Geographia Technica, Vol. 20, Issue 1, pp 228 to 248

GIS-BASED LANDSLIDE VULNERABILITY MAPPING ALONG THE SUMATRAN FAULT: A CASE STUDY IN PASAMAN REGENCY, INDONESIA

Helfia EDIAL[1*]***, Paus ISKARNI***[1]***, Endah PURWANINGSIH***[1]***, Ratna WILIS***[1]***, Deded CHANDRA***[1]***, Jon HAFNIL***[2]***, Sutria DESMAN***[3]

DOI: 10.21163/GT_2025.201.16

ABSTRACT

The study aims to provide an in-depth analysis of the influence of geological characteristics, land cover, slope levels, and rainfall intensity on landslide susceptibility. The study investigates the impact of the Sumatran Fault's active segments on geological instability and examines how human activities and climatic factors contribute to landslide risks. A quantitative approach integrates geological conditions, slope analysis, land cover classification, and rainfall data, validated through field testing. Data sources include geological maps, Shuttle Radar Topography Mission (SRTM) data, Landsat 9 Operational Land Imager (OLI) and Thermal Infrared Sensor (TIRS) 2024, and historical rainfall records. Supervised classification using the Maximum Likelihood algorithm and overlay analysis facilitated the identification of landslide-prone zones. The results reveal that igneous rocks dominate 41 % of the area, followed by sedimentary (33 %) and metamorphic rocks (25 %), with steep slopes (24–45%) covering 39 %. Annual rainfall exceeds 1500 mm, with areas receiving >2500 mm constituting 46 % of the region. These factors, combined with deforestation and unsustainable land practices, heighten landslide risks, particularly in the western fault zone. High-vulnerability areas account for 13 % of the region, concentrated in steep and fault-affected zones, while medium-vulnerability zones dominate at 86 %. The study concludes that Pasaman Regency requires integrated strategies, including slope stabilization, reforestation, and sustainable land-use practices, to mitigate landslide risks. Infrastructure resilience, community-based disaster management, and climate adaptation measures are critical for reducing socioeconomic impacts and enhancing environmental sustainability. The findings provide actionable insights for disaster risk reduction and land-use planning, emphasizing the interplay between natural and anthropogenic factors in landslide vulnerability.

Key-words: *Sumatran fault; Landslide vulnerability; Pasaman regency; Geological characteristics; GIS-based analysis.*

1. INTRODUCTION

Indonesia, an archipelago of over 17,000 islands, is located in a region highly prone to natural disasters due to its position within the Pacific Ring of Fire (Astari et al., 2024; Putra et al., 2023). Among these disasters, landslides often linked to erosion occur frequently and can cause significant damage (Korup et al., 2007). Landslides refer to the downhill movement of rock, debris, or soil masses, resulting in loss of life, damage to infrastructure, and considerable economic impacts (Alexander, 2005). The risk of landslides is exacerbated by a combination of geological complexity, heavy rainfall, and human activities, especially in areas with active faults, such as Pasaman Regency in West Sumatra Province.

----

[1]*Department of Geography, Universitas Negeri Padang, Padang-Indonesia. (HE) helfia.edial@fis.unp.ac.id, (PI) iskarni.pausi@fis.unp.ac.id, (EP) endahgeo@fis.unp.ac.id, (RW) ratna_geografi@fis.unp.ac.id, (DC) dededchandra@fis.unp.ac.id*

[2]*Faculty of Engineering, Muhammadiyah University of West Sumatra, Padang-Indonesia, (JH) jon_hafnil@umsb.ac.id*

[3]*Study Program of Civil Engineering, Sekolah Tinggi Teknologi Payakumbuh, Payakumbuh-Indonesia, sutriadesman@sttpyk.ac.id*

[*] *Corresponding author*

To provide context from Elfendi & Asrawat (2025), preliminary information on floods and landslides in the Dua Koto Subdistrict, Pasaman, West Sumatra, dated December 14, 2023, highlights the significant impacts of extreme weather. On this date, heavy rainfall caused both floods and landslides in Tonang Raya Village, Dua Koto Sub-district, Pasaman. While the event did not result in any fatalities or injuries, the local health department, in coordination with relevant agencies, took immediate measures to mitigate the effects, including setting up health monitoring stations and ensuring the availability of emergency services. Octavia & Ophiyandri (2025) add series of landslides triggered by a 6.1 magnitude earthquake in Pasaman in February 2022 led to fatalities and several missing persons in Nagari Malampah, highlighting the region's susceptibility to both seismic and weather-related disasters. This ongoing vulnerability underscores the need for comprehensive disaster risk management strategies, especially in regions prone to heavy rainfall and steep terrain, as seen in recent events.

The Sumatran Fault, or the Semangko Fault, is a prominent geological feature extending from Aceh north to Lampung south (Natawidjaja, 2018; Julzarika et al., 2021). This fault consists of several active segments, including the Angkola, Barumun, and Sumpur segments, which pass through Pasaman Regency (Sahara et al., 2018; Wulandari et al., 2023; Dewanto et al., 2022). The activity along these segments increases the region's vulnerability to landslides, particularly during or after seismic events (Setiawan et al., 2020). Pasaman Regency features a varied geological composition, with 31 geological units classified as sedimentary, igneous, or metamorphic rocks, each contributing differently to the area's landslide susceptibility (Santoso et al., 2023). Landslides in Pasaman Regency have caused substantial losses, severely impacting housing, industrial facilities, and agricultural lands. These disasters disrupt social stability and result in significant economic declines. A critical contributing factor is insufficient consideration of slope stability, geological structures, and natural processes during infrastructure development. For example, subdistricts such as North Rao and Bonjol, which are traversed by the Semangko Fault, are highly vulnerable. This vulnerability is attributed to weathered rock formations like slate, phyllite, and breccia, combined with high rainfall (Barber, 2000). Inadequate land cover planning in these areas often neglects the risks posed by unstable slopes, further exacerbating the problem.

Human activities, such as deforestation and unsustainable land cover practices, are major contributors to landslides. Activities like forest logging, converting forested areas into agricultural land, and urban expansion destabilize slopes and accelerate erosion (Blanco-Canqui et al., 2008). In Pasaman Regency, forests dominate the landscape, followed by plantations and rice fields. However, agricultural practices on steep slopes with gradients of 24–45%, which cover 39.2% of the region (Ruwaidah & Rizali, 2022), significantly increase landslide risks. The ongoing transformation of natural landscapes into agricultural and urban zones underscores the urgent need for sustainable land cover practices that balance development and environmental preservation. Furthermore, climate change has intensified the frequency and severity of landslides by increasing rainfall variability and triggering extreme weather events (Gariano & Guzzetti, 2016). Pasaman Regency receives an annual rainfall exceeding 1,500 mm, with peak precipitation occurring between October and January (Nurdin et al., 2020; Santoso et al., 2023). Heavy and prolonged rainfall saturates the soil, diminishing its shear strength and heightening the risk of slope failures (Liu et al., 2021). Implementing adaptive strategies to mitigate the impacts of climate change is vital for ensuring the long-term resilience of communities and ecosystems in landslide-prone areas.

Mitigating landslide risks necessitates a multidisciplinary approach that integrates geological, hydrological, and environmental assessments with community-based disaster management strategies (Kumar, 2024). A comprehensive evaluation of landslide vulnerability includes analyzing geological formations, rock hardness, land cover changes, slope levelss, and precipitation patterns. Developing a robust scientific understanding of these factors is essential for identifying areas at risk and implementing effective mitigation measures. Emphasis must be placed on sustainable engineering solutions and land-use practices that enhance slope stability, thereby minimizing the environmental and socioeconomic consequences of landslides. The study aims to provide an in-depth analysis of the influence of geological characteristics, land cover, slope levels, and rainfall intensity on landslide susceptibility. The novelty of this study lies in its multi-parameter overlay approach, which combines detailed geological classifications with high-resolution land cover and rainfall data specific to Pasaman Regency. The anticipated outcomes of this study are expected to make a significant contribution to disaster risk reduction efforts and the promotion of sustainable land management practices.

2. METHODS

This study employs a quantitative approach to assess landslide vulnerability in Pasaman Regency. The methodology combines field observations, on-site measurements, and satellite imagery analysis, ensuring a comprehensive evaluation of risk factors. To guarantee the reliability and accuracy of the findings, validation is carried out through field testing, providing a robust framework for interpreting the results.

2.1. Study location

The study focuses on Pasaman Regency in West Sumatra Province, a region intersected by the active Sumatran Fault. Astronomically, the study area is situated between latitudes 0°55' N to 0°06' S and longitudes 99°45' to 100°21' E with a total area of 394763 ha. More details can be seen on the map in **Fig. 1** below.

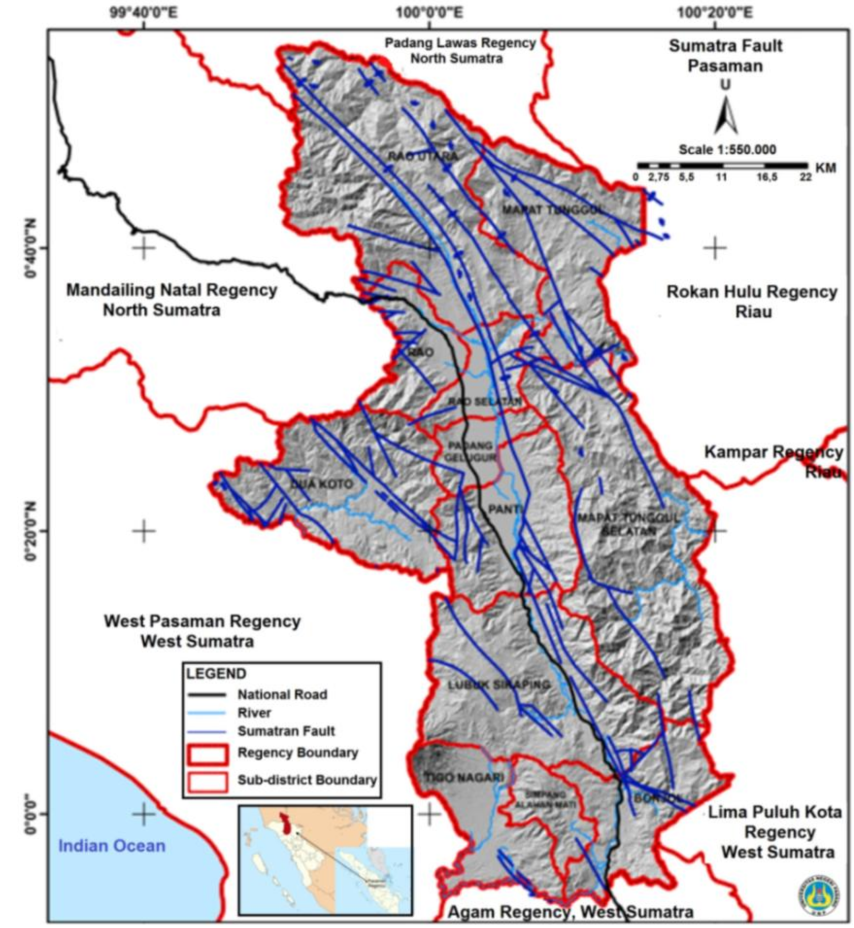

Fig. 1. Map of study location in the Sumatra Fault in Pasaman Regency.

This region exhibits a complex interplay of geological, topographical, and climatic conditions, making it highly susceptible to landslides and an ideal case study for vulnerability assessment. Its geological diversity and proximity to active fault segments significantly amplify its risk for natural disasters, particularly landslides. To enhance the spatial precision of the analysis, GIS tools are employed for mapping and overlaying critical parameters such as slope levels, land cover, rainfall distribution, and geological characteristics. This spatial approach enables a detailed visualization of landslide-prone zones and their correlation with environmental and anthropogenic factors. Additionally, the integration of high-resolution satellite imagery and spatial modeling facilitates the identification of vulnerable areas and aids in developing targeted mitigation strategies. This GIS-based analysis contributes to a more sustainable approach to managing disaster risks by providing actionable insights into land cover planning and environmental conservation.

2.2. Study Procedure

At this stage, various datasets and analytical tools are utilized to ensure a comprehensive assessment. Geological mapping is conducted to determine rock types and their spatial distribution using the Geological Map of the Lubuk Sikaping and Padang Sheets at a 1:250,000 scale, published by the Geological Agency of the Ministry of Energy and Mineral Resources (ESDM) of the Republic of Indonesia. Slope mapping is derived from Shuttle Radar Topography Mission (SRTM) data, while land cover classification employs Landsat 9 Operational Land Imager (OLI) and Thermal Infrared Sensor (TIRS) 2024 imagery to analyze vegetation and land cover patterns. Rainfall analysis uses a 10-year dataset (2010–2020) to study precipitation trends and variability, providing critical insights into rainfall-related landslide triggers.

ArcMap 10.4.1 software is utilized for supervised classification, applying the Maximum Likelihood algorithm to produce precise land cover mappings (Dewata et al., 2024; Atef et al., 2024). Slope categories are reclassified into predefined levels to facilitate comparative analyses. Overlay analysis integrates thematic maps of geological features, slope classifications, land cover, and rainfall data to delineate zones prone to landslides. This integrative approach combines multiple environmental and geological factors to provide a holistic vulnerability assessment.

The validation stage is pivotal for ensuring the accuracy and reliability of the generated maps and analyses. Field tests are performed to ground-truth classified maps and validate spatial analyses. Quantitative validation employs the Confusion Matrix and Kappa Accuracy Test to evaluate the reliability of land cover classifications and landslide vulnerability analyses (Chowdhury, 2024). This rigorous validation process ensures the results reflect real-world conditions, minimizing errors and uncertainties in the final outputs.

The final stage focuses on categorizing landslide vulnerability zones into high, medium, or low levels. This involves evaluating the interactions among key factors, including geological conditions, slope classifications, land cover dynamics, and rainfall intensity. By utilizing high-resolution data, and geospatial analyses, this approach enhances spatial accuracy and provides actionable insights for sustainable land-use planning and disaster risk mitigation.

2.3. Data Analysis Techniques

Guided classification, also referred to as supervised classification, is a process conducted under the supervision of analysts. Class groupings are defined based on the unique characteristics of each class, known as class signatures, which are derived from creating sample areas, or training areas (Putra et al., 2023). This approach involves selecting representative pixel samples for each class or object of interest. These samples, referred to as Regions of Interest (ROIs), are utilized to extract the pixel value characteristics specific to each class or object (Xiao et al., 2015). The accuracy test is an essential step to evaluate the reliability of the classification model. This test determines the degree of agreement between the classified image and the reference data (Alqadhi et al., 2021). Producer's accuracy measures the probability (%) that a pixel is correctly classified, reflecting how accurately each category has been identified. User's accuracy, on the other hand, represents the likelihood (%)

that a pixel from the classified image accurately corresponds to the actual field data (Stuckens et al., 2000). The formula for the Kappa Accuracy Test is as follows:

$$\text{Kappa Accuracy} = \frac{N \sum_{i=1}^{r} X_{ii} - \sum_{i=1}^{r} X_{i+}.X_{+1}}{N^2 - \Sigma X_{i+}.X_{+i}} 100\%$$

where: N = Total number of pixels in the sample; X_{ii} = Diagonal values in the contingency matrix for the i-th row and i-th column; X_{i+} = Total number of pixels in the i-th row; and X_{+i} = Total number of pixels in the i-th column

The accuracy test not only validates the effectiveness of the classification process but also strengthens spatial decision-making. By integrating GIS-based accuracy assessments, this method provides critical insights for sustainable land management and disaster mitigation planning. Accurate classification supports environmental sustainability by enabling precise monitoring of land cover changes, thereby informing policies aimed at reducing erosion and landslide risks.

The assessment of landslide vulnerability in Pasaman Regency was conducted using a quantitative approach that integrates thematic maps representing four critical parameters contributing to landslide risk, namely geological conditions, land cover, slope levels, and rainfall intensity. According to Masruroh et al. (2024), these maps were utilized to analyze the spatial distribution of each factor and their combined effect on the region's susceptibility to landslides. Based on the overlay analysis (Tešić et al., 2020), three distinct landslide vulnerability zones were identified: namely low vulnerability, medium vulnerability, and high vulnerability (Upadhyay, 2024). Each zone corresponds to varying levels of risk, determined by the interaction of the four parameters. High-vulnerability zones are typically characterized by steep slopes, fragile geological formations, and high rainfall. In contrast, low and medium vulnerability zones are associated with more stable geological and topographical conditions, making them less prone to landslides (Triyatno et al., 2020; Beshir et al., 2024). The following analysis provides detailed descriptions of the parameters contributing to these vulnerability zones, offering insights into the factors that influence landslide risk across Pasaman Regency. The detailed analysis of each parameter is presented below.

2.3.1. Geological conditions and scoring

The geological conditions of Pasaman Regency are diverse, with a variety of rock types that significantly influence landslide susceptibility. The geological map, which categorizes the region into sedimentary, igneous, and metamorphic rocks (Geological Map of the Lubuk Sikaping and Padang Sheets at a 1:250,000 scale), shows varying vulnerability across different regions. For more clarity, see **Table 1** below.

Table 1.

Distribution of geological conditions and vulnerability scores in Pasaman Regency.

Rock Type	Score
Igneous	1
Sedimentary	2
Metamorphic	3

These rock types are distributed unevenly across the region, with igneous rocks being the most dominant, followed by sedimentary and metamorphic rocks. Igneous rocks, especially in regions influenced by fault lines like the Semangko Fault, are prone to weathering and are more likely to cause landslides when combined with steep slopes and heavy rainfall. In contrast, sedimentary and metamorphic rocks offer greater stability but still require mitigation efforts in fault-affected zones.

2.3.2. Land cover and scoring

Land cover plays a critical role in stabilizing slopes and mitigating landslide risks. The results from the Landsat 9 OLI/TIRS 2024 analysis highlight the distribution of key land cover types across Pasaman Regency. For more clarity, see **Table 2** below.

Table 2.

Distribution of land cover and vulnerability scores in Pasaman Regency.

Land Cover	Score
Forest	1
Plantation	2
Ricefield	2
Shrubs	2
Water Bodies	3
Built-up Land	3
Open Land	3
Dry Field	3

Forested areas are key to stabilizing slopes, particularly in high-risk regions influenced by fault lines. Plantations, ricefields, and shrubs pose medium risks due to their impact on soil stability, while built-up areas and water bodies represent areas with high erosion and flood risks. Sustainable land management practices are crucial in regions with higher levels of human activity to mitigate these risks.

2.3.3. Slope levels and scoring

Slope analysis conducted using SRTM data shows that steep slopes significantly contribute to landslide susceptibility, particularly in regions intersected by active fault lines. For more clarity, see **Table 3** below.

Table 3.

Distribution of slope levels and vulnerability scores in Pasaman Regency.

Slope Levels	Score
24% - 45%	1
< 15%	2
15% - 24%	2
> 45%	3

The most dominant slopes are in the 24% - 45% range, which are prone to landslides, especially along fault lines. The steeper slopes, categorized as >45%, are particularly vulnerable and need urgent mitigation. Flatter and mediumly sloped areas are more suitable for settlements and agriculture, with a medium level of risk.

2.3.4. Rainfall conditions and scoring

Rainfall data for Pasaman Regency was processed to identify regions vulnerable to rainfall-induced landslides. Areas with high rainfall are significantly more prone to slope failure, especially in regions with steep terrain. For more clarity, see **Table 4 below**.

Table 4.

Distribution of rainfall and vulnerability scores in Pasaman Regency.

Annual Rainfall (mm)	Score
1500 - 2500	1
> 2500	2

Regions experiencing high rainfall (>2500 mm/year) are at a much higher risk of landslides. Heavy rainfall combined with steep terrain, especially in the High Vulnerability Zone, amplifies the risk of slope failure. Areas with medium rainfall still face risks, but the overall threat is lower.

2.3.5. Landslide vulnerability zones in Pasaman Regency

The landslide vulnerability zones in Pasaman Regency have been identified through a comprehensive analysis of key geological and environmental parameters. Based on the integration of geological conditions, land cover, slope levels, and rainfall intensity, three distinct vulnerability zones were established (Low, Medium, and High). These zones reflect varying levels of risk, determined by the interaction of these factors. **Table 5** below summarizes the characteristics and scoring for each vulnerability zone, providing an overview of the land's susceptibility to landslides. The subsequent analysis further explains the spatial distribution and significance of each zone in terms of landslide risk across the region.

Table 5.

Landslide vulnerability zones in Pasaman Regency.

Vulnerability Zone	Score	Key Characteristics
Low	1	Dominated by flat terrain with alluvial and metamorphic rocks, minimal risk of landslides.
Medium	2	Predominantly sedimentary rocks with medium slopes and rainfall. Landslides are rare to medium.
High	3	Steep slopes, high rainfall, and fragile igneous rocks in fault zones. High risk of landslides.

For the research methodology, the study categorizes landslide vulnerability into three distinct zones (low, medium, and high). Low vulnerability zones are characterized by flat terrain and alluvial or metamorphic rocks, which present minimal landslide risk. Medium vulnerability zones are predominantly found in areas with sedimentary rocks, medium slopes, and rainfall. These regions experience a rare to medium occurrence of landslides. High vulnerability zones, which include steep slopes, high rainfall, and fragile igneous rocks, are at the highest risk for landslides, particularly in fault-affected areas. This classification helps in understanding the spatial distribution of landslide risks across Pasaman Regency.

3. RESULTS

3.1. Geological Conditions of Pasaman Regency

Based on observations from the Geological Map of the Lubuk Sikaping and Padang Sheets at a scale of 1:250,000, produced by the Geological Agency of the Ministry of Energy and Mineral Resources (ESDM) of the Republic of Indonesia, the geological conditions of Pasaman Regency are defined by a diverse range of rock formations and active fault lines. This makes the region significant for the study of geological processes, disaster mitigation, and sustainable land management. Observational data and geological mapping reveal that the rock outcrops in Pasaman Regency consist of 31 geological units. These units are classified into three primary rock types: sedimentary, igneous, and metamorphic rocks. Their distribution and respective areas are summarized in **Table 6** and **Figure 2** below.

Table 6.

Distribution of rock types in Pasaman Regency.

Rock Type	Area (Ha)	Percentage (%)	Score
Igneous	163124	41	1
Sedimentary	131005	33	2
Metamorphic	100634	25	3
Total area of Pasaman Regency	**394763**	**100**	

Source: Results of observations from the Geological Map of the Lubuk Sikaping and Padang Sheets at a scale of 1:250.000.

In **Table 6** and **Figure 2** the distribution of three primary rock types in Pasaman Regency igneous, sedimentary, and metamorphic rocks along with their respective areas and proportions. These rock types are distributed unevenly across the region, reflecting the geological diversity shaped by active fault lines and tectonic processes. Igneous rocks are the most dominant, covering 41 % of the area (163124 ha). These rocks, often associated with volcanic activity, are prevalent in regions influenced by the Semangko Fault and its segments (Sieh & Natawidjaja, 2000). Their presence suggests significant tectonic and volcanic processes that have shaped the region’s geological history.

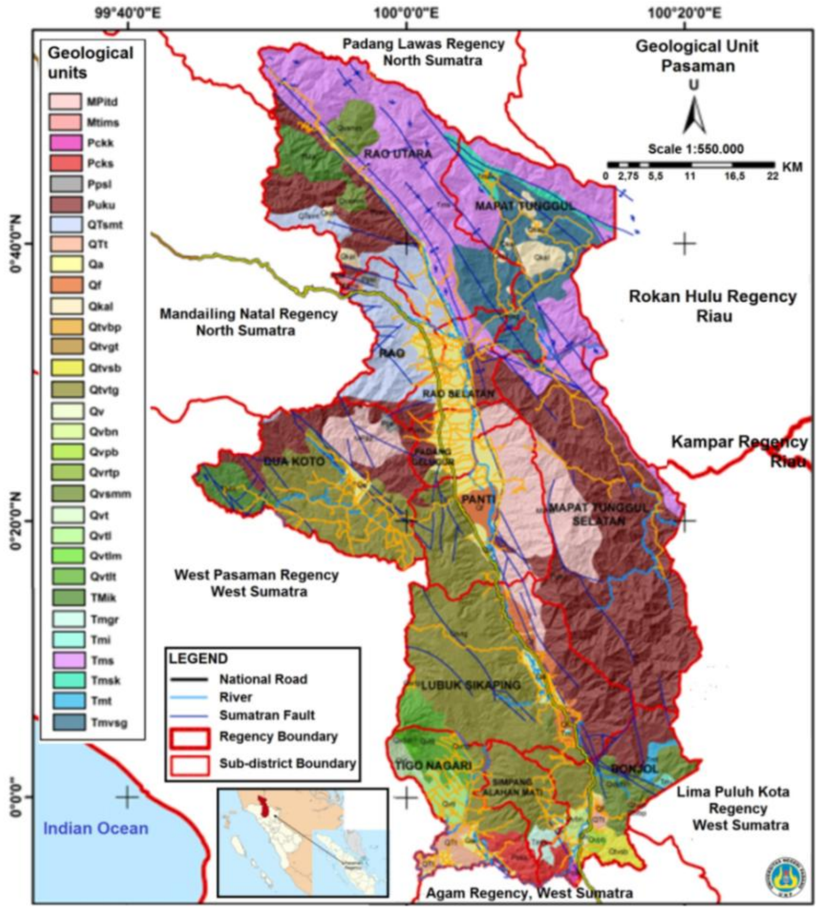

Fig. 2. Map of geological unit in Pasaman Regency (Source: Geological Map of the Lubuk Sikaping and Padang Sheets at a 1:250,000 scale).

The igneous formations, including andesite and other volcanic rocks, form much of the hilly and mountainous terrain (Aryantie et al., 2023). However, these steep slopes are prone to landslides, especially in areas with high rainfall. Sustainable land cover practices and slope stabilization measures are essential to mitigate these risks.

Sedimentary rocks account for 33% of the total area (131005 ha), making them the second most prevalent rock type. These rocks, typically deposited in low-energy environments like basins, include formations such as shale, sandstone, and limestone. Sedimentary layers often serve as aquifers or reservoirs for groundwater, which are vital for agricultural activities (Keesari et al., 2015). Their relatively flat terrain makes them more suitable for settlements and farming. Metamorphic rocks, which 25 % of the area (100634 ha), are typically found in regions that have experienced intense tectonic activity. These rocks, such as slate, phyllite, and schist, are generally harder and more resistant to weathering compared to sedimentary rocks (Yao et al., 2015). However, when weathered, they may become susceptible to slope instability, particularly in hilly areas. The presence of metamorphic rocks in fault-affected zones underscores the need for careful planning and infrastructure development to mitigate geological hazards. The geological diversity in Pasaman Regency highlights the need for sustainable land management practices that align with the distinct characteristics of each rock type. Igneous rock regions, with their significant geothermal potential, offer opportunities for renewable energy development, which could drive local economic growth. Sedimentary rock regions, being well-suited for agriculture and settlements, require effective erosion control measures to ensure long-term productivity and prevent land degradation. In contrast, metamorphic rock regions present opportunities for conservation and reforestation, which are essential for mitigating natural disasters such as landslides.

This diverse geological composition makes Pasaman Regency a prime candidate for the development of a geopark. The area's varied rock formations and distinctive geomorphological features offer significant opportunities for educational tourism and environmental conservation. These initiatives can foster socio-economic growth while ensuring long-term sustainability. The geological landscape of Pasaman Regency is highly diverse across its regions, shaped by the intricate interactions of rock types, active fault lines, and climatic conditions. The distinct geological characteristics of each region and their potential contributions to sustainable development are shown in **Table 7** below.

Table 7.

Geological conditions and management recommendations for areas around the Semangko Fault.

Areas	Geological Conditions	Rock Type & Hardness	Management Recommendations
North Rao	Intersected by the Semangko Fault, dividing the region into western and eastern parts.	– Weathered Phyllite (Pckk), Hardness: 4–5 – Slate (Puku), Hardness: 4 – Breccia (Qvsmm), Hardness: 6	– Implement integrated slope management strategies. – Strengthen conservation of vegetation cover. – Enforce strict land cover regulations to mitigate landslides and soil erosion.
South Rao	Fault boundary separating volcanic tuff in the west and phyllite in the east.	– Volcanic Tuff (Qtvsb), Hardness: 4 – Phyllite, predominantly in forested areas	– Preserve forested areas to maintain ecological balance and reduce erosion. – Implement sustainable agroforestry practices to enhance disaster resilience.
Panti	Dominated by volcanic tuff sedimentary rocks in the northern hills; flat alluvial plains in the central region.	– Volcanic Tuff Sedimentary Rocks – Andesite Igneous Rocks (QTt), Hardness: 6 – Alluvial Deposits (Qf)	– Promote sustainable agricultural practices, especially in the central plains. – Implement erosion control and reforestation programs in hilly terrains. – Explore geothermal energy potential in areas with hot springs.
Lubuk Sikaping	Geologically diverse, with various rock formations and fault depressions.	– Quarter Andesite (Qa) – Quarter Fluvial (Qf) – Breccia Rocks (Qvsmm) – Volcanic Quarter Rocks (Qv) - Slate (Puku)	– Develop geopark potential for educational tourism and conservation. – Utilize GIS-based land cover planning for sustainable development.
Bonjol	Marked by slate and breccia volcanic quarter rocks, with sub-fault activity.	– Slate (Puku) – Breccia Volcanic Quarter Rocks (Qvsmm) – Quarter Fluvial (Qf) – Quarter Pumice Tuff, Hardness: 4–6	– Prioritize conservation efforts to reduce soil erosion. – Promote afforestation to stabilize slopes. – Use GIS-based assessments for disaster mitigation strategies. – Explore geothermal potential for renewable energy projects and tourism development.

Source: Hikmatullah et al. (1990).

This is derived from the Explanatory Booklet of the Land Unit and Soil Map of the Lubuk Sikaping Sheet (0715), Sumatra: Land Resources Evaluation and Planning Project, Soil Data Base Management and the Geological Map of the Lubuk Sikaping (Hikmatullah et al., 1990) and results of observations from the Geological Map of the Lubuk Sikaping and Padang Sheets at a scale of 1:250.000.

3.2. Land Cover 2024 Conditions of Pasaman Regency

To identify and analyze the land cover in Pasaman Regency, image interpretation was conducted using Landsat 9 OLI/TIRS 2024. The interpretation involved composing specific bands to enhance the visualization and differentiation of various land cover types. The composite bands used were Bands 4, 3, and 2 (Natural Band) and Bands 6, 5, and 3. These combinations allow for a detailed analysis of natural and anthropogenic land cover features, highlighting vegetation, water bodies, and urbanized areas. The supervised classification method ensures high accuracy by leveraging field data and expert knowledge for calibration.

The results of the analysis were used to generate a detailed land cover map of Pasaman Regency, highlighting the spatial distribution of key land cover types, including forests, plantations, agricultural lands, water bodies, and built-up areas in 2024. This map provides critical insights into the region's current land cover patterns and serves as a foundation for assessing environmental sustainability and disaster mitigation planning. These efforts align with global goals for sustainable development and climate resilience. The detailed land cover in Pasaman Regency, highlighting these classifications for land cover, can be seen in **Table 8** and the map in **Fig. 3** below.

Table 8.

Distribution of land cover 2024 in Pasaman Regency.

Land Covers	Area (Ha)	Percentage (%)	Score
Forest	304573	77	1
Plantation	43770	11	2
Ricefield	20940	5	2
Shrubs	16472	4	2
Water Bodies	2516	1	3
Built-up Land	1369	0	3
Open Land	2810	1	3
Dry Field	2313	1	3
Total area of Pasaman Regency	**394763**	**100**	

Source: Results of data analysis from Landsat 9 OLI/TIRS 2024.

The spatial distribution of land cover types, as visualized in **Fig. 3** above, demonstrates a strong relationship between natural features and human activities. Forested areas are concentrated in the central and southern regions, which feature higher elevations and frequently intersect with the Sumatran Fault. These regions are vital for disaster risk mitigation, as forest cover reduces the likelihood of landslides in steep and fault-affected zones. In contrast, plantations are concentrated in relatively flatter northern areas, underscoring their suitability for agriculture. Built-up areas are minimal and scattered, primarily near subdistrict centers like Lubuk Sikaping, indicating controlled urbanization consistent with the region's rural character.

The land cover conditions in Pasaman Regency, as depicted in **Table 2** above shows that the region's land cover dynamics for 2024. Forests dominate the landscape, covering 305473 ha, which accounts for 77 % of the total area. This extensive forest coverage highlights the region's rich biodiversity and ecological importance. Forests play a pivotal role in maintaining slope stability, regulating the hydrological cycle, and serving as carbon sinks. Their conservation is crucial, particularly in fault-affected areas that are vulnerable to landslides and soil erosion.

Plantations constitute the second-largest land cover type, occupying 43770 ha or 11 % of the total area. These plantations are predominantly located in the northern and northeastern regions, where medium slopes and suitable soil conditions support agricultural activities.

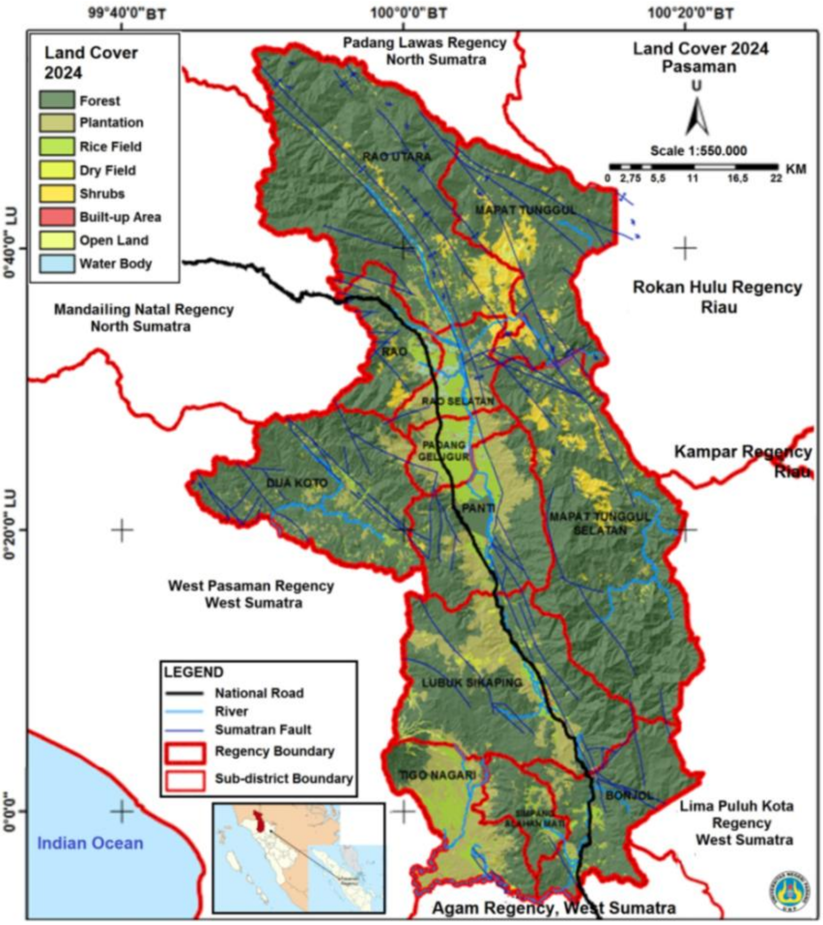

Fig. 3. Map of land cover 2024 in Pasaman Regency.

While plantations contribute significantly to the local economy, implementing sustainable agricultural practices such as agroforestry and soil conservation techniques is essential to prevent land degradation and sustain productivity over the long term. Built-up land and open fields collectively make up less than 0 % of the total land cover, reflecting the predominantly rural and natural character of Pasaman Regency.

These areas are essential for infrastructure development and urban expansion but must be carefully managed to avoid encroaching on ecologically sensitive zones. Rice fields, covering 20940 ha or 5%, and dry field, covering 2313 ha or 1 %, play a vital role in ensuring food security and supporting local livelihoods. Promoting sustainable farming methods in these areas is critical to mitigate erosion and adapt to climate variability. Shrubs and water bodies, which represent 16472 ha or 4 % and 2516 or 1 % of the land cover respectively, also contribute to the region's ecological balance. Shrublands act as transitional ecosystems that support wildlife, while water bodies and rivers are crucial for hydrological stability and agricultural irrigation. The proximity of different land cover types to fault lines emphasizes the importance of integrated spatial planning and disaster risk reduction strategies. Additionally, sustainable watershed management is critical for maintaining water bodies and rivers, which are essential for ecological health and agricultural productivity. To ensure the accuracy of the supervised classification results and validate the reliability of the land cover mapping, an Accuracy Test was conducted. This involved creating a Confusion Matrix, as shown in **Table 9**. The matrix compares predicted land cover categories with reference data, identifying areas of agreement and discrepancies.

Table 9.

Confusion Matrix Land Cover Pasaman Regency.

Land Cover Class	Water Bodies	Forest	Built-up	Open Land	Plantation	Rice field	Shrubs	Dry Field	Total
Water Bodies	4	0	0	0	0	0	0	0	4
Forest	0	5	0	0	0	0	0	0	5
Built-up Land	0	0	4	0	0	0	0	0	4
Open Land	0	0	0	4	0	0	0	0	4
Plantation	0	1	0	0	6	0	1	0	8
Ricefield	0	0	0	0	0	4	0	0	4
Shrubs	0	1	0	0	0	0	3	0	4
Dry Field	0	0	0	0	0	0	0	3	3
Total	**4**	**7**	**4**	**4**	**6**	**4**	**4**	**3**	**36**

Source: Results of data analysis 2024.

Metrics such as producer accuracy, user accuracy, and the Kappa coefficient were used to assess the performance and precision of the classification method applied to Landsat 9 OLI/TIRS 2024 imagery. These insights are critical for evaluating the effectiveness of the classification process and refining future land cover analyses.

The accuracy test results for the land cover classification in Pasaman Regency show an overall accuracy of 92 % and a Kappa Accuracy Test value of 90 %, exceeding the minimum interpretation accuracy standard of 85%. These values confirm that the classification is highly reliable and consistent. The Maximum Likelihood Algorithm used in the supervised classification effectively distinguishes different land cover types, such as forests, plantations, rice fields, and built-up areas. The confusion matrix in **Table 9** shows minimal misclassification, further validating the accuracy of the land cover map. This reliable classification is essential for various applications, namely 1) Accurate mapping of forests and plantations supports conservation efforts and biodiversity protection; 2) Identifying land cover near fault lines helps prioritize slope stabilization and landslide mitigation; 3) Precise classification of rice fields and plantations aids in optimizing land cover for agriculture; and 4) Accurate mapping of built-up and open land areas guides controlled urban development. The high accuracy also highlights the importance of satellite imagery, field validation, and GIS-based analysis in producing reliable results.

3.3. Slope Levels in Pasaman Regency

The slope levels in Pasaman Regency were analyzed using SRTM data processed with the slope tool in ArcMap 10.4.1 software. This method calculates the gradient of terrain for each pixel, producing raster data that was then reclassified into slope classes such as flat, gently sloping, mediumly steep, steep, and very steep. The reclassified raster data was converted into polygons to calculate the area in hectares for each slope category. The resulting slope map provides a clear visualization of the region's topography. This analysis is crucial for various applications. Areas with steep slopes are identified as more prone to landslides, especially in regions with active faults or high rainfall, helping in disaster risk reduction. Flat and gently sloping areas are better suited for agriculture and urban development, while steep regions require careful planning to minimize erosion and environmental impact. Additionally, the slope data supports conservation efforts, such as targeted reforestation and soil erosion control, while also highlighting potential ecotourism opportunities in geologically unique areas. The detailed slope map, showing the distribution of slope levels, can be seen in **Table 10** and the map in **Fig. 4** below. It can be observed that the most dominant Slope Levels in Pasaman Regency fall within the category of 24-45%, covering an area of 154878 ha or 39 %. This indicates that a significant portion of the region consists of mediumly steep slopes. These areas are predominantly located along the fault zones and hilly terrains, as shown on the map, which aligns with the region's geological complexity. The slopes ranging from 15-24%, covering 91754 ha or 23 %, represent gently sloping areas commonly utilized for agriculture and plantations, as observed in regions with fertile soils and flatlands near river systems.

Table 10.
Slope levels distributions in Pasaman Regency.

Slope Levels	Area (Ha)	Percentage (%)	Score
24% - 45%	154878	39	1
< 15%	132235	33	2
15% - 24%	91754	23	2
> 45%	15896	4	3
Total area of Pasaman Regency*	**394763**	**100**	

Source: Results of data analysis 2024.

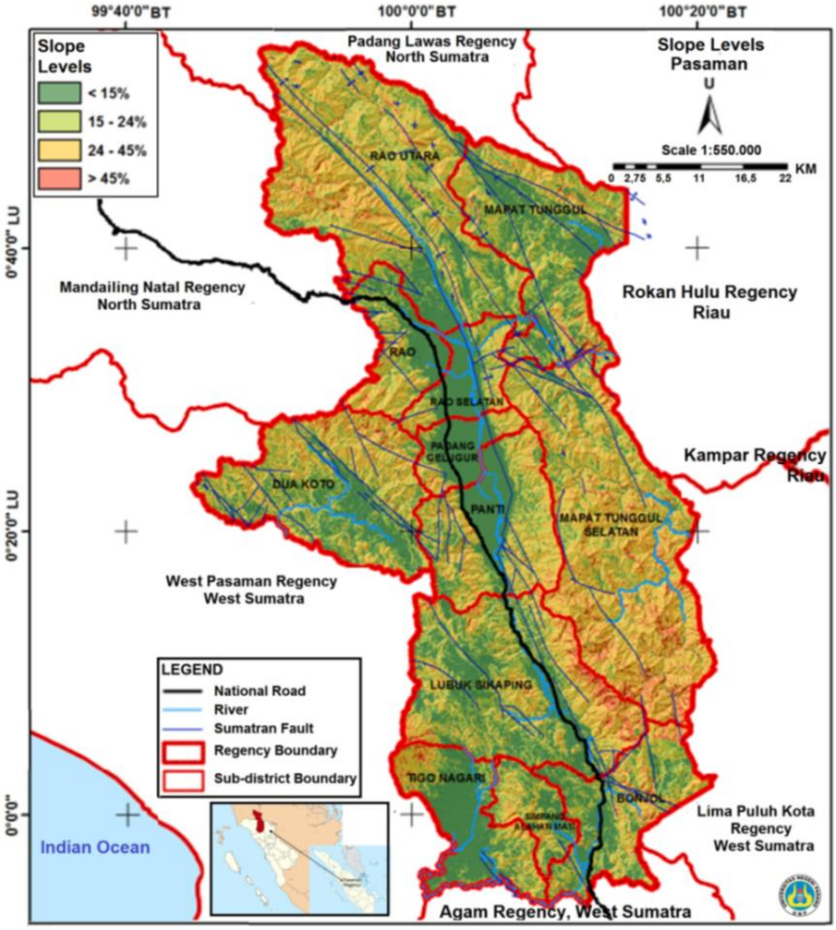

Fig. 4. Map of slope levels in Pasaman Regency.

Meanwhile, slopes below 15% occupy 132235 ha or 33 %, making them ideal for settlements and infrastructure development. However, the smallest slope category (>45%) constitutes only 4% of the total area (15896 ha), representing very steep regions that are highly vulnerable to erosion and landslides. The distribution of slope levels across Pasaman Regency indicates a terrain that varies from flat to steep, requiring integrated land cover planning and environmental management. Steeper slopes, which dominate much of the area, necessitate sustainable practices such as terracing, reforestation, and slope stabilization to prevent soil erosion and support ecological balance. Flatter regions, on the other hand, provide opportunities for sustainable agricultural expansion and urban development while minimizing the risk of natural disasters.

3.4. Rainfall Conditions in Pasaman Regency

Rainfall patterns are vital for understanding the environmental dynamics of Pasaman Regency, particularly its vulnerability to natural disasters such as landslides. Prolonged and intense rainfall increases soil saturation, weakens shear strength, and significantly raises the risk of slope failures in steep regions (Igwe, 2016). As such, monitoring rainfall trends is essential for disaster preparedness and mitigation efforts. Additionally, rainfall data plays a key role in sustainable water resource management for the region. By integrating rainfall patterns into land cover planning, Pasaman Regency can achieve a better balance between development objectives and environmental conservation. The combination of rainfall data with slope analysis and land cover mapping provides a comprehensive approach to environmental management. This enables policymakers to identify vulnerable areas and prioritize sustainable development strategies effectively. For this study, rainfall data for Pasaman Regency were sourced from the Agency of Water Resources Management in West Sumatra Province. Data were collected from five rainfall monitoring stations over 10 years, from 2010 to 2020. The detailed rainfall data are presented in **Table 11** and **Tabel 12** below.

Table 11.

Annual rainfall data by station in Pasaman Regency (2010–2020).

Year	Rainfall Station/Post				
	Ganggo Mudiak	Ujung Gading	Rao	Muaro Tanjung	Bendungan Panti/Rao
2010	4561	5862	1706	2138	1646
2011	3716	2044	1663	2612	6193
2012	4013	1230	1779	2512	2371
2013	4468	1820	2736	2864	2633
2014	3945	7430	1945	2377	1893
2015	4016	5902	1945	3052	1076
2016	3426	4574	1592	3052	2392
2017	5571	4205	2445	4352	2393
2018	4036	2735	2445	3550	2596
2019	4101	3750	2445	3550	1740
2020	3539	3999	1945	3162	1300
Total	**45391**	**43551**	**22647**	**33221**	**26234**
Average	***4126***	***3959***	***2059***	***3020***	***2385***

Source: Data 2024 in the Agency of Water Resources Management in West Sumatra Province.

Table 12.

Annual rainfall distribution in Pasaman Regency.

Annual Rainfall (mm)	Area (Ha)	Percentage (%)	Score
1500 - 2500	212309	54	1
> 2500	183700	46	2

Source: Results of data analysis 2024.

The annual rainfall data is then processed using ArcMap 10.4.1 software with the Isohyet method to create contour lines representing areas of equal rainfall (Singh & Fiorentino, 2013; Venkatramanan et al., 2019; Bhattacharya et al., 2020). This produces raster data, which is reclassified into rainfall classes for easier interpretation. The raster data is then converted into polygons, allowing for precise calculations of each rainfall class's area in hectares. The resulting annual rainfall map, shown in **Table 11** and **Table 12** above, shows the distribution of rainfall across Pasaman Regency. Regions with higher rainfall intensity can be identified for landslide risk management, while areas with lower rainfall can guide irrigation and water conservation efforts. This analysis is essential for sustainable water resource management, helping to align agricultural practices, disaster planning, and environmental conservation with local rainfall patterns (Srivastav et al., 2021). By integrating this data with slope and land cover maps, policymakers can develop strategies to balance development with environmental protection. The detailed rainfall map, showing the annual rainfall distribution (2010–2020), can be seen in the map in **Fig. 5** below.

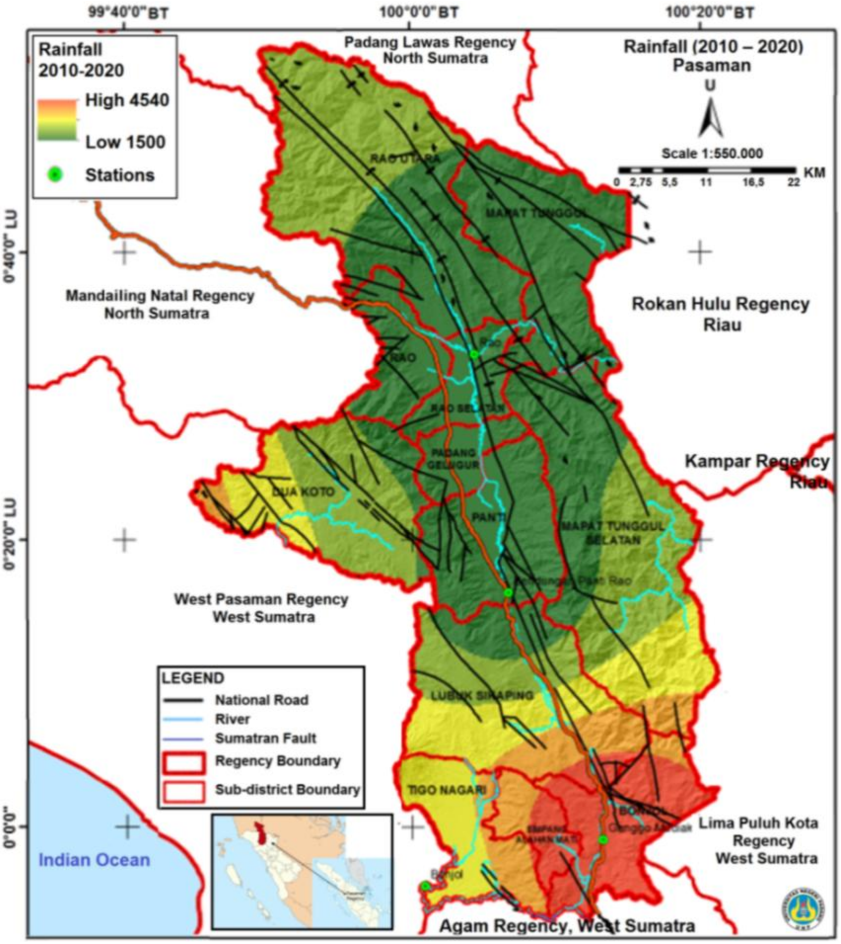

Fig. 5. Map of Annual Rainfall Distribution (2010–2020) in Pasaman Regency.

Based on **Fig. 5**, the annual rainfall distribution in Pasaman Regency is classified as medium to high, with average rainfall consistently exceeding 1500 mm each year. This highlights the region as a high-rainfall area, receiving a significant volume of precipitation annually. Such rainfall patterns play a crucial role in shaping the region's hydrological and environmental systems. Understanding these rainfall trends is vital for effective water resource management, including irrigation planning, flood control, and ensuring water availability for agriculture and other sectors. Moreover, the high rainfall levels contribute to the region's susceptibility to natural hazards, such as landslides and erosion, particularly in areas with steep slopes. Addressing these risks requires integrated planning and sustainable land cover strategies to protect both infrastructure and ecosystems. This information serves as a foundation for developing targeted mitigation measures and promoting environmental resilience, ensuring that communities in Pasaman Regency can adapt to and sustainably manage the impacts of its rainfall characteristics.

3.5. Landslide Vulnerability of Pasaman Regency

The assessment of landslide vulnerability in Pasaman Regency was conducted by overlaying thematic maps representing four key parameters contributing to landslide risk, namely geological characteristics, land cover, slope levels, and rainfall intensity. These maps, as shown in the overlay (**Fig. 6**), illustrate the spatial distribution of each parameter and their combined impact on landslide susceptibility. The integration of these factors provides a detailed and comprehensive understanding of the region's susceptibility to landslides, emphasizing areas at risk of slope failures. From the overlay analysis, three distinct landslide vulnerability zones were identified, namely low vulnerability, medium vulnerability, and high vulnerability. These zones represent varying levels of risk based on the interplay of the five parameters. High-vulnerability zones are characterized by steep slopes, fragile geological units, and areas experiencing high rainfall, while low and medium-vulnerability zones are associated with more stable geological and topographical conditions. The area of each vulnerability zone was calculated to quantify the extent of landslide-prone regions in the regency. This classification is essential for effective disaster risk reduction and prioritizing mitigation efforts. High-vulnerability zones require immediate attention through reforestation, slope stabilization, and sustainable land cover practices to reduce erosion and landslide risks. Medium and low-vulnerability zones, although less critical, demand proactive monitoring to prevent future risk escalation caused by land cover changes or climate variability. The results of the overlay analysis, including the area and percentage of each vulnerability classification, are summarized in **Table 13** below.

Table 13.

Slope levels distributions in Pasaman Regency.

No	Vulnerability Zone	Area (Ha)	Percentage (%)
1	Low	1895	0
2	Medium	340891	86
3	High	51977	13
Total area of Pasaman Regency*		**394763**	**100**

Source: Results of data analysis 2024.

In general, Pasaman Regency falls predominantly within the medium landslide vulnerability zone, which covers an area of 340891 ha or 86 % of the region. This is followed by the high-vulnerability zone, which spans 511977 ha or 13 %. Lastly, the low-vulnerability zone is the smallest, covering 1895 ha or 0 %. The high-vulnerability zones are typically areas where landslides frequently occur. These regions are characterized by geological conditions dominated by igneous rocks and are commonly found in hilly areas or cliffs that have been disrupted by infrastructure development, such as highways, mining operations, and buildings. Inappropriate land cover, such as planting fibrous-rooted vegetation or converting forests into agricultural fields, exacerbates these vulnerabilities. Additionally, high annual rainfall exceeding 2500 mm intensifies the risk of landslides, particularly on unstable slopes. The medium-vulnerability zones generally experience less frequent landslides, with rates classified as rare to medium. The geological conditions in these areas are dominated by sedimentary and metamorphic rocks. Landslides in these zones typically occur due to a combination of natural factors, such as earthquakes and steep slopes, and human activities, such as slope cutting, land cover changes, and construction. High rainfall levels, coupled with these factors, further contribute to the potential for landslides.

As illustrated on the map, medium-vulnerability areas are marked in yellow. The low-vulnerability zones are regions with a minimal risk of landslides. Landslides in these areas are rare and usually occur only when there is a disturbance on the slopes. Geologically, these zones are dominated by alluvial rocks and are located in lowland areas, making them relatively stable against landslides. As highlighted on the map, low-vulnerability zones are marked in green, representing areas with high stability and minimal landslide risk. These regions are less likely to require intensive mitigation efforts but still benefit from regular monitoring. The detailed spatial distribution of these vulnerability zones can be visualized on the overlay map in **Fig. 6**, which combines key parameters contributing to landslide risks. Landslide-prone areas with high levels of vulnerability are predominantly concentrated west of the main active fault, following a linear pattern from north to south. This distribution is largely influenced by geological characteristics, with igneous rocks being the dominant type in the western region. While volcanic or igneous rocks are compact and generally resistant to landslides, their susceptibility increases when exposed to weathering processes, elevated temperatures, and intense rainfall.

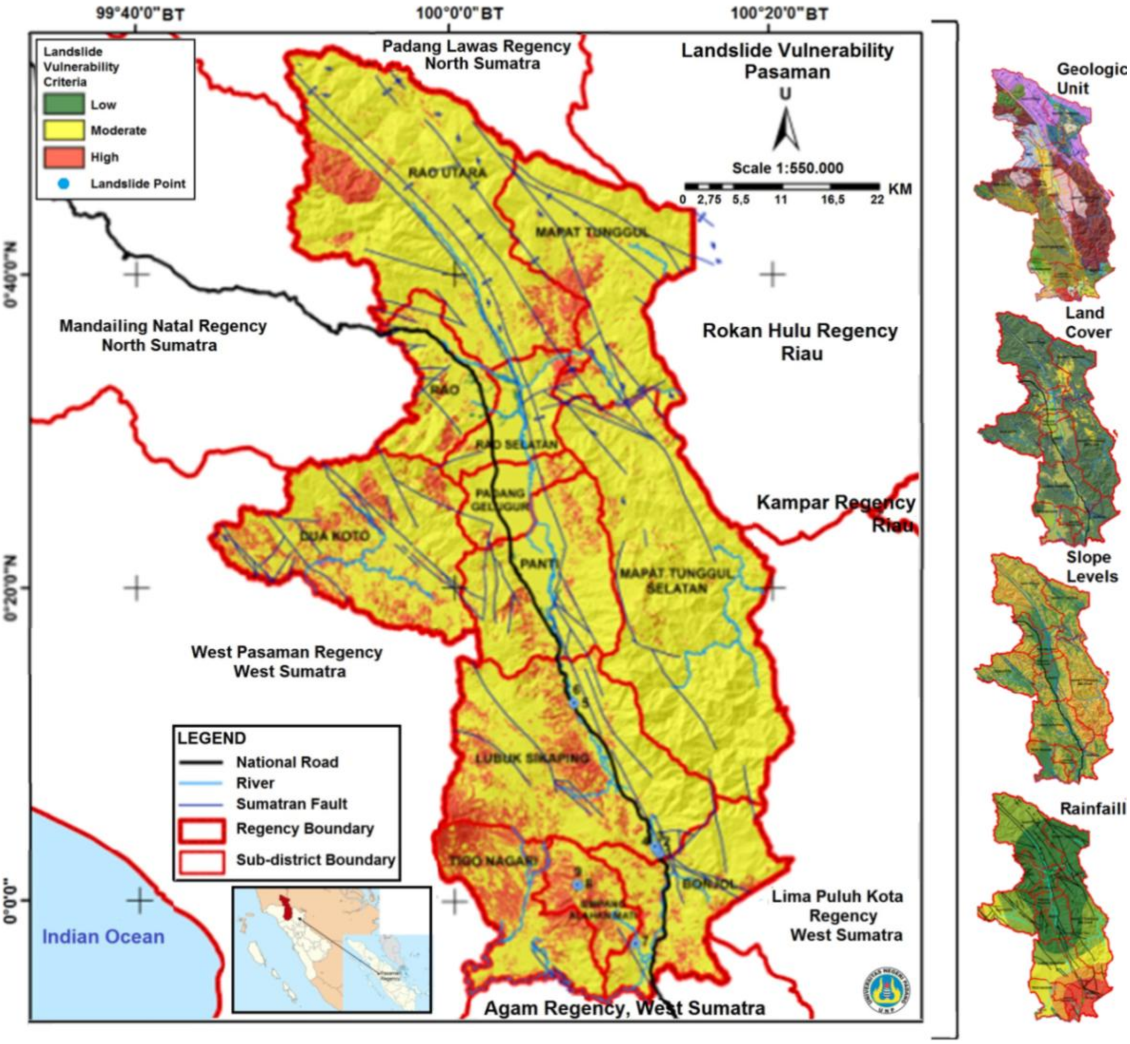

Fig. 6. Map of landslide locations in Pasaman Regency.

These combined factors weaken the structural integrity of the rocks, significantly raising the risk of slope failure. Edial et al (2018); Triyatno et al (2020) similarly highlighted that regions experiencing significant rainfall and steep slopes are more prone to landslides due to reduced shear strength and increased soil saturation. Land cover also plays a critical role in influencing landslide vulnerability. The western region, with its diverse land cover types such as plantations, rice fields, dry fields, shrubs, and open land, exhibits greater slope instability compared to the eastern region, which is predominantly covered by forests and shrubs. These findings are consistent with Hermon et al (2019); Mohanty et al. (2024), who underscored the stabilizing effect of forest cover in mitigating landslide risks. Furthermore, improper land cover practices, including the expansion of agricultural land and the conversion of forests into plantations, exacerbate the vulnerability of slopes in the western region. The impact of the Semangko Fault is especially evident along critical infrastructure, such as the Sumatra Central Cross Road. This highway, which follows the fault's trajectory through steep valleys and flat grabens, is highly susceptible to landslides. Areas such as Nagari Ganggo Mudik Hilir and Nagari Sundata, where steep slopes and geological instability intersect, are particularly at risk. These observations align with Radityo et al. (2024), who found that roads constructed along active fault lines are highly vulnerable to slope failures. Similarly, district roads like Jalan Kumpulan Padang Sawah, which also crosses the active Semangko Fault, share comparable risks. Ojomo et al. (2024) further emphasized that transportation infrastructure located along fault zones is at heightened risk of both landslides and earthquakes.

The socioeconomic consequences of these vulnerabilities are profound. Landslides often result in the disruption of road access, hindering the movement of goods and people and leading to substantial economic losses. These findings are consistent with Purwar et al. (2024); Osronita et al (2024); Hamdani et al (2024), who emphasized the significant economic impact of landslides on transportation networks and local economies. Such disruptions can create cascading effects, particularly in regions like Pasaman Regency, where communities are highly dependent on these routes for trade and daily activities.

This study successfully achieves its objectives of identifying landslide-prone zones and analyzing the factors contributing to their vulnerability. The study novelty lies in its multi-parameter approach, integrating geological characteristics, land cover, slope levels, rainfall intensity, and fault activity through GIS-based analysis. Unlike previous studies, this study provides a localized and comprehensive spatial vulnerability assessment specifically tailored to the conditions of Pasaman Regency, emphasizing the interplay between active fault lines and human activities in landslide risks. Liu et al. (2021) also emphasized the importance of using multiple parameters to gain a more accurate understanding of landslide hazards. To mitigate the high landslide vulnerability in Pasaman Regency, several targeted strategies are essential. Efforts should focus on slope stabilization, reforestation, and adopting sustainable land cover practices. Maintaining forest cover in the eastern regions, while regulating agricultural expansion in the west, is crucial for minimizing slope instability and preventing future landslides. Sahara et al. (2018) also advocated for such measures, highlighting the need to maintain ecological stability in fault-affected zones.

Enhancing infrastructure resilience is equally critical. Drainage systems along major roads, such as the Sumatra Central Cross Road and district roads, should be upgraded to manage water runoff during heavy rainfall, thereby reducing the likelihood of slope failure. Alexander (2005) stressed the importance of incorporating sustainable engineering solutions to mitigate landslide risks along critical infrastructure. Additionally, establishing community-based monitoring systems and emergency response plans can enhance preparedness and reduce the socioeconomic impact of landslides. By aligning these mitigation efforts with the principles of environmental sustainability, Pasaman Regency can enhance long-term disaster resilience and foster sustainable development.

4. CONCLUSIONS

The geological conditions of Pasaman Regency consist of diverse rock formations and active fault lines, shaping the region's landscape and environment. These formations include sedimentary, igneous, and metamorphic rocks. Igneous rocks dominate, covering 41 % of the area, and are linked to volcanic activity along the Semangko Fault. Although these rocks create hilly and mountainous terrains, they are prone to landslides, especially in areas with heavy rainfall. Land cover analysis in 2024 shows that forests dominate 77 % of the region, playing a key role in stabilizing slopes, regulating water cycles, and reducing landslide risks, particularly in areas near fault lines. Plantations make up 11 % and are mostly found on medium slopes.

However, poor land management in these areas could increase erosion and landslide risks. Built-up land and open areas account for less than 0 %, reflecting the rural nature of the region. Slope analysis reveals that 39 % of Pasaman Regency consists of mediumly steep slopes (24–45%), mostly located near fault zones. These areas are highly vulnerable to landslides due to their steepness and geological instability. Gently sloping areas (15–24%), covering 23 %, are suitable for agriculture and plantations, while flatter terrains (<15%), covering 33 %, are ideal for settlements and infrastructure. Very steep slopes (>45%), though only 4% of the region, require careful management to reduce erosion and disaster risks. Rainfall in Pasaman Regency is medium to high, with annual averages exceeding 1500 mm. This rainfall contributes to the region hydrology but also increases landslide risks in steep and fault-prone areas.

Combining rainfall data with slope and land cover maps helps create effective disaster management strategies. Landslide vulnerability mapping identifies three zones (high, medium, and low). High-vulnerability areas, covering 13 % of the region, are found west of the Semangko Fault and are characterized by steep slopes, fragile geological formations, and high rainfall. These areas need immediate interventions such as reforestation, slope stabilization, and controlled land use. Medium-vulnerability zones, covering 86 %, require monitoring to prevent increased risks, while low-vulnerability zones, covering 0 %, remain stable but benefit from regular oversight. To reduce disaster risks, settlements should be developed only in flat areas far from fault lines, avoiding steep or weathered zones.

Land cover changes must consider geological and slope conditions, focusing on conserving forests in the east and regulating agricultural expansion in the west. In high-risk areas, slopes should be stabilized using vegetation and engineering methods, and transportation routes should be avoided during heavy rains to prevent accidents. Drainage systems on major roads, such as the Sumatra Central Cross Road, must be improved to manage water runoff and reduce slope failures. Lastly, the potential for geothermal energy in igneous rock zones should be explored sustainably, and the development of parks can promote tourism and education, contributing to sustainable growth.

ACKNOWLEDGEMENTS

The author would like to express gratitude to the academic community of the Department of Geography at Universitas Negeri Padang (UNP) for their invaluable assistance in data collection, field ground checks, and data analysis. The author also extends thanks to the Institute for Research and Community Service or LP2M UNP for facilitating field validation based on personal geological databases related to Sumatra.

REFERENCES

Alexander, D. (2005). Vulnerability to landslides. *Landslide hazard and risk*, 175–198. https://doi.org/10.1002/9780470012659

Alqadhi, S., Mallick, J., Balha, A., Bindajam, A., Singh, C. K., & Hoa, P. V. (2021). Spatial and decadal prediction of land use/land cover using multi-layer perceptron-neural network (MLP-NN) algorithm for a semi-arid region of Asir, Saudi Arabia. *Earth Science Informatics, 14*, 1547–1562. https://doi.org/10.1007/s12145-021-00633-2

Aryantie, M. H., Hidayat, M. Y., Widodo, T., Putra, A., & Dewata, I. (2023). Environmental perspectives to the rejection of Javanese karst mining in systematic literature reviews. *International Journal of Sustainable Development and Planning, 18*(12), 3757–3764. https://doi.org/10.18280/ijsdp.181207

Astari, A. J., Aliyan, S. A., Bratanegara, A. S., Muslim, A. B., Nurawaliyah, V. I., & Mohamed, A. A. A. (2024). Understanding the scope of regional geography: A perspective from Indonesia's geographic region. *E3S Web of Conferences*. 600, 02018. https://doi.org/10.1051/e3sconf/202460002018

Barber, A. J. (2000). The origin of the Woyla Terranes in Sumatra and the Late Mesozoic evolution of the Sundaland margin. *Journal of Asian Earth Sciences, 18*(6), 713–738. https://doi.org/10.1016/S1367-9120(00)00024-9

Beshir, S., Moges, A., & Dananto, M. (2024). Assessing Groundwater Potential Zones and Their Implications for Landslides in the Upper Wabe-Shebele River Basin of Southeastern Ethiopia. *Journal of Engineering, 2024*(1), 7044576. https://doi.org/10.1155/2024/7044576

Bhattacharya, R. K., Chatterjee, N. D., & Das, K. (2020). Estimation of erosion susceptibility and sediment yield in ephemeral channels using RUSLE and SDR model: Tropical plateau fringe region, India. In *Gully erosion studies from India and surrounding regions*. 163–185. https://doi.org/10.1007/978-3-030-23243-6_10

Blanco-Canqui, H., & Lal, R. (2008). Soil erosion under forests. In *Principles of soil conservation and management*. 321–344. https://doi.org/10.1007/978-3-031-30341-8

Dewanta, B. G., Priadi, R., Heliani, L. S., Natul, A. S., Yanis, M., Suhendro, I., & Julius, A. M. (2022). The 2022 Mw 6.1 Pasaman Barat, Indonesia earthquake, confirmed the existence of the Talamau segment fault based on teleseismic and satellite gravity data. *Quaternary, 5*(4), 45. https://doi.org/10.3390/quat5040045

Dewata, I., Putra, A., Hamdi., Hasmira, M. H., Driputfany, D. M., Fajrin., Yulius, H., Hidayat, M., Yusran, R., & Arman (2024). Water quality of Batang Merao watershed and implementation of Landsat 8 OLI for the transparency of Lake Kerinci waters. *Journal of Sustainability Science and Management, 19*(4), 110–121. http://doi.org/10.46754/jssm.2024.04.009

Edial, H., Muchtar, B., & Dewata, I. (2019). Evaluation of land use to critical Batang Kuranji watershed in Padang City. *IOP Conference Series: Earth and Environmental Science, 314*(1), 012004. http://doi.org/10.1088/1755-1315/314/1/012004

Elfendi, R., & Asrawati, A. (2025). Trauma healing for children affected by the Pasaman, West Pasaman earthquake. *E3S Web of Conferences*. 604, 05008. https://doi.org/10.1051/e3sconf/202560405008

Gariano, S. L., & Guzzetti, F. (2016). Landslides in a changing climate. *Earth-Science Reviews, 162*, 227–252. https://doi.org/10.1016/j.earscirev.2016.08.011

Hamdani, D. M., Barlian, E., Dewata, I., Gusman, M., Putra, A., & Heldi, H. (2024). Ecological study of the influence of mining workers on mining area communities. *AIP Conference Proceedings, 3001*(1), 080018. https://doi.org/10.1063/5.0184175

Hikmatullah., Suwandi, V., Chendy T.F., Hidayat, A., Affandi, U., & Dai, J. (1990). *Explanatory booklet of the Land Unit and Soil Map of the Lubuk Sikaping Sheet (0715), Sumatra: Land Resources Evaluation and Planning Project, Soil Data Base Management*. Centre for Soil and Agroclimate Research, Agency for Agricultural Research and Development, Ministry of Agriculture.

Hermon, D., Ganefri., Putra, A., & Oktorie, O. (2019). Characteristics of melanic epipedon based on biosequence in the physiography of Marapi-Singgalang, West Sumatra. *IOP Conference Series: Earth and Environmental Science, 314*(1), 012010. https://doi.org/10.1088/1755-1315/314/1/012010

Igwe, O. (2016). Predisposing factors and the mechanisms of rainfall-induced slope movements in Ugwueme, South-East Nigeria. *Bulletin of Engineering Geology and the Environment, 75*(2), 623–636. https://doi.org/10.1007/s10064-015-0767-0

Julzarika, A., Aditya, T., Subaryono, S., & Harintaka, H. (2021). The latest DTM using InSAR for dynamics detection of Semangko fault-Indonesia. *Geodesy and Cartography, 47*(3), 118–130. https://doi.org/10.3846/gac.2021.12621

Keesari, T., Ramakumar, K. L., Prasad, M. B. K., Chidambaram, S., Perumal, P., Prakash, D., & Nawani, N. (2015). Microbial evaluation of groundwater and its implications on redox condition of a multi-layer sedimentary aquifer system. *Environmental Processes, 2*, 331–346. https://doi.org/10.1007/s40710-015-0067-5

Korup, O., Clague, J. J., Hermanns, R. L., Hewitt, K., Strom, A. L., & Weidinger, J. T. (2007). Giant landslides, topography, and erosion. *Earth and Planetary Science Letters, 261*(3–4), 578–589. http://dx.doi.org/10.1016/j.epsl.2007.07.025

Kumar, P. (2024). Social and economic impact in the landslide-prone zones and related policies. In *Landslides in the Himalayan Region: Risk Assessment and Mitigation Strategy for Sustainable Management* (pp. 499–529). Springer Nature Singapore. https://doi.org/10.1007/978-981-97-4680-4_22

Liu, Y., Deng, Z., & Wang, X. (2021). The effects of rainfall, soil type and slope on the processes and mechanisms of rainfall-induced shallow landslides. *Applied Sciences, 11*(24), 11652. https://doi.org/10.3390/app112411652

Masruroh, H., Irawan, L. Y., & Anam, C. (2024). Comprehensive spatial analysis landslide susceptibility modelling, spatial cluster analysis and priority zoning for environment analysis. *International Journal of Environmental Science and Technology*, 1-22. https://doi.org/10.1007/s13762-024-05950-9

Mohanty, S., Biswas, M., & Mishra, S. S. (2024). Impact of urbanization on landslide incidences in the Indian Himalayan Region. *Journal of Geosciences, 2*(1), 20–24. https://doi.org/10.61577/jgi.2024.100004

Natawidjaja, D. H. (2018). Updating active fault maps and slip rates along the Sumatran Fault Zone, Indonesia. *IOP Conference Series: Earth and Environmental Science*. 118, 012001. https://doi.org/10.1088/1755-1315/118/1/012001

Octavia, D. M., & Ophiyandri, T. (2025). Identification of post-disaster housing reconstruction using a lean reconstruction approach (case study: Pasaman earthquake in 2022). *E3S Web of Conferences*. 604, 15002. https://doi.org/10.1051/e3sconf/202560415002

Ojomo, O., Rathje, E. M., Wang, P., Lavrendiatis, G., Zimmaro, P., Asimaki, D., & Stewart, J. P. (2024). Regional earthquake-induced landslide assessments for use in seismic risk analyses of distributed gas infrastructure systems. *Engineering Geology, 340*, 107664. https://doi.org/10.1016/j.enggeo.2024.107664

Osronita, Anwar, S., Fatimah, S., & Putra, A. (2024). Sustainability assessment for geo-tourism in Sawahlunto Province with environment approach. *Journal of Sustainability Science and Management, 19*(10), 48–58. http://doi.org/10.46754/jssm.2024.10.005

Purwar, D., Flacke, J., Guzman, E. A., & Sliuzas, R. (2024). A qualitative analysis of cascading effects of critical infrastructure service failure post torrential floods in formal & informal settlements: The case of Medellin City, Colombia. *Sustainable and Resilient Infrastructure*, 1–17. https://doi.org/10.1080/23789689.2024.2340924

Putra, A., Dewata, I., Hermon, D., Barlian, E., Umar, G., Widodo, T., & Damanhuri, H. (2023). Activity recommendations based on an environmental approach in zoning of marine protected areas (MAPS) Pariaman City-Indonesia. *EnvironmentAsia, 16*(3), 57–67. https://doi.org/10.14456/ea.2023.35

Putra, A., Triyanto., Darwis, R., Dewata, I., Tanto, T. A., Mustapha, M. A., Razi, P., & Rahadian, Z. (2023). Suitability of mangrove ecosystems as a protected zone based on land-use changes. *Physical Oceanography, 30*(6), 866-881. http://physical-oceanography.ru/repository/issues/2023/06/11

Radityo, D., Al Farishi, B., Hendrawan, R. N., & Sadisun, I. A. (2024). Slope stability analysis throughout roads around Bukit Barisan Selatan National Park (BBSNP) using the Fellenius method. *Journal of Geoscience, Engineering, Environment, and Technology, 9*(3), 273–280. https://doi.org/10.25299/jgeet.2024.9.3.14902

Ruwaidah, N., & Rizali, A. (2022). The influence of landscape composition on the diversity and abundance of beetles in rice cultivation. *Journal of Tropical Plant Protection, 3*(2), 53–62. https://doi.org/10.21776/ub.jtpp.2022.003.2.3

Sahara, D. P., Widiyantoro, S., & Irsyam, M. (2018). Stress heterogeneity and its impact on seismicity patterns along the equatorial bifurcation zone of the Great Sumatran Fault, Indonesia. *Journal of Asian Earth Sciences, 164*, 1–8. https://doi.org/10.1016/j.jseaes.2018.06.002

Santoso, E., Pramono, S., Permana, D., Prayitno, B. S., & Karnawati, D. (2023). Identification of vulnerability due to the Pasaman M6.2 earthquake on 25 February 2022 using satellite-based methods and field surveys. *Indonesian Geotechnical Journal, 2*(2), 21–38. https://doi.org/10.56144/igj.v2i2.43

Setiawan, B., Saidi, T., Yuliannur, A., Polom, U., Ramadhansyah, P. J., & Ali, M. I. (2020). Ambient noise analysis for characterizing sub-surface dynamic parameters. *IOP Conference Series: Materials Science and Engineering*. 712(1), 012012. https://doi.org/10.1088/1757-899X/712/1/012012

Sieh, K., & Natawidjaja, D. (2000). Neotectonics of the Sumatran fault, Indonesia. *Journal of Geophysical Research: Solid Earth, 105*(B12), 28295–28326. https://doi.org/10.1029/2000JB900120

Singh, V. P., & Fiorentino, M. (Eds.). (2013). *Geographical information systems in hydrology*. 26. Springer Science & Business Media. https://link.springer.com/book/10.1007/978-94-015-8745-7

Srivastav, A. L., Dhyani, R., Ranjan, M., Madhav, S., & Sillanpää, M. (2021). Climate-resilient strategies for sustainable management of water resources and agriculture. *Environmental Science and Pollution Research, 28*(31), 41576–41595. https://doi.org/10.1007/s11356-021-14332-4

Tešić, D., Đorđević, J., Hölbling, D., Đorđević, T., Blagojević, D., Tomić, N., & Lukić, A. (2020). Landslide susceptibility mapping using AHP and GIS weighted overlay method: a case study from Ljig, Serbia. *Serbian Journal of Geosciences*, *6*(1), 9-21. https://doi.org/10.18485/srbjgeosci.2020.6.1.2

Triyatno., Bert, I., Idris, I., Herman, D., & Putra, A. (2020). Hazards and morphometry to predict the population loss due to landslide disasters in Koto XI Tarusan – Pesisir Selatan. *International Journal of GEOMATE, 19*(76), 98–103. https://doi.org/10.21660/2020.76.ICGeo12

Upadhyay, V. (2024). Landslide Hazard Risk and Vulnerability Monitoring—GIS Based Approach. In *Landslide: Susceptibility, Risk Assessment and Sustainability: Application of Geostatistical and Geospatial Modeling*. 53-86. https://doi.org/10.1007/978-3-031-56591-5_3

Venkatramanan, S., Viswanathan, P. M., & Chung, S. Y. (Eds.). (2019). *GIS and geostatistical techniques for groundwater science*. Elsevier. https://shop.elsevier.com/books/gis-and-geostatistical-techniques-for-groundwater-science/venkatramanan/978-0-12-815413-7

Wulandari, R., Chan, C. H., & Wibowo, A. (2023). The 2022 Mw6.2 Pasaman, Indonesia, earthquake sequence and its implications for seismic hazard in central-west Sumatra. *Geoscience Letters, 10*(1), 25. https://doi.org/10.1186/s40562-023-00279-6

Yao, K., Pradhan, B., & Idrees, M. O. (2017). Identification of rocks and their quartz content in Gua Musang Goldfield using advanced spaceborne thermal emission and reflection radiometer imagery. *Earth Sciences Journal*, 43(1), 145–157. https://doi.org/10.1155/2017/6794095