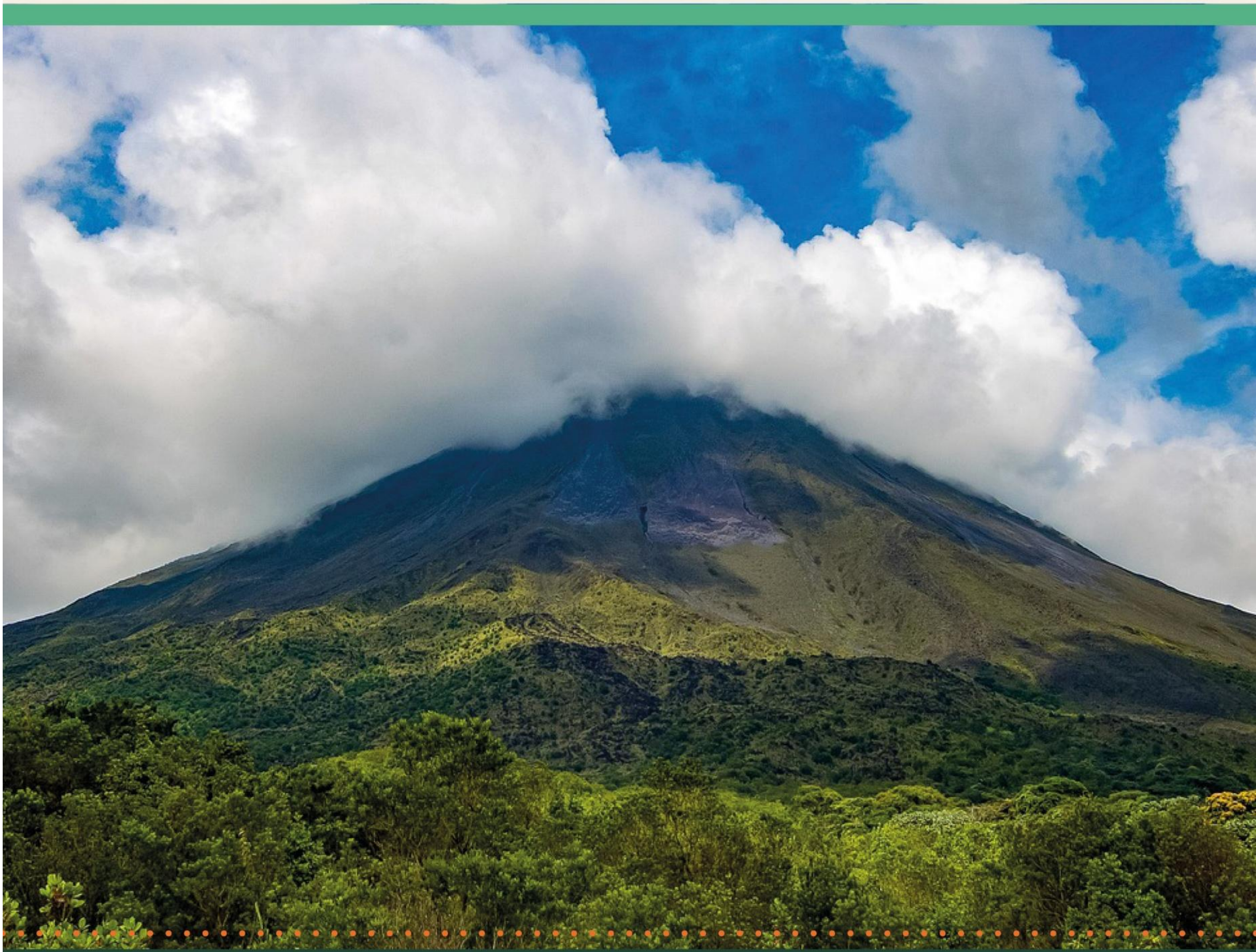

Risk Assessment and Capacity Development in Costa Rica

Review of Existing Geological Hazard Data and Models and Recommendations for Risk Assessment

April 2025

Prepared for:

Global Risk Modelling Alliance

SUGESE Superintendencia General de Seguros

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CONTENT

1 INTRODUCTION

The Global Risk Modelling Alliance (GRMA) program, sponsored by the InsuResilience Solutions Fund (ISF), has the primary objective of strengthening the capacity of countries and cities in climate and disaster risk analysis for financial purposes. This initiative seeks to fill critical gaps in models and data, enhancing climate and disaster risk assessments at the national and subnational levels.

In the case of Costa Rica, GRMA identified and co-defined, together with local partners, the specific needs of the country in order to offer open tools for risk management, as well as data and access to operational expertise in risk financing.

This report presents the results of the review of existing data and models related to geological hazards, along with recommendations for their use and application in the risk assessments foreseen within the framework of the project—Task 3 of the Terms of Reference. It describes the types of information available, and the models used for generating hazard maps related to landslides, volcanic eruptions, and earthquakes in Costa Rica, which may be useful or suitable for probabilistic risk assessment. This document corresponds to deliverables 3.1.a, 3.1.b, 3.1.c, 3.2.a, 3.2.b, 3.2.c, 3.3.a, 3.3.b, and 3.3.c of the Terms of Reference, which aim, where possible, to make use of existing data, maps, and models—specifically in the case of geohazards—that have been previously applied in similar assessments in Costa Rica.

The Inception Report for this consultancy provided a general overview of hazard and risk studies conducted in Costa Rica, mainly over the past two decades. The report noted that while some of these studies have adopted a probabilistic approach, they are generally the exception. Most hazard assessments have been qualitative in nature, using categories such as high, medium, and low, and have had little or no practical relevance for risk studies, which, in turn, have been virtually non-existent.

Nevertheless, it is important to highlight that the information generated over the years, through various academic or institutional, national or international initiatives, represents a valuable asset for the country, even if it cannot be directly used for probabilistic risk assessment.

For the purposes of this project, it is important to emphasize that the resolution and completeness of the available information is highly variable and fragmented, and that in general, previous studies, despite being labeled as hazard or risk studies, cannot be directly used if the goal is to obtain risk results based on probabilistic metrics. Consequently, this report establishes as a starting point that while data, maps, and studies of various kinds do exist, most cannot serve as a foundation for the objectives of this project. Instead, they should be considered as inputs or references against which certain results may be compared. Following this perspective, available information and models in Costa Rica were assessed to determine their potential use in risk evaluation within this project. The evaluation considered criteria such as scale, resolution, applicability, and availability, in order to determine their possible use and relevance, leading to the following conclusions:

- **Landslide Hazard**: Despite numerous studies, only one model meets the required standards for risk assessment purposes—the GIRI-CDRI model. This model meets the quality criteria for the applications foreseen in this consultancy. However, as it was built using global data, this project presents an opportunity to update and enhance it using higher-resolution local data available in

Costa Rica. This work may be carried out jointly with LANAMME/ECG, the lead institution of the Technical Working Group for Operational Project 1[1].

- **Volcanic Hazard**: Probabilistic models are available for volcanoes posing a hazard to National Route 2 (RN2), particularly Turrialba and Irazú. These models were developed during the CAPRA Project (2008) in Costa Rica and used for training under the GRAF Project. They meet the minimum quality standards for use in GRMA risk assessments. However, here too, there is an opportunity to update and improve the resolution of these models using more detailed local data. This work may also be carried out in collaboration with LANAMME/ECG, as leader of the Technical Working Group of Operational Project 1.
- **Seismic Hazard:** Unlike the previous cases, multiple models with similar methodological approaches exist. However, the only model with complete baseline information, which is also the most up-to-date and meets all quality standards for direct use in GRMA's seismic risk evaluations in Costa Rica, is the ASLAC model. This model has also been previously used by the international insurance industry and has served as a reference for CCRIF.

This report is structured into the following sections:

Section 1: This introduction.
Section 2: Summary of available landslide hazard information and models, and improvement and adaptation proposals.
Section 3: Summary of available volcanic hazard information and models, and improvement and adaptation proposals.
Section 4: Summary of available seismic hazard information and models, and justification for the most appropriate model.
Section 5: Overview of the geological hazard and risk training program, including participating Costa Rican institutions and the current progress status.

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[1] The role of the TWG Leader does not imply contractual responsibility for the product of this consultancy.

2 LANDSLIDE HAZARD

In general, mass movement processes can be defined as the downslope movement of a volume of rock or soil near the Earth's surface, mainly due to the force of gravity. These mass movements play an important role in the erosion process, as material is transported from one elevation to a lower one and subsequently carried away by rivers or streams. Mass movement processes occur continuously on slopes, some very slowly and others suddenly, often with disastrous consequences. Any perceptible downslope movement of rock, soil, or a mixture of both is generically referred to as a landslide.

In this project, the modelling of landslide hazard is applied specifically to Operational Project 1: Disaster and Climate Risk Assessment for Road Infrastructure – National Route 2 (RN2), Pan-American Highway.

2.1 Landslide events along National Route 2

To provide context on the landslide hazard relevant to this project, it is important to highlight that National Route 2, also known as the Southern Inter-American Highway, is one of the most strategic logistical corridors of Costa Rica. This road connects the Greater Metropolitan Area with the southern region of the country, enabling the flow of goods, people, and services between San José and the Panamanian border. However, due to its route through mountainous terrain, unstable volcanic soils, and areas of high rainfall, this infrastructure is highly susceptible to landslides, which have historically had a significant impact on national mobility, trade, and the country's economy (Quesada-Román, 2015; Monge Sandí, 2022).

One of the most severe events in recent years occurred in October 2022, when a low-pressure system brought persistent rainfall that triggered multiple landslides along the section between La Hortensia and El Jardín de Pérez Zeledón. The road was closed for several days, severely disrupting the movement of both light and heavy vehicles. The closure caused estimated economic losses of over one billion colones per day (approximately USD 1.8 million), as transporters had to use longer and less safe alternative routes (Monge Sandí, 2022). Additionally, communities such as Rivas and San Isidro del General experienced reduced access to hospitals, schools, and supply networks, exacerbating the social impact of the event. The infrastructure suffered damage to retaining walls, stormwater drainage systems, and the structural base of the roadbed (Monge Sandí, 2022).

The segment that crosses Cerro de la Muerte has been a recurrent site of landslides, particularly between kilometres 60 and 90. In August 2021, a large landslide forced the complete closure of the road for more than 48 hours, significantly affecting national logistics. Years earlier, in June 2017, another event of similar magnitude impacted the División area, cutting off several rural communities. The combination of steep slopes, unstable vegetation, and poor visibility due to fog has contributed to a long history of incidents—some of which have involved fatalities due to traffic accidents occurring during or after the landslides (Quesada-Román, 2015).

One of the most impactful events in recent history was caused by Tropical Storm Nate in October 2017. The exceptional rainfall associated with this storm triggered more than twenty critical landslides along the Southern Inter-American Highway, particularly in the cantons of Pérez Zeledón, Buenos Aires, and Osa (Muñoz Barrantes, 2017). The road sustained extensive structural damage, including bridge collapses, blocked culverts, and slope failures. The Térraba River bridge in Paso Real was at risk of collapse due to scouring, while several communities lost access to electricity and drinking water for several days. Repairs to this route required an investment of over ₡10 billion (some reports estimate up to ₡13 billion), according to the Ministry of Public Works and Transportation (MOPT) and the National Emergency Commission (CNE) (Bosque, 2017).

In July 2015, a significant landslide in the El Empalme area between Cartago and Pérez Zeledón caused an interruption of traffic for over 36 hours. Continuous rainfall saturated the soils, leading to the collapse of unstabilized slopes and the preventive evacuation of nearby homes (Quesada-Román, 2015).. Such incidents have been frequent in this section due to insufficient cross drainage and the lack of deep roadside ditches to effectively manage stormwater runoff.

In addition to rainfall-induced events, several earthquakes with epicentres near the Panamanian border have indirectly affected National Route 2. Tremors such as the Chiriquí earthquakes in 2003 and 2021 caused slope instability and road surface cracks in areas like Paso Canoas and San Vito. Although they did not trigger large-scale landslides, these earthquakes prompted the National Road Council (CONAVI, for its Spanish acronym) to carry out emergency inspections and preventive stabilization works to avoid potential future collapses (Lanamme-UCR, 2017).

Despite its essential role in international trade, the maintenance of National Route 2 has largely been reactive, and structural mitigation measures have not been implemented consistently. The lack of investment in retaining walls, permanent geotechnical monitoring systems, and drainage redesign has contributed to the repeated failure of the same critical points year after year. This results not only in direct economic costs for repairs, but also in cumulative impacts on national productivity and road safety (Quesada-Román, 2015).

In conclusion, landslides along National Route 2 represent an ongoing challenge for national connectivity, affecting not only road infrastructure but also the trade corridor and community access to essential services. Adapting to this type of hazard requires a comprehensive approach that includes territorial planning, strategic investments in resilient infrastructure, the implementation of early-warning technologies for mass movement detection, and effective coordination among risk management and road development institutions. This southern segment of the Inter-American Highway will remain a strategic national artery, and its sustainability and safety must be treated as a national priority.

2.2 Components Required for Landslide Hazard Modeling

A probabilistic risk assessment of a road segment such as National Route 2 (RN2) requires an evaluation of the landslide hazard, which involves understanding and accounting for at least four fundamental aspects that govern this phenomenon:

- The loads acting on blocks or masses of material that may slide.
- The role of water in altering the mechanical properties of slope materials.
- The geological structure of the slope and human-induced modifications.
- The influence of triggering events, such as earthquakes or intense rainfall.

Loading conditions, water content and its impact on the strength of slope materials, geological structure, and human interventions all contribute to *susceptibility*, which refers to the intrinsic conditions that favor instability.

Triggering events, on the other hand, are external to the slope conditions and must be addressed separately and incorporated when estimating landslide hazard. This is usually done through *triggering thresholds*, which are models that define the intensity level (of rainfall or strong ground motion, as applicable) at which a landslide is likely to occur on a slope.

In summary, a landslide hazard model intended for use in disaster risk assessments must be composed of three sub-models: *susceptibility, triggering thresholds, and triggering events*.

2.3 Available Information and models

Given the types of data required for landslide hazard assessment, this section presents a summary of existing information and models related to landslides in Costa Rica, particularly along National Route 2, and discusses both the potential and limitations of the available data for probabilistic hazard and risk evaluation. This section also provides a description of the data and models that can be directly used in the probabilistic risk modelling foreseen for this project, as well as the modifications or adjustments that may be necessary to achieve reliable results.

2.3.1 Baseline and Reference Information

Baseline and reference information for landslide hazard modelling refers to data or map layers related to the phenomenon, its occurrence and environmental conditions associated with its manifestation. These data alone do not constitute complete models of any of the required components mentioned earlier. The following describes the available information.

2.3.1.1 Landslide catalogue

The landslide catalogue is an inventory of historical events containing information on activity of type of mass movement processes, their spatial distribution, the process type, and their characteristics. In this case, the Sistema Nacional de Información Territorial (SNIT) portal includes natural hazard layers managed by the Comisión Nacional de Prevención de Riesgos y Atención de Emergencias (CNE). Two vector layers with georeferenced landslide data across Costa Rica have been identified[2].

The *Landslide* layer (see Figure 1), contains 1,126 records of mass movement phenomena triggered by hydrometeorological and seismic events that caused slope instability. In addition to the location of events, this layer contains information on the affected area and perimeter for most records. However, it does not distinguish between types of mass movement processes or specific event characteristics. According to the metadata of the layers, it is used for updating national hazard zones, identifying areas prone to landslides, and supporting decision making within the Sistema Nacional de Gestión del Riesgo.

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[2] Map layers are available to download in the following link: https://www.snitcr.go.cr/ico_servicios_ogc_info?k=bm9kbzo6NDU=&nombre=CNE

The *Landslide Crowns* layer (see Figure 2), includes information on areas identified as having potential for landslides triggered by intense rainfall or seismic activity.

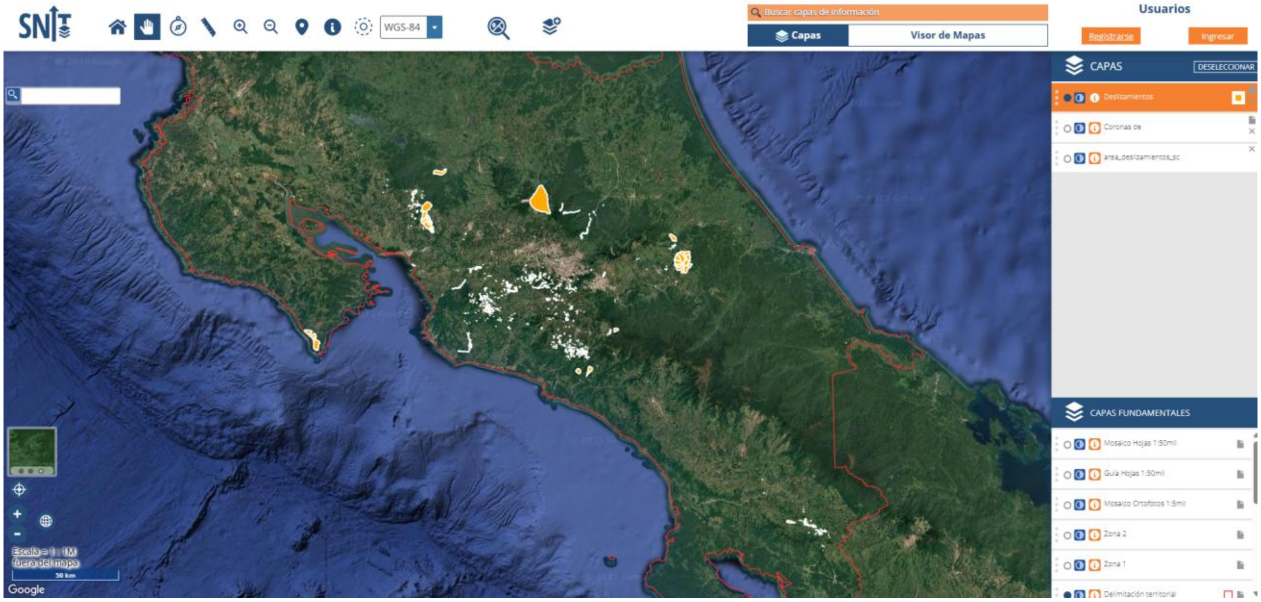


Figure 1. Visualization of the Landslides layer on the SNIT map

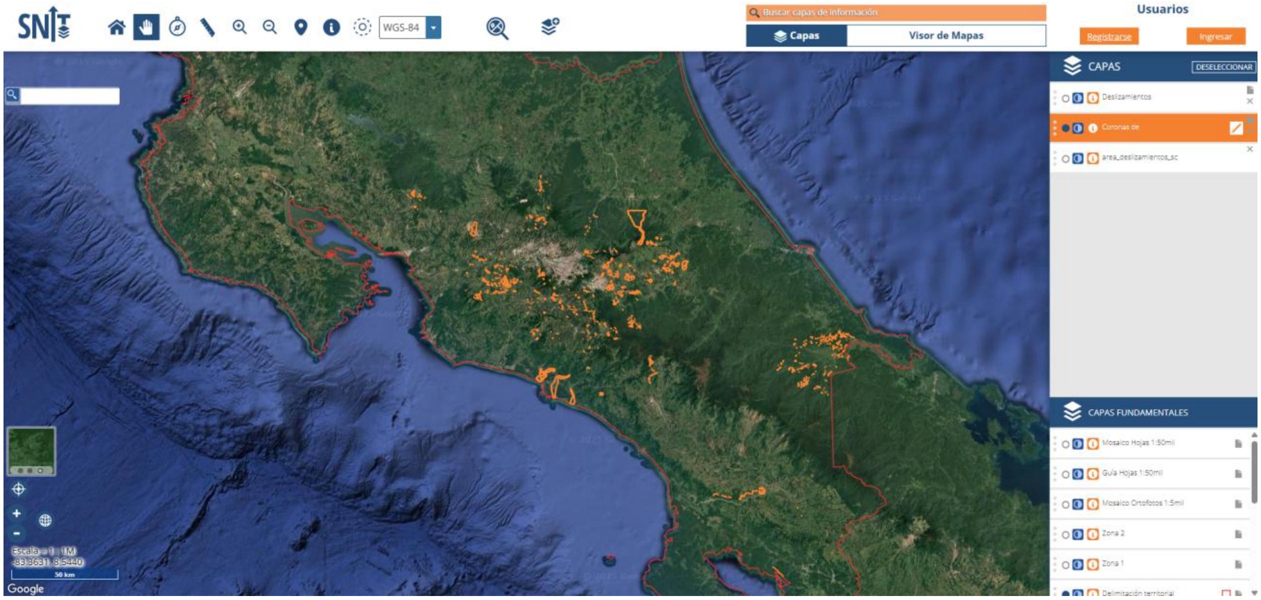


Figure 2. Visualization of the Landslides Crown layer on the SNIT map

This information serves to corroborate and justify the susceptibility values used in the modelling for the GRMA Project and is considered suitable for this purpose.

2.3.1.2 *LANAMME/ECG UCR Geographic Information System*

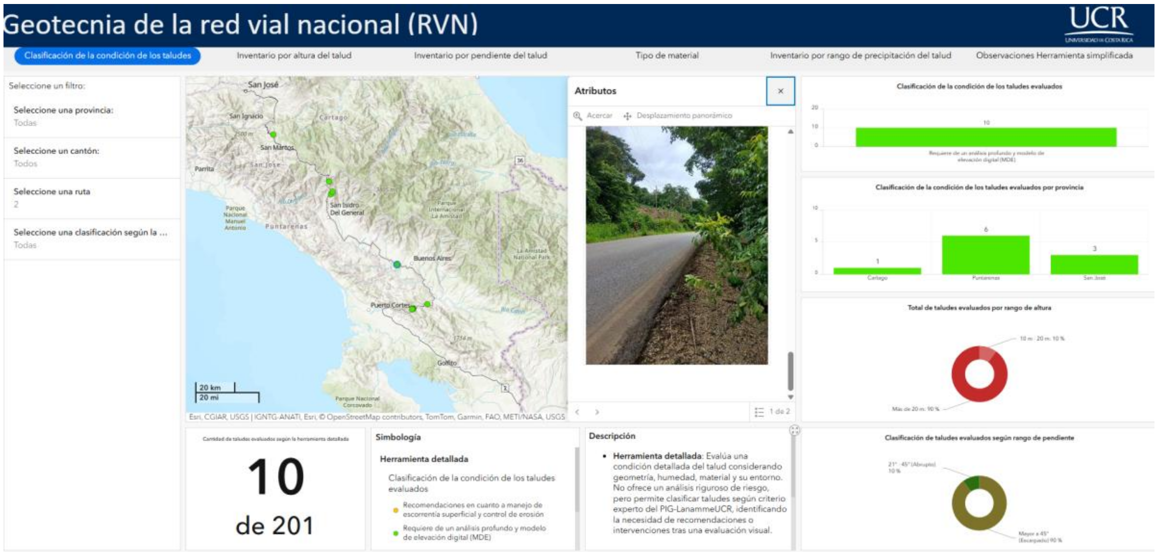
The Geographic Information System (GIS) of the Laboratorio Nacional de Materiales y Modelos Estructurales from the Universidad de Costa Rica (LANAMME/ECG-UCR) contains data related with the national road network (RVN) of Costa Rica, particularly regarding structural conditions of road segments.

For landslides, the GIS includes data under the *Geotechniques of the national road network*, which provides sampling points along major roads of the country. These include detailed slope studies and assessments of slopes prone to landslides.

The LANAMME/ECG GIS offers detailed information for 201 locations along the RVN, 10 of which are located on the RN2. At each of these points, information is provided on general slope condition, slope height, gradient, predominant material type, average annual precipitation range, and photographs of the slopes. This detailed dataset is complemented with 2710 simplified observation point, 115 of which are located on the RN2, for which general conditions are established, and photographs are included.

In addition to geotechnical information, the LANAMME/ECG GIS includes data on road network elements, specifically bridges and road segment from both the national and local road networks, as well as information from technical audits. This information will be considered in the exposure model for RN2. These datasets are available and have already been requested from LANAMME/ECG through the Superintendencia General de Seguros (SUGESE), which is expected to formally submit the request.

This information is also appropriate to corroborate and justify the susceptibility values used in the modelling for the GRMA project.



Seleccione un filtro:

Seleccione una provincia: Todas

Seleccione un cantón: Todos

Seleccione una ruta 2

Seleccione una clasificación según la ... Todas

10 de 201

Herramienta detallada

Clasificación de la condición de los taludes evaluados

- Recomendaciones en cuanto a manejo de escorrentía superficial y control de erosión
- Requiere de un análisis profundo y modelo de elevación digital (MDE)

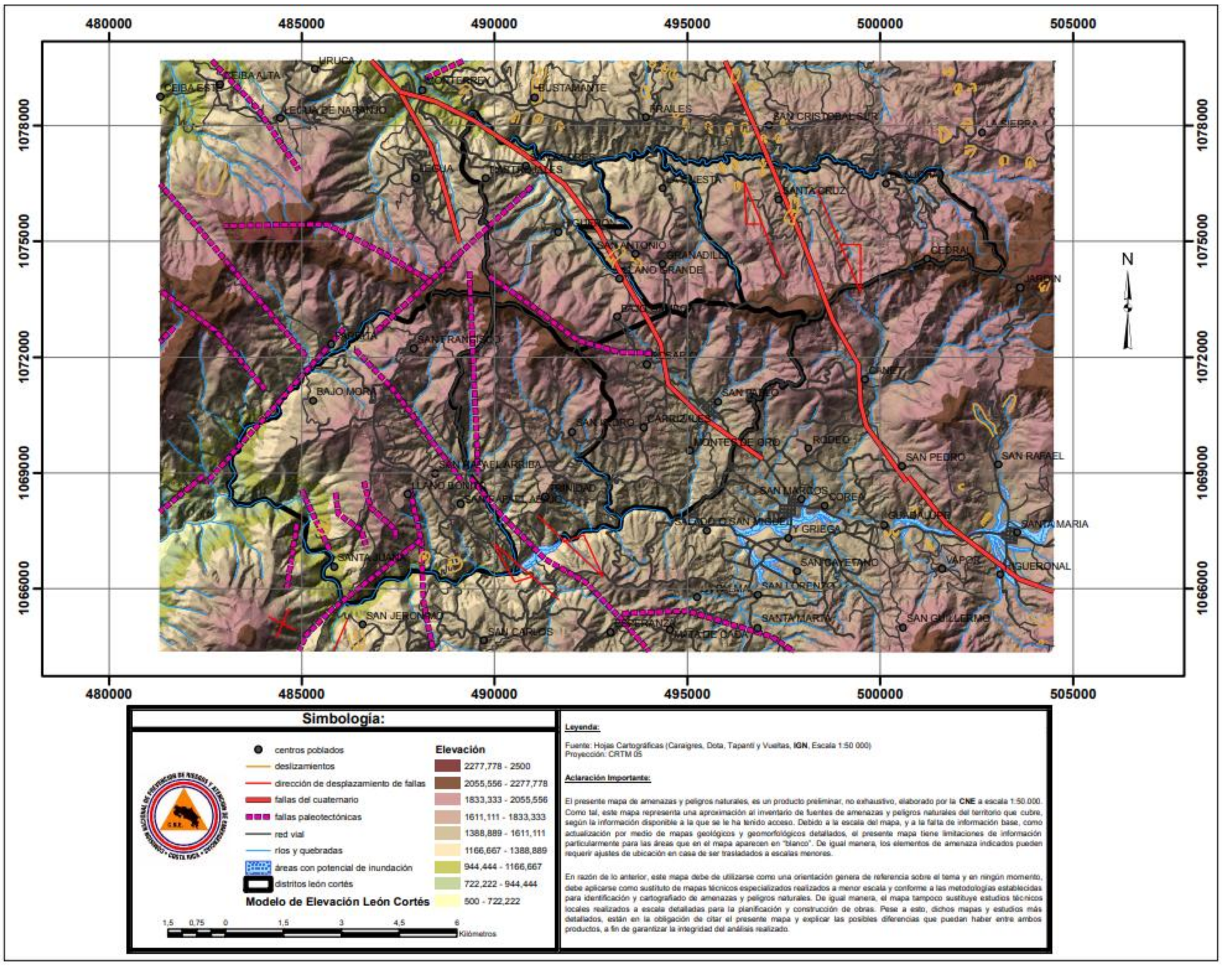
- **Herramienta detallada**: Evalúa una condición detallada del talud considerando geometría, humedad, material y su entorno. No ofrece un análisis riguroso de riesgo, pero permite clasificar taludes según criterio experto del PIG-LanammeUCR, identificando la necesidad de recomendaciones o intervenciones tras una evaluación visual.

Figure 3. Visualization geotechnical information points along RN2. LANAMME/ECG UCR GIS viewer.

2.3.1.3 *CNE Hazard maps*

The CNE has developed simplified maps of natural hazards information at the canton level for the whole country[3]. These maps provide an approximation to of natural hazards sources within the Costa Rican territory, including polygons representing potential landslide zones.

However, these maps are only available in PDF format, and the underlying georeferenced data have not been made accessible. Therefore, this information is not suitable for use in modelling and is considered insufficient for probabilistic hazard modelling. Nevertheless, these maps and information can be used for visual comparison with the susceptibility layer employed in the hazard model.



Leyenda:

Fuente: Hojas Cartográficas (Caraigres, Dota, Tapantí y Vueltas, **IGN**, Escala 1:50 000)
Proyección: CRTM 05

Aclaración Importante:

El presente mapa de amenazas y peligros naturales, es un producto preliminar, no exhaustivo, elaborado por la **CNE** a escala 1:50.000. Como tal, este mapa representa una aproximación al inventario de fuentes de amenazas y peligros naturales del territorio que cubre, según la información disponible a la que se le ha tenido acceso. Debido a la escala del mapa, y a la falta de información base, como actualización por medio de mapas geológicos y geomorfológicos detallados, el presente mapa tiene limitaciones de información particularmente para las áreas que en el mapa aparecen en "blanco". De igual manera, los elementos de amenaza indicados pueden requerir ajustes de ubicación en caso de ser trasladados a escalas menores.

En razón de lo anterior, este mapa debe de utilizarse como una orientación genera de referencia sobre el tema y en ningún momento, debe aplicarse como sustituto de mapas técnicos especializados realizados a menor escala y conforme a las metodologías establecidas para identificación y cartografiado de amenazas y peligros naturales. De igual manera, el mapa tampoco sustituye estudios técnicos locales realizados a escala detalladas para la planificación y construcción de obras. Pese a esto, dichos mapas y estudios más detallados, están en la obligación de citar el presente mapa y explicar las posibles diferencias que puedan haber entre ambos productos, a fin de garantizar la integridad del análisis realizado.

Figure 4. Natural hazards map of the Cantón de León Cortés. Prepared by CNE.

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[3] Maps are available in https://www.cne.go.cr/reduccion_riesgo/mapas_amenzas/.

2.3.2 RECLAIMM/CEPREDENAC-Norway Project

It is also important to make reference to the RECLAIMM project (*Capacity Building for Landslide Risk Management in Central American Countries*), a joint initiative between the Centro de Coordinación para la Prevención de Desastres de América Central (CEPREDENAC) and the Government of Norway (NGI – Norwegian Geotechnical Institute). Its main objective was to strengthen the capacity of Central American countries in Landslide Risk Management and Mitigation.

In Costa Rica, the project focused on the development of landslide susceptibility maps, considering factors such as geology, slope, land use and precipitation patterns. Although RECLAIMM was implemented in multiple countries in the region, the specific information about its implementation in Costa Rica is limited and the georeferenced products, such as the susceptibility map, have not been made accessible. Only a static image presented in Figure 5 was found, but the associated dataset is unavailable.

As such, this information is inappropriate and insufficient to use in modeling and can only be employed for visual comparison with the susceptibility layer used in the current model.

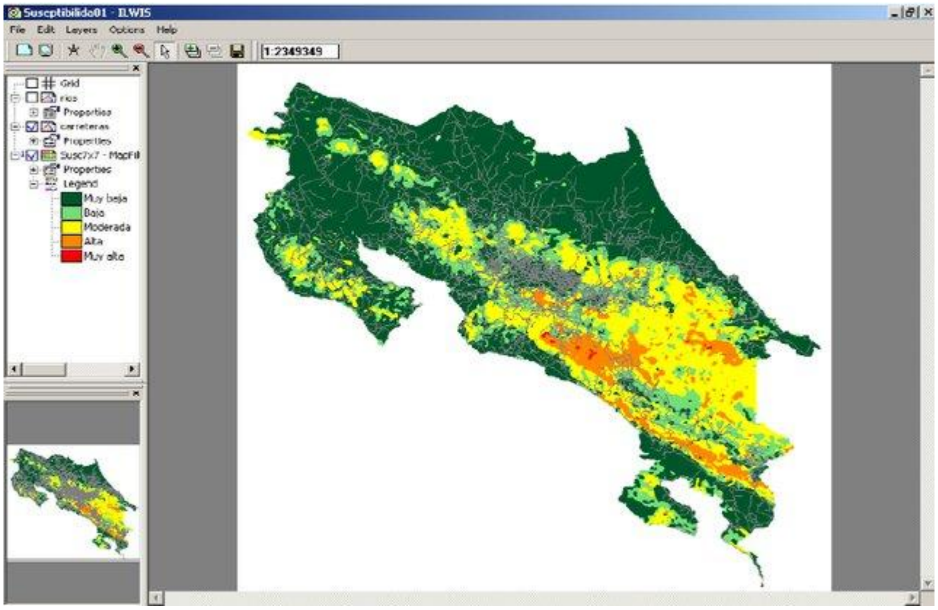

Figure 5. Image of the landslide susceptibility map of Costa Rica – RECLAIMM project. Sourced from ResearchGate.

2.3.3 CDRI-GIRI Model

As part of the Global Infrastructure Resilience Index (GIRI) project developed by the Coalition for Disaster Resilience Infrastructure (CDRI), a fully probabilistic landslide hazard model was produced. Unlike previous models, this one incorporates landslide hazard triggered by earthquakes and precipitation (including the effects of climate change) on a global scale.

This landslide hazard model, available for Costa Rica, is methodologically consistent with the requirements for risk modelling under the GRMA project, meaning it includes both landslide susceptibility and triggering thresholds suitable for probabilistic hazard assessment.

While the GIRI-CDRI model also includes triggering models (for heavy rainfall and earthquakes), these will not be used in the GRMA project, as a higher resolution rainfall model is being developed specifically for Costa Rica as part of flood modelling under Operational Project 1, and for the Strategic and Operational Projects 2 and 3.

It is worth noting that the hazard quantification methodology of the GIRI-CDRI model, aligns with the approach proposed in the *Guía Metodológica para la Integración del Análisis del Riesgo en los proyectos de infraestructura pública vial de Costa Rica*, developed in 2024[4].

Accordingly, the GIRI-CDRI model is the best available option. However, given its relatively low resolution and the fact that it was built using information from global databases, it would be feasible to carry out an update and improvement to adapt the model to the more detailed information available in the country.

2.3.3.1 Susceptibility model GIRI-CDRI

The GIRI-CDRI landslide susceptibility model covers the entire territory of Costa Rica, using a mosaic of four 5°x 5°rectangular grids with a spatial resolution of 90 meters. It classifies slope susceptibility into five categories, based on the Mora-Vahrson (1994) method. Each pixel is assigned a landslide susceptibility value, representing the annual probability of a potentially destructive landslide, using the following contributing factors: topographic slope, lithology, vegetation cover, and soil moisture, as described below:

$$S = S_r \cdot S_l \cdot S_h \cdot S_v \qquad \text{Equation 1}$$

where S is the landslide susceptibility, S_r is the slope factor, S_l is the lithology factor, S_h is the soil moisture factor, and S_v is the vegetation cover factor. S ranges from 0 to 1 and can be interpreted as an *intrinsic probability* of slope failure. It represents susceptibility only and does not yet reflect the actual probability of landslide occurrence, as triggering events are not included at this stage. The GIRI-CDRI susceptibility map for Costa Rica is shown in Figure 6.

The five susceptibility categories range from 1= very low to 5 = very high. These classes correspond to thresholds of landslide occurrence probability, which are linked to triggering intensity levels, as described below.

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[4] The formulation of this document was led by the Instituto Meteorológico Nacional (IMN), the Agencia Española de Cooperación Internacional para el Desarrollo (AECID), and the University of Costa Rica Foundation, with funding from EUROCLIMA. The guide is part of the Projective Action: Capacity Building for the Use of Climate Information to Strengthen Decision-Making Processes in Costa Rica.

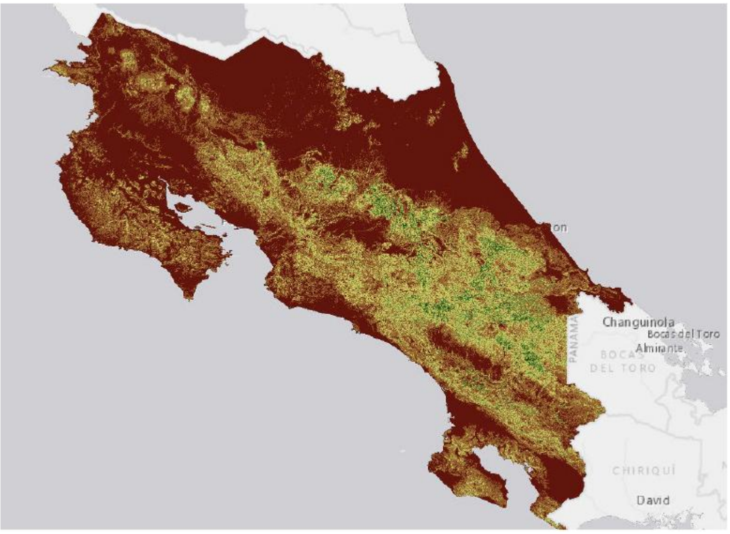

Figure 6. Landslide susceptibility map of Costa Rica - CDRI-GIRI led by INGENIAR

2.3.3.2 *GIRI-CDRI Triggering thresholds model*

The triggering threshold model used in GIRI-CDRI, as described by Palau et al., 2022, is a simplified model that correlates susceptibility categories with intensity levels of triggering event, to establish corresponding landslide probability. It extends the susceptibility model by assigning an event probability based on the intensity of the triggering hazard.

Table 1 presents the rainfall-landslide threshold according to GIRI-CDRI, based on the standardized 24-hour precipitation (P_n), defined as:

$$P_n = \frac{P_{24h} - \mu_{24h}}{\sigma_{24h}} \qquad \text{Equation 2}$$

Where P_{24h} is the 24-hour accumulated rainfall of the event (day) considered, μ_{24h} and σ_{24h} are the multiannual mean and the standard deviation of daily precipitation at the evaluation site.

Table 1. Rainfall-landslide threshold (GIRI-CDRI)

Range P_n	**Susceptibility category**				
	Susc. 1	**Susc. 2**	**Susc. 3**	**Susc. 4**	**Susc. 5**
$P_n < 0.3$	0%	0%	0%	0%	0%
$0.3 \leq P_n < 2.0$	0%	1%	2%	3%	5%
$2.0 \leq P_n < 3.7$	0%	2%	3%	5%	10%
$3.7 \leq P_n < 5.0$	0%	3%	5%	10%	15%
$P_n > 5.0$	0%	5%	10%	15%	20%

For seismic triggers, a similar classification is used based on Peak Ground Acceleration (PGA), which correlates with susceptibility categories to estimate the probability of seismically induced landslides. PGA is expressed as a fraction of gravitational acceleration.

Table 2. Earthquake landslide threshold.

Range PGA	Susceptibility category				
	Susc. 1	**Susc. 2**	**Susc. 3**	**Susc. 4**	**Susc. 5**
$0.05g \leq PGA < 0.15g$	0%	0%	0%	0.1%	0.5%
$0.15g \leq PGA < 0.25g$	0%	0%	0.1%	0.5%	1%
$0.25g \leq PGA < 0.35g$	0%	0.1%	0.5%	1%	5%
$0.35g \leq PGA < 0.45g$	0%	0.5%	1%	5%	10%
$PGA \geq 0.45g$	0%	1%	5%	10%	40%

2.3.3.3 *Proposed adjustments to the GIRI-CDRI model.*

In collaboration with the technical team at LANAMME/ECG, which leads the Technical Working Group of Operational Project 1, focused on risk assessment for national road RN2 of Costa Rica, updates will be made to improve the landslide susceptibility quantification, using the method proposed in the Inception Report for this consultancy.

This approach incorporates multiple susceptibility factors, improving upon the original GIRI-CDRI model, which considers only 4. Additionally, efforts will be made to improve the spatial resolution, ideally to 12.5 meters, or at least 30 meters, particularly in the vicinity of the RN2 corridor.

Finally, input from LANAMME/ECG experts and other specialists involved in the project will be sought to assess the relevance of the triggering thresholds currently used in the GIRI-CDRI model, and to determine whether adjustments are needed to align them with local conditions in Costa Rica

It is important to highlight that the full GIRI-CDRI dataset is available and remains the best data source currently available for the tasks outlined in the Terms of Reference of this consultancy. The purpose of the adjustment is not due to inadequacy, but rather to take advantage of the opportunity to integrate higher quality information and local expertise, which will ultimately enhance the project and deliver results better aligned with local specific characteristics of Costa Rica.

2.4 Selected Model

Based on the above, the GIRI-CDRI model has been selected for the landslide hazard component, as it is coherent and consistent with the requirements necessary for probabilistic risk assessments. This model meets the quality criteria established for the applications foreseen in this consultancy.

However, given that it was developed using global data sources, there is an opportunity to update and enhance the model by incorporating higher resolution local data available in Costa Rica. This update Will be carried out in collaboration with LANAMME/ECG, which leads the Technical Working Group of Operational Project 1.

2.5 Spatial Data on Landslide

The available geospatial datasets associated with this model are provided as part of Annex 1 of this report. The information related to landslide susceptibility triggered by rainfall and earthquakes includes grids with a spatial resolution of 90 meters covering the entire national territory.

The climatic data on precipitation and climate change scenarios to be obtained under Task 2 of this project will allow, after refinement, the generation of annual frequency maps (return periods) of landslide hazard maps, and subsequently, probabilistic risk maps.

2.6 Summary of Landslide Models and Information

Model or information	Observations	Availability	Limitations	Advantages	Type of information
Landslide Catalogue (SNIT - CNE)	Includes 1,126 events with spatial information, area, and perimeter; does not detail process type.	Available through SNIT viewer	Does not differentiate process types or specific event characteristics	Useful for validating susceptibility values; good national coverage	Historical, spatial, vector-based
LANAMME/ECG-UCR Geographic Information System	Includes 201 detailed geotechnical points and 2,710 simplified observation points; 10 and 115 located along RN2 respectively.	Available upon formal request to LANAMME/ECG	Point data; not continuous coverage	High technical quality; includes photos, slope, height, material type, etc.	Point-based, technical, observational
CNE Hazard Maps	Simplified hazard maps at the canton level, available in PDF format.	Public access to PDF, no underlying georeferenced data	Cannot be integrated into spatial models due to lack of GIS base	Provides a general hazard overview; useful as a visual reference	Cartographic, visual, institutional
RECLAIMM Project / CEPREDENAC - Norway	Development of a regional susceptibility map; only an image is available, no database.	Image available online (ResearchGate)	No access to underlying georeferenced data	Provides regional context; useful for reference visualization	Image-based, referential, regional
GIRI-CDRI Model (Global Infrastructure Resilience Index)	Complete probabilistic model; includes susceptibility and triggering thresholds (rainfall and earthquake).	Fully available (included in Annex 1)	90m resolution; based on global datasets, subject to local improvement	Coherent, comprehensive, validated model already compatible with GRMA	Probabilistic, raster-based, global

3 VOLCANIC HAZARD

Probabilistic volcanic hazard estimation is a very recent field of application within catastrophic risk modelling. Its purpose is to describe in probabilistic terms, the occurrence process of volcanic eruptive episodes, aiming to characterize a collection of events that represent all the ways in which volcanic hazards can manifest across the territory.

Calculation volcanic hazard required modelling volcanic activity, determining the likelihood that volcanic products are emitted from specific vents, modelling the distribution of volcanic products, and integrating these components into a stochastic catalogue of eruptive episodes that are mutually exclusive and collectively exhaustive.

In this consultancy, volcanic hazard modelling is specifically applied to Operational Project 1: Disaster and Climate Risk Assessment for Road Infrastructure – National Route 2 (RN2), Pan-American Highway.

3.1 Volcanic events affecting National Route 2, RN2

National Route 2 of Costa Rica has historically been exposed to various natural hazards, including volcanic phenomena. Although volcanic impacts have often been indirect, they are significant due to the route's passage through steep slopes, volcanic terrains, and mountainous regions near active centers like Turrialba and Irazú volcanoes. These factors have played an important role, although often indirectly, due to the interaction between geological activity and local climatic conditions (Vahrson & Cartín, 2020).

The 2014-2017 eruptive activity of Turrialba Volcano stands out as a major event affecting road infrastructure. During this period, the volcano experienced multiple phreatic and magmatic eruptions, producing columns reaching over 3,000 meters above the crater. Ash dispersal carried by trade winds led to significant deposits across the Central Valley, including sections of RN2, particularly between San José, Curridabat and Cartago. Although ash thickness rarely exceeded 5 millimetres, its persistence caused cumulative impacts (Duarte, 2016).

Key effects included reduced visibility on the road, especially during peak hours and light rainfall, increasing accidents risk. Blockages in culverts and drainage systems, increasing susceptibility to localized flooding and shallow landslides, particularly at Taras, Ochomogo, and Cerro de la Muerte (LANAMME-UCR, 2015).

Regarding Irazú Volcano, although its recent activity has been more intermittent and less explosive, it remains relevant. Increased seismic and fumarolic activity in 2020, combined with hydrological instability, indirectly affected RN2, especially in the segment connecting Cartago to Cerro de la Muerte. Soil saturation, influenced by volcanic impacts on underground hydrology, contributed to several landslides, forcing emergency interventions by the National Road Council (CONAVI) (Alvarado, 1993; Sojo, 2018).

In particular, around kilometer 25, near the city of Cartago, there is a succession of historical and prehistoric laharic fans formed from eruptions of the Irazú Volcano, whose crater is located about 16 km from the site. These fans have been formed by the accumulation of volcanic material. They were built up through the deposition of material from the volcano during episodes of primary lahars (triggered by an eruption) and secondary lahars (not triggered by an eruption). This material has traveled along the

Reventado River, affecting the city of Cartago and potentially the National Route 2 (RN2), which currently passes through the area—just as it did during the volcanic activity between 1963 and 1965 (Gunther Vahrson & Cartín, 2020).Components Required for Volcanic Hazard Modelling

Various approaches exist for volcanic hazard evaluation, traditionally emphasizing deterministic explanations for observed events allowing a description of the eruption occurrence conditions, path and propagation of volcanic products and potential effects. While these approaches provide valuable context, they are insufficient for probabilistic risk modelling as required under the GRMA project Terms of Reference.

Probabilistic volcanic hazard modelling requires defining specific components to simulate a collection of volcanic-derived events for risk modelling:

- Eruption occurrence model expresses eruptions as a stochastic process, stationary or not.
- Eruption column collapse regime model determines the likelihood and magnitude of pyroclastic flows.
- Product transit or propagation models simulate the intensity and extent of volcanic products—particularly ashfall, pyroclastic flows, lahars, ballistic projectiles, and shock waves (to a lesser extent, lava flows)[5].

Based on the existence or absence of these submodels, available information has been evaluated for its suitability in risk modeling under the GRMA project.

3.2 Available Information and Models

Although Costa Rica has over ten significant volcanic structures, five exhibit active behaviour. For Operational Project 1, the focus i son Turrialba and Irazu volcanoes given their relevant to RN2.

Table 3. -General characteristic of Turrialba and Irazú volcanoes

Characteristic	Turrialba Volcano	Irazú Volcano
Volcano type	Stratovolcano (Alvarado et al., 2006)	Stratovolcano (Alvarado et al., 2006)
Main activity type	Vulcanian, phreatomagmatic plinian (Reagan et al. 2006; Martínez et al., 2012)	Vulcanian, Plinian (Alvarado & Soto, 2002)
Explosivity	Explosive (moderate) (Pacheco et al., 2015)	Explosive (high in history) (Alvarado et al., 1997)
Recent activity	Ash emissions, light explosions (Ruiz et al., 2017)	Fumaroles, low activity since 1990s (Barquero et al., 2000)
Notable eruptive events	2014–2017: frequent ash emissions (Ruiz et al., 2017; Conde et al., 2019)	1963–1965: major plinian eruption (Alvarado & Soto, 2002)
Eruption column height	Up to 3,000 m above crater (Ruiz et al., 2017)	Over 8,000 m in plinian eruptions(Alvarado & Soto, 2002)
Impact on RN2	Ash, reduced visibility (Pacheco et al., 2015)	Potential lahars, ashfall (Alvarado et al., 2006; ICE, 2011)

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[5] This is because the explosive nature of the Turrialba and Irazú volcanoes, along with the type of magma involved, reduces the likelihood of lava flows occurring.

3.2.1 Volcanic Hazard Studies

Studies led by the Risk Research Analysis Unit of the CNE have assessed volcanic hazards for Turrialba and Irazú. They seek to establish the regions potentially affected by volcanic products resulting from the activity of these volcanoes, with an emphasis on the extent of the products and the intensity of the potential impact

3.2.1.1 Turrialba volcano

The study titled *"Volcanic Hazard of Turrialba, Costa Rica"* (Alvarado et al., 2020a) provides information on the geological setting of the volcanic edifice, its morphology, its eruptive history in both geological and historical times, as well as simulations of eruptive scenarios with the potential intensities generated on the terrain.

The information contained in this study is useful for the parameterization of probabilistic hazard models that will be used in the framework of the GRMA project. However, it is clarified that the study does not provide a probabilistic hazard modelling. In other words, while the information is highly valuable, the results obtained are not sufficient to be directly used for the probabilistic risk assessment in this project.

3.2.1.2 Volcanic hazard of Irazú

The study titled *"Volcanic Hazards of Irazú, Costa Rica"* (Alvarado et al., 2020b) follows a structure similar to that of the Turrialba volcano study, providing information on the geological setting of the volcanic edifice, its morphology, its eruptive history in both geological and historical times, as well as simulations of eruptive scenarios with the potential intensities generated on the terrain.

The information contained in this study is highly useful for the parameterization of probabilistic hazard models. However, it is clarified that the study does not provide a probabilistic hazard modelling. In other words, while the information is highly valuable, the results obtained are not sufficient to be directly used for the probabilistic risk assessment in this project.

3.2.2 Probabilistic Models from the CAPRA Project

As part of the CAPRA project (2008), probabilistic volcanic hazard models were developed for nine volcanoes in Costa Rica, including Poas, Arenal, Irazú, Turrialba, Rincón de la Vieja, Tenorio, Barva, Miravalles and Orosí. These models were updated in 2010 by INGENIAR-CIMNE, incorporating better activity rate data, eruption magnitudes, morphology, and material properties.

The models are implemented in VHAST software (Bernal, 2010) within the CAPRA-ROBOT platform, covering ashfall, pyroclastic flows, lahars, and, less frequently, lava flows.

Models for Turrialba and Irazú are aligned with the 2024 Methodological Guide for integrating risk analysis into public road infrastructure projects in Costa Rica.

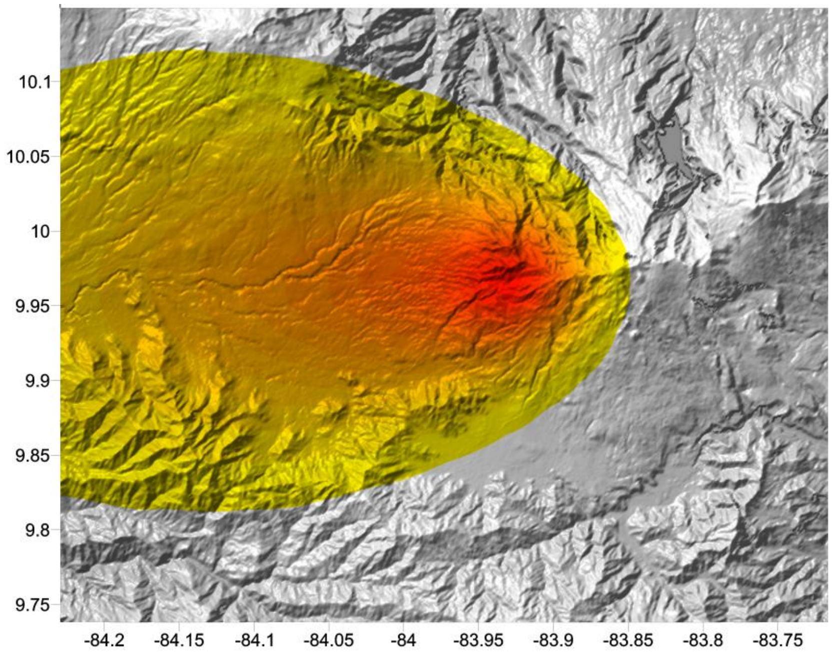

Figure 7. Ashfall scenario – Irazú volcano

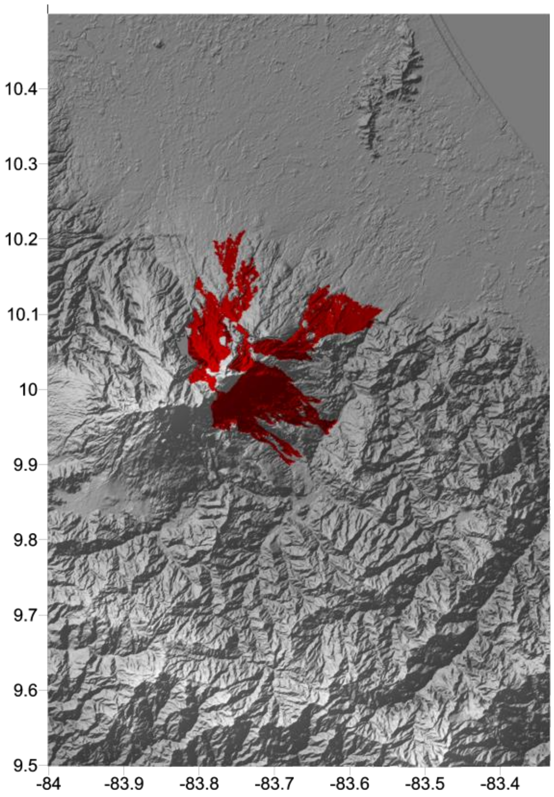

Figure 8. Pyroclastic Flow scenario – Turrialba volcano

3.2.2.1 Proposed adjustments to CAPRA Probabilistic Models

In collaboration with LANAMME/ECG, updates of the probabilistic volcanic hazard estimation for Turrialba and Irazu volcanoes will include: the incorporation of the latest volcanic activity and morphology information (Alvarado et al., 2020a, 2020b), improvement of model of resolution to 12.5 meters around volcanic structures and RN2, updating base modelling parameters, adding ballistic projectile and shock wave hazard evaluations.

Though CAPRA models are the best currently available for the activities in the Terms of Reference of this project, updating them allows for greater precision and local adaptation

3.3 Selected Model

For volcanic hazard, probabilistic models developed under the CAPRA project (2008) for Turrialba and Irazu volcanoes will be used. They meet the minimum quality standards for GRMA risk evaluations. As with landslides, there is an opportunity to update and improve resolution using locally available detailed data, a process to be conducted jointly with LANAMME/ECG

It is important to note that the use of this volcanic hazard model allows for the evaluation of effects not only on infrastructure assets but also on environmental impacts, should they need to be assessed in the future. In the case of crops, it would require the use of a specific vulnerability model for tephra fall (ash fall). Vulnerability models for other volcanic hazards are considered binary due to the high destructive capacity of these phenomena. Crop vulnerability to tephra fall is based on the evaluation of the phenological characteristics of plants, which determine their biological response to the alteration of their natural environment. Generally, plants close the stomata of their leaves to reduce water loss through transpiration, which results in a decrease in their photosynthesis rate, growth rate, and final yield. Vulnerability modelling can be conducted following the yield calculation methodology proposed by FAO (AquaCrop model). Therefore, the model can be useful for risk assessment of ecosystem services.

3.4 Spatial Data on Volcanoes

The geospatial datasets related to volcanic hazard modelling are provided as part of Annex 1 of this report. They include: Probabilistic volcanic hazard parameters from the Volcanic Hazard Analysis and Simulation Tool, VHAST model (CAPRA-ROBOT), for Irazú and Turrialba**,** Topography based on four geospatial fragment tiles of the Digital Elevation Model (DEM), with a spatial resolution of 12.5 meters, covering part of Costa Rica's territory, specifically the region traversed by RN2 and the area where the Turrialba and Irazú volcanoes are located.

The CAPRA/VHAST models are already available for use in producing probabilistic volcanic hazard maps, for example, ashfall maps with different return periods. Based on event-based frequency information, it is also possible to subsequently obtain probabilistic risk assessments. Additionally, specific event scenarios can be generated.

3.5 Summary of Volcanic Hazard Models and Information

Model or Information Source	Observations	Availability	Limitations	Advantages	Information Type
Volcanic Hazard Study – Turrialba (Alvarado et al., 2020a)	Geological and eruptive scenario study, useful for parameterization	Available as a technical document	Not a direct probabilistic model; no stochastic catalogue	Recent data; useful for updating models	Geological, contextual, technical
Volcanic Hazard Study – Irazú (Alvarado et al., 2020b)	Similar to Turrialba; includes historical simulations	Available as a technical document	Not directly usable for risk modeling	Strong technical basis for updating probabilistic models	Geological, contextual, technical
CAPRA Probabilistic Models (VHAST – INGENIAR-CIMNE)	Developed for 9 volcanoes; includes ashfall, flows, lahars, and lava	Available, implemented in CAPRA-ROBOT	Requires parameter updates and resolution improvement	Complete, validated probabilistic modeling	Probabilistic, geospatial, technical
Proposed CAPRA Model Adjustments	Resolution improvement (12.5m), incorporation of new data and phenomena (ballistics, shock waves)	In development with LANAMME/ECG	Not yet implemented; depends on technical progress	Will achieve more detailed and locally precise models	Proposed modeling, technical, applied

4 SEISMIC HAZARD

In general, the purpose of seismic hazard assessment is to describe, in probabilistic terms, the natural occurrence process of earthquakes, their intensity and effects across the territory. The goal is to fully dimension the problem considering not only past events but also those that have not yet occurred. This involves, first, modelling the occurrence of ruptures in the Earth's crust, preserving key characteristics such as released seismic moment, rupture size, and orientation; second, measuring the frequency of earthquake occurrence and their temporal distribution, in statistical consistency with seismological catalogues; and third, establishing the strong motion intensities at any location resulting from specific earthquake events.

Under this project, work will be based on available information from previous efforts conducted in Costa Rica. The most relevant and complete studies identified are presented below.

4.1 Relevant Seismic Events in Costa Rica

Situated along the Pacific Ring of Fire, Costa Rica has historically experienced high seismicity due to the interaction between major tectonic plates, primarily the Cocos and Caribbean Plates. This geological setting has produced numerous significant earthquakes that have profoundly shaped the history of the country in terms of human, economic, and structural impacts (Alonso-Henar et al., 2013).

One of the most significant events in history of Costa Rica was the Cartago Earthquake occurred on Map 4, 1919. This magnitude 6.4ML earthquake had a devastating impact on Cartago city. Over 80% of buildings collapsed, approximately 700 fatalities, thousands injured and displaced (Alonso-Henar et al., 2013). The disaster led to urban restructuring and relocation of many families. This earthquake marked a turning point in seismic risk management in the country, although at that time there were still no seismic-resistant building regulations in place (Alonso-Henar et al., 2013).

Decades later, on April 22, 1991, another great magnitude earthquake occurred near Pandora, in Limón region, in the Caribbean coast. With a magnitude 7.7Mw, one of the strongest recorded in Costa Rica (Quesada-Román, 2021). Although the epicentre was in a less populated area, there were 48 deaths, over 500 injuries, and 7,000 damaged homes (Nishenko et al., 2021). Critical infrastructure was heavily affected, which difficulted rescue and assistance (Denyer et al., 1994; Moya, 2021); and significant ground deformations were observed.

Later, on March 25, 1990, Cóbano Earthquake was reported. With a magnitude of 7.0Ms, impacted the Nicoya Peninsula. Although less destructive, it caused notable material damage to housing, roads, and rural schools (Protti & Schwartz, 1994). Significant material losses were recorded from this earthquake. This event reinforced the awareness of seismic risk in the Pacific region and motivated more rigorous studies about seismic energy accumulation in the Nicoya peninsula, which is considered one of the greatest seismic areas of the country (Alonso-Henar et al., 2013).

More recently, Cinchona earthquake, on January 8, 2009, represents a relevant milestone in seismic history in Costa Rica. With a magnitude of 6.2Mw, near volcano Poás, this earthquake had severe damage in Cinchona and Vara Blanca, and other sectors in Alajuela canton. 29 deaths, over 90 injured, 2,000 displaced. Landslides triggered by the earthquake were a major cause of fatalities and infrastructure collapse (LANAMME UCR 2009; Monge Sandí, 2009).

Another significant event occurred on September 5, 2012, in Sámara/Nicoya. With a magnitude of 7.6Mw, off the northern Pacific coast. Although structural damage was considerable, affecting over 2,300 buildings), fatalities were low. Critical facilities such as hospitals and schools suffered significant damage.

4.2 Components Required for Seismic Hazard Modelling

Probabilistic seismic hazard modelling follows a well-established methodology, originating in the late 1960s from the pioneering works of Luis Esteva in Mexico and Alin Cornell in the United States. This robust methodology has subsequently formed the foundation for approaches to the probabilistic evaluation of all types of natural hazards. In fact, the basic principles of modern catastrophic risk modelling can be traced back to Esteva's and Cornell's seismic hazard modelling research.

Seismic hazard assessment requires three essential components:

- Source Model: Describes the geometry and spatial distribution of rupture locations in the area under analysis.
- Seismicity Model: Enables the probabilistic modelling of earthquake occurrence over time across different magnitudes for each source.
- Ground Motion Prediction Model (GMPE): Defines strong ground motion intensity as a random variable, based on earthquake magnitude and source-to-site distance.

The existence and quality of these submodels in Costa Rica have been assessed to determine their suitability for seismic risk modelling within the GRMA project framework.

4.3 Available Information and Models

This section presents a summary of the existing seismic hazard models for Costa Rica, outlining their potential and limitations for direct use in risk modelling under the project.

4.3.1 RESIS II Model

The Seismic Risk Reduction in Guatemala, El Salvador, and Nicaragua Project, with Regional Cooperation for Honduras, Costa Rica, and Panama (RESIS II) (NORSAR et al., 2008) was a regional initiative aimed at assessing seismic hazard, vulnerability, and risk across six Central American countries, including Costa Rica. The project was developed with the collaboration of local institutions such as the Red Sismológica Nacional and the Escuela Centroamericana de Geología at the Universidad de Costa Rica, as well as the Instituto Costaricense de Electricidad (ICE) and international experts in seismology and geotechnical engineering from the Universidad Politécnica de Madrid, Central America, and Europe.

In the case of Costa Rica, the study focused primarily on the probabilistic seismic hazard assessment, taking into account the country's historical and recent seismicity. A seismic catalogue was developed, based on the national seismic catalogue and a regional catalogue (Rojas et al. ,1993). Updated through December

2007, with contributions from local catalogues (El Salvador, Nicaragua, Costa Rica, and Panama), and data from the Central America Seismological Center (CASC).

The catalogue included significant events dating back to 1522, considering moment magnitudes (Mw) of 3.5 or greater. From this data, major seismogenic sources were identified and classified into three broad categories: crustal sources, interplate subduction sources, intraplate subduction sources. To estimate expected ground acceleration at various locations, appropriate attenuation models were used: Climent et al. (1994) and Zhao et al. (2006) for crustal faults, Youngs et al. (1997) for interplate subduction sources, and Zhao et al. (2006) and Youngs et al. (1997) for intraplate subduction sources.

Seismic hazard calculations were performed using the CRISIS2007 software (part of the CAPRA platform). RESIS II results included: Peak Ground Acceleration (PGA) maps, spectral Acceleration (SA) maps at periods of 0.1, 0.2, 0.5, 1, and 2 seconds, maps for return periods of 500, 1000, and 2500 years, seismic hazard curves for San José City, and uniform hazard spectra for the same return periods. The maps obtained, such as the one shown in Figure 9, were fundamental for establishing the requirements for the development of seismic-resistant building codes and for land-use planning in Costa Rica.

The RESIS II model is methodologically compatible with catastrophic risk modelling practices. In fact, during the development of the CAPRA platform (by the World Bank, IDB, and UNDRR in 2008 in Costa Rica), INGENIAR-CIMNE incorporated the RESIS II model into the CAPRA platform. Therefore, the model and its results are currently available and remain foundational references for projects like the Global Risk Assessment Framework (GRAF), developed later with support from UNDRR for the CNE.

The results of RESIS II and GRAF are fully compatible with the seismic risk modelling intended under the GRMA project. Although they remain key references in Costa Rica’s public sector, more recent and comprehensive models have been developed, some of which build upon RESIS II and GRAF contributions. A synopsis of these newer models and their advantages will be presented below.

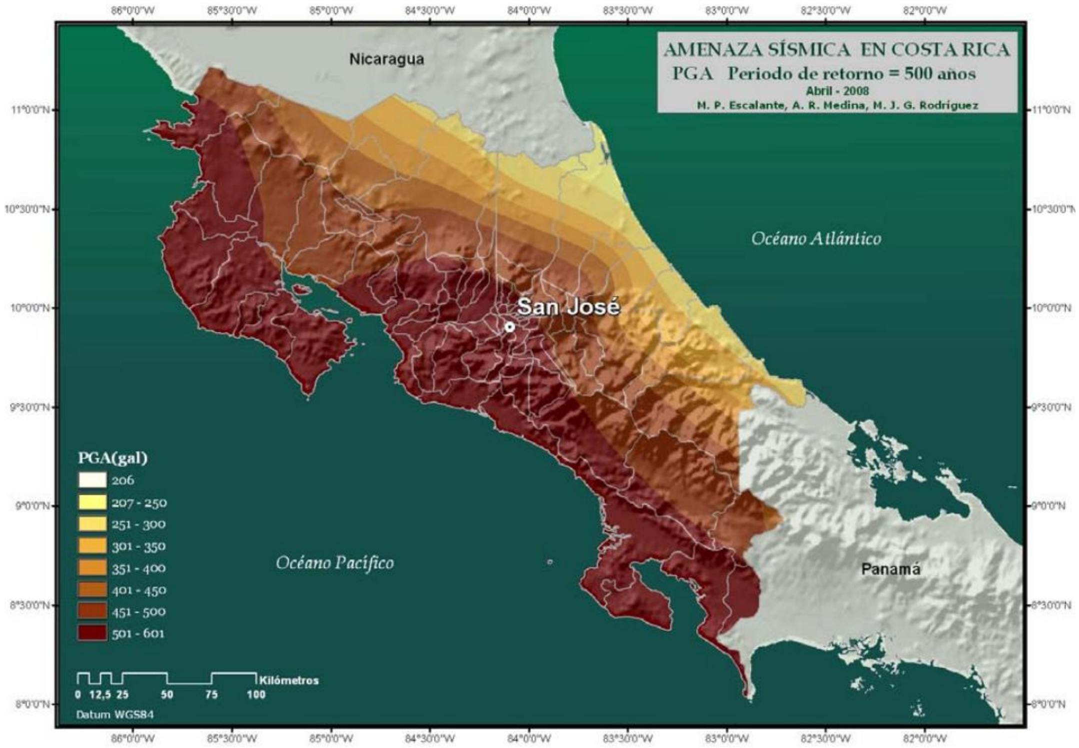

Figure 9. Seismic hazard map (PGA) for a 500-year return period. (Taken from NORSAR et al., 2008)

4.3.2 Seismic Hazard Model of Costa Rica 2022

This was a joint project involving researchers from the University of Costa Rica, including the Laborartorio de Ingeniería Sísmica (LIS), RSN, LANAMME/ECG, and the departments of Psychology and Social Work, as well as researchers from the ICE. The main objective was to develop a new seismic hazard model for the country and to contextualize the seismic experiences of rural communities to promote risk mitigation policies.

The model was developed using the earthquake database compiled by Arroyo-Solórzano and Linkimer (2021), based on information from LIS, RSN, and seismological agencies in Panama and Nicaragua. The catalogue covers events from 1522 to 2020, with moment magnitudes (Mw) ranging from 0.3 to 7.7.

For seismic zoning, the proposal by Alvarado et al. (2017) was used, defining 28 zones across Costa Rica and adjacent areas. These zones were grouped into three tectonic domains: upper plate (18 zones), interplate (5 zones), intraplate (5 zones). Ground motion prediction models (GMPEs) were applied through specific weighted combinations for each source type: intraplate zones: Abrahamson et al. (2016), Montalva et al. (2017), Kanno et al. (2006), García et al. (2005), Lin & Lee (2008), interplate zones: Kanno et al. (2006), Zhao et al. (2006), Montalva et al. (2017), and crustal sources: Cauzzi et al. (2015), Kanno et al. (2006), Boore et al. (2014)

Seismic hazard calculations were performed using OpenQuake software of Global Earthquake Model (GEM, 2020). The PGA maps for 475- and 2475-year return periods, along with corresponding spectral accelerations, classified Costa Rica into four seismic hazard levels: extremely

- High: Nicoya, Osa, and Burica Peninsulas (directly over the interplate subduction zone),
- Very High: Most of Guanacaste Province,
- High: Central regions, including San José (~41% of the territory), and
- Moderate: Talamanca Range and northern Costa Rica

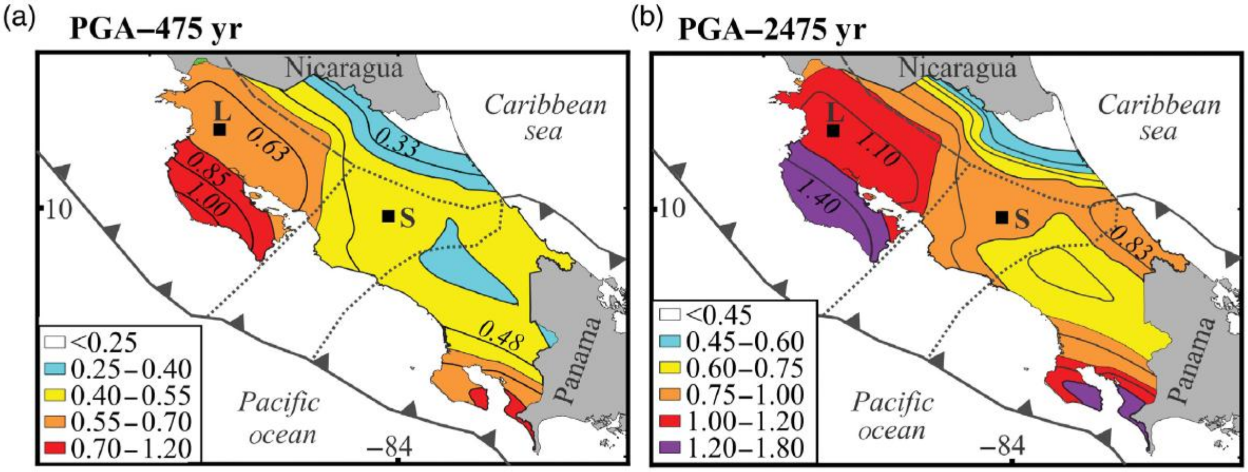

Figure 10. Results of the Costa Rica seismic hazard model for selected intensity measures (PGA) for return periods of (a) 475 and (b) 2475 years. (Taken from Hidalgo Leiva et al., 2022)

However, the base information required to apply this model for GRMA project risk evaluation is not available. Although the geometric source, seismicity, and attenuation models used are known, the detailed digital data necessary for application is missing. Therefore, this model won't be considered for seismic risk evaluation in the country.

4.3.3 ASLAC Model

A Regional Seismic Hazard Model for Latin America and the Caribbean (Amenaza Sísmica para Latino América y el Caribe, ASLAC) was also developed with the aim of supporting not only seismic building codes but also catastrophic risk evaluation for asset portfolios—particularly useful for the insurance and reinsurance industry. Although most countries in the region already had their own national probabilistic seismic hazard models, regional integration was difficult due to discontinuities at political-administrative borders, lack of integration of transnational faults, and use of different ground motion prediction models (GMPEs).

The ASLAC model (Salgado-Gálvez et al., 2018) became the first harmonized probabilistic seismic hazard model for Latin America and the Caribbean. It covers the region completely, continuously, homogeneously, and comprehensively at a national-scale resolution, including shared seismic faults and neighbouring countries.

The key aspects of ASLAC development were: Seismic catalogue updated with international sources (Engdahl & Villaseñor, 2002; Storchak et al., 2013; USGS-NEIC, 2015), complemented with local sources. The catalogue covers events from 1900 to 2015, minimum Mw = 4.0.

Tectonic zoning focused exclusively on seismotectonic characteristics, ignoring political borders. Subregions were defined for seismic source assignment. For instance, Central America: events between the subduction trench and 40 km depth isoline classified as interplate; outside, intraplate (>40 km depth) or crustal (≤40 km depth).

Attenuation models were selected based on regional seismotectonics. Hybrid relationships were applied, assigning weighted combinations of two or more models to the different sources. In Central America: Chiou-Youngs (2014) and Climent et al. (1994) for crustal sources, each weighted 0.5; and model Zhao et al. (2006), Lin & Lee (2008), and Youngs et al. (1997) for interplate and intraplate sources, each weighted 0.33.

Seismic hazard evaluation followed the PSHA methodology, using CRISIS2015 software (Ordaz et al., 2015). Outputs include seismic hazard curves, uniform hazard spectra (UHS), and maps for various return periods.

Additionally, a synthetic earthquake catalogue was generated defined as events mutually exclusive and collectively exhaustive, and each event has an associated frequency of occurrence. This catalogue which includes more than 1 million events is stored in a .AME file, compatible with open and licensed platforms like CAPRA.

Figure 11 shows the seismic hazard maps of Costa Rica obtained from the ASLAC model. On the left, the map corresponding to a 500-year return period is presented, and on the right, the map for a 2,500-year return period, both expressed in terms of PGA.

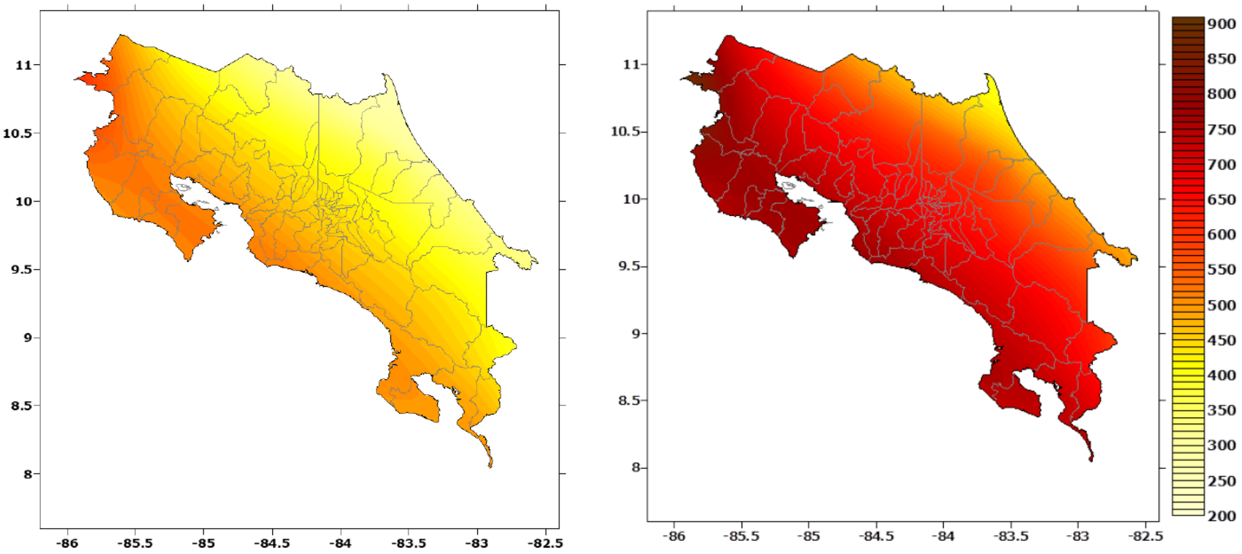

Figure 11. Seismic hazard maps for Costa Rica. Left: PGA for 500-year return period. Right: PGA for 2500-year return period. Calculated by INGENIAR-CIMNE using CAPRA-ROBOT. Units in cm/s².

The ASLAC model is currently the most advanced and updated seismic hazard model for Latin America and the Caribbean. It is used in catastrophic risk models for loss estimation in the insurance sector and referenced by institutions like CCRIF, and brokers such as AON, Willis Re, JLT, AXA. It has been certified by the Financial Superintendence of Colombia for solvency and pricing in insurance companies.

The consulting team has full access to the ASLAC model and the complete synthetic catalogue, enabling its direct application in the GRMA project analyses.

4.4 Selected Model

For the seismic hazard evaluation in this project, the ASLAC model has been selected as the best option, meeting all quality criteria required for direct application in GRMA risk assessments in Costa Rica. Beyond its technical strength, the model's prior use in the insurance sector supports its validity and practical applicability for real-world risk management, aligning with the needs of the GRMA project and other initiatives across Latin America and the Caribbean.

4.5 Spatial Data on Earthquakes

The available geospatial datasets related to this model are provided as part of Annex 1 of this report. They include a synthetic earthquake catalogue generated for probabilistic seismic hazard representation in Costa Rica, based on the ASLAC model. The information in the described .AME file allows for the generation of seismic hazard maps for different return periods.

4.6 Summary of Seismic Hazard Models and Information

Model or Information Source	Observations	Availability	Limitations	Advantages	Information Type
RESIS II Model (NORSAR et al., 2008)	Historical, validated model; includes PGA and SA maps for various return periods	Available via CAPRA; integrated by INGENIAR-CIMNE	Outdated; replaced by more recent models	Methodologically compatible, useful as reference	Probabilistic, geospatial, technical
Costa Rica Seismic Hazard Model (2022)	Developed by UCR, RSN, ICE, LANAMME/ECG; includes zoning and maps for 475 and 2475 years	Not available for this project (missing base inputs)	No access to detailed source and attenuation models	Updated, detailed, institutionally validated	Academic, technical, not implemented
ASLAC Model (Salgado-Gálvez et al., 2018)	Harmonized model for LAC; includes full synthetic catalogue	Fully available; accessible to the consultant	No relevant limitations for GRMA	Most updated and robust model; used by CCRIF and insurers	Probabilistic, geospatial, stochastic

5 CAPACITY BUILDING PROGRAM

As part of the capacity-building process in the use of seismic, volcanic, and landslide hazard data for risk assessments, the Disaster Risk Probabilistic Modelling Course is being developed under this project.

This course is aimed at professionals, specialists, and researchers involved with the GRMA - Costa Rica Technical Working Group, as well as staff from other local entities, with academic backgrounds in earth sciences, engineering, mathematics, physics, econometrics, or financial/actuarial analysis.

The main objective of the course is to provide participants with the scientific foundations necessary to understand, perform, and interpret risk modelling. Upon completing the training process, participants will be capable of conducting risk assessments for natural hazards using advanced tools from the CAPRA-ROBOT system.

The asynchronous virtual course officially began on March 18, 2025. It has an approximate duration of 24 weeks with an estimated workload of 2 hours per week, although the actual duration depends on each participant's personal dedication. The course covers all modelling topics outlined in the GRMA - Costa Rica project, as detailed in the Inception Report for this consultancy. This includes training activities on seismic, volcanic, and landslide hazard and risk assessment.

5.1 Participantes en el curso virtual asincrónico

Participants enrolled in the asynchronous virtual course were selected through a consultation process conducted by SUGESE, which handled the institutional call for participation. Each institution, following SUGESE's request, defined which of its staff or related experts would participate in the course.

Currently, the course has 56 registered participants, coming from various institutions associated with the project, as detailed below:

Table 4. Number of participants by institution

Institution	Enrolled
Aseguradora del Itsmo (ADISA) S.A.	1
Aseguradora Sagicor Costa Rica S.A.	1
ASSA Compañía de Seguros	1
Banco Central de Costa Rica (BCCR)	2
Comisión Nacional de Prevención de Riesgos y Atención de Emergencias (CNE)	8
Davivienda Seguros Costa Rica S.A.	1
Escuela de Geología, Universidad de Costa Rica	5
Futurismo	3
Instituto Meteorológico Nacional (IMN)	3
Instituto Nacional de Seguros	2
Laboratorio Nacional de Materiales y Modelos Estructurales, Universidad de Costa Rica (LANAMME/ECG)	8
MAPFRE Seguros Costa Rica S.A.	2

Institution	Enrolled
Ministerio de Agricultura y Ganadería (MAG)	3
MNK Seguros	1
Municipalidad de Heredia	5
Seguros LAFISE Costa Rica S.A.	1
Sistema de Banca para el Desarrollo	2
Superintendencia General de Seguros (SUGESE)	7

The course is structured into three main modules:

- Module 1: Fundamentals
- Module 2: Components of Risk Modeling
- Module 3: Advanced Applications

The content and scope of Module 2 are presented below, as it contains the specific training activities on landslide, volcanic, and seismic hazard assessment.

5.2 Module 2 – Components of Risk Modeling

Module 2 focuses on the modeling of natural hazards and the assessment of vulnerability of exposed elements. In this module, each participant can select their hazard of interest among those covered by the GRMA project. The module provides materials related to hazard modeling for all phenomena included in the GRMA project.

Given the scope of this report, a summarized description is presented here of the modules related specifically to the assessment of landslide, volcanic, and seismic hazards.

5.2.1 Landslides

This module begins by covering the methods required to integrate climate change into the assessment of hydrometeorological risks, given that phenomena such as intense rainfall—a key trigger for landslides are significantly affected by this phenomenon. Climate change is incorporated as a modifier of meteorological forcings, altering traditional risk metrics and leading to imprecise probability estimates.

To address this deep uncertainty, the theory of random sets is introduced, providing a solid mathematical basis for rigorously considering climate change effects in risk evaluations. Global climate projections up to the year 2100 are also employed to illustrate the simulation process of meteorological variables indexed to multiple future scenarios.

Subsequently, the course addresses mass movement processes, landslide classification, and propensity assessment. Artificial Neural Networks (ANN) are introduced as a tool for modelling susceptibility and hazard from landslides triggered by rainfalls and earthquakes.

Table 5 presents the topics of each unit related to landslide hazard.

Table 5. Module 2 Syllabus: Landslide

Unit	Title	Topics
1	Basic Concepts of Climate Change	• Earth's climate system • Energy balance • General atmospheric circulation • Radiative forcing • Greenhouse gas emissions • Global circulation models • Global projections
2	Integration of Climate Change in Hazard and Risk Modeling	• Downscaling • Stochastic simulation • Scaling rules • All variations model
3	Mass Movements	• Mass movement processes • Landslide classification • Landslide propensity • Introduction to neural networks
4	Landslide Susceptibility	• Modeling of slope susceptibility
5	Landslide Hazard Modeling	• Rainfall-landslide thresholds • Rain-triggered landslides • Earthquake-triggered landslides

Theoretical sessions will be complemented by hands-on exercises where students will learn to use specialized software tools for landslide hazard modelling, including:

Drought Pro: An advanced simulation tool that enables stochastic modeling of meteorological forcing, particularly rainfall as a triggering phenomenon for landslides. The system was initially conceived for drought modeling (hence its name) but has since evolved into a general climate simulation system. Using a stochastic climate generator, Drought Pro creates multiple simulations of meteorological variables—such as precipitation and temperature—based on the available historical daily series from the territory. Given these capabilities, it is now employed in the probabilistic modeling of a wide range of phenomena, including droughts, floods, landslides, and wildfires, by enabling the construction of probabilistic models of meteorological forcing.

Landslide Hazard Mapper (LHM): A specialized tool for probabilistic landslide hazard assessment. Landslide susceptibility is evaluated through an Artificial Intelligence model—specifically a Deep Learning ANN—trained to classify each site as either susceptible or not (in terms of its probability of being susceptible) based on its intrinsic characteristics. Triggering factors are defined as a set of seismic or rainfall events, each associated with thresholds for seismic acceleration and rainfall intensity. LHM calculates the probability of exceeding these thresholds upon the occurrence of each triggering event and then aggregates, for each site, the total probability of landslide occurrence.

Participants will be capable of conducting probabilistic landslide hazard modeling for subsequent risk estimation, using these tools, which are aligned with the CAPRA methodology employed in the GRMA project. These skills are consistent with the objectives of Operational Project 1, aimed at strengthening technical capacities for disaster risk assessment in the road infrastructure sector.

5.2.2 Volcanoes

This module presents the conceptual foundations for probabilistic volcanic hazard assessment. It covers fundamental volcanology concepts and the probabilistic modelling of volcanic products, including ashfall, pyroclastic flows, lahars (mudflows), and lava flows.

Table 6 shows the topics included in each unit related to the volcanic hazard.

Table 6. Module 2 Syllabus: Volcanoes

Unit	Title	Topics
1	Volcanism	• Origin and manifestation of volcanism • Types of volcanoes • Eruptive styles • Volcanic Explosivity Index • Main volcanic products
2	Eruption Column Collapse Regimes	• Eruption magnitudes • Column forcing mechanisms • Collapse regimes • Distribution of buoyant and collapsed materials
3	Volcanic Product Modeling	• Lava flows • Pyroclastic density currents (PDCs) • Lahars • Ashfall • Ballistic projectiles
4	Volcanic Hazard	• Probabilistic modeling of eruption occurrence • Recurrence periods vs return periods • Probabilistic integration

Hands-on exercises will train participants in the use of specialized software for volcanic hazard modelling, such as:

VHAST (Volcanic Hazard Analysis and Simulation Tool): A probabilistic volcanic hazard modeling tool that covers lava flows, pyroclastic flows, ashfall, and lahars (volcanic mudflows). VHAST allows the definition of probable emission sites for volcanic products over a topographic mesh, from which event-by-event distribution models of volcanic products are executed. The tool incorporates eruption column collapse models to robustly represent the hazard associated with explosive eruptions of Vulcanian or Plinian-type volcanoes.

By the end of the module, participants will be capable of conducting probabilistic volcanic hazard modeling for risk estimation purposes, using these tools, fully aligned with the CAPRA methodology employed in the GRMA project. These capabilities are consistent with the goals of Operational Project 1, aimed at strengthening technical capacities for disaster risk assessment in the road infrastructure sector.

5.2.3 Earthquakes

The earthquake module first introduces the conceptual foundations for probabilistic seismic hazard assessment, covering basic seismology, strong ground motion characterization, seismic hazard evaluation methodology, and site response effects.

Table 7 presents the topics included in each unit related to the seismic hazard.

Table 7. Module 2 Syllabus: Earthquakes

Unit	Title	Topics
1	Basic Seismology	• Plate tectonics • Geological faults • Seismic source models • Seismic moment and magnitude • Dislocation distribution and seismic moment release • Seismic waves • Focal mechanisms
2	Strong Ground Motion	• Accelerograms • Source spectra • Random vibrations • Ground motion attenuation models • Structural response
3	Probabilistic Seismic Hazard Assessment (PSHA)	• Seismogenic sources • Seismicity modeling • Attenuation • Stochastic catalogues • Hazard integration • Deterministic evaluation
4	Site Effects	• Definition of site effects • Estimation techniques • 1D elastic response • 1D nonlinear response • Regional site effects

Hands-on sessions will train participants on specialized software tools for seismic hazard modelling, including:

Strong Motion Analyst (SMA): A program for seismic signal processing, site response analysis, ground motion attenuation evaluation, and seismic catalogue processing.

R-CRISIS: The seismic hazard module of the CAPRA-ROBOT platform, developed mainly by Mario Ordaz (UNAM, Mexico). It is a versatile tool for conducting Probabilistic Seismic Hazard Assessments (PSHA) and is used globally across industries such as nuclear energy, insurance, building codes, and seismic microzonation.

By the end of the module, participants will be capable of performing probabilistic seismic hazard modeling for subsequent risk estimation, using these tools, which are associated with the CAPRA methodology employed in the GRMA project. These skills are aligned with the objectives of the Strategic Project, as well as Operational Projects 1 and 3, strengthening the integration of technical tools into disaster risk management efforts in the road infrastructure and tourism sectors.

It is also important to highlight that, given the conceptual similarity of the probabilistic evaluation approaches discussed, participants will likewise gain an understanding of how models such as RESIS II and GRAF have contributed to the seismic hazard assessment in Costa Rica.

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ANNEX 1: GEOHAZARDS MODELS DATASET

As part of the products included in this deliverable, a web repository (Drive) was established to host the landslide, volcanic, and seismic hazard models available for Costa Rica, which will be used in the risk modelling within this project. This repository compiles deliverables 3.1.b, 3.2.b, and 3.3.b, corresponding to the geospatial datasets for landslide, volcanic, and seismic hazards.

Below is a list of the files that comprise this dataset.

The link to access the dataset is:

https://1drv.ms/f/c/3cbf1924fdfe9005/Eg7zJGLtYoBDvqQReY3N2qkBu48YXkE5o4VE_Hj7QJLJHA?e=y7gZNV

Landslide Hazard

Rainfall triggered

This directory contains the files corresponding to the landslide susceptibility grids triggered by rainfall, covering the entire territory of Costa Rica.

The spatial resolution is 90 meters.

File	**Format**
n05w085_sus	.grd
n05w090_sus	.grd
n10w085_sus	.grd
n10w090_sus	.grd

Files with the .grd extension are raster data files generated and used by Surfer software, developed by Golden Software. These files contain a regular grid of numerical values representing a continuous variable across space, typically used for modelling topographic surfaces, geophysical distributions, or spatial interpolation results.

Earthquake triggered

This directory contains the files corresponding to the landslide susceptibility grids triggered by earthquakes, covering the entire territory of Costa Rica.

The spatial resolution is also 90 meters.

File	**Format**
n05w085_sus	.grd
n05w090_sus	.grd
n10w085_sus	.grd
n10w090_sus	.grd

Volcanic Hazard

VHAST projects

This directory contains the following files:

File	**Format**
IRAZÚ	.vpr
TURRIALBA	.vpr

These files contain the parameters of the probabilistic volcanic hazard model, in the project format of the VHAST software (Volcanic Hazard Analysis and Simulation Tool), which is part of the CAPRA-ROBOT platform. The .vpr files store this information in XML format, including eruption recurrence data for a selected magnitude measure (in this case, the Volcanic Explosivity Index, VEI), the location of emission points, and parameters defining the execution of volcanic product distribution models, including control parameters defined as random variables.

Topography

This directory contains the following files:

File	**Format**
AP_26652_FBS_F0150_RT1.dem	.tif
AP_26900_FBS_F0160_RT1.dem	.tif
AP_26900_FBS_F0170_RT1.dem	.tif
AP_26900_FBS_F0180_RT1.dem	.tif

These grids correspond to geospatial fragments of the Digital Elevation Model (DEM) generated from PALSAR sensor data (Phased Array type L-band Synthetic Aperture Radar) onboard the Japanese ALOS satellite (Advanced Land Observing Satellite). The DEM has a spatial resolution of 12.5 meters, and the grids contain elevation values expressed in meters above sea level.

Each .tif file (GeoTIFF format) represents a tile covering a specific geographic area. In this case, the four available grids cover part of Costa Rica, specifically the region crossed by the RN2 highway and the areas where the Turrialba and Irazú volcanoes are located.

Seismic Hazard

This directory contains the following file.

File	**Format**
ASLAC2_CRI_Parametric	.AME

The .AME file format contains a synthetic earthquake catalogue, generated to probabilistically represent the seismic hazard of Costa Rica calculated with the ASLAC model.

This catalogue includes a set of 27,900 simulated earthquake events, defined as Mutually Exclusive and Collectively Exhaustive (MECE), ensuring a complete and non-redundant representation of seismic phenomena. Each event contains information about its location, magnitude, annual occurrence frequency, and parameters needed to compute the first two statistical moments (mean and standard deviation) of the expected spectral accelerations.

This type of file is essential for probabilistic seismic risk modeling, as it allows for the evaluation of the variability and recurrence of potential seismic scenarios. .AME files are compatible with various open-source and licensed analysis tools, including those integrated into the CAPRA-ROBOT platform.