, A.; Teller, J. Land Policies for Landslide Risk Reduction in Andean Cities. *Habitat Int.* **2021**, *107*, 102298. [CrossRef]