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GIS-Based Landslide Hazard Zonation for Disaster Resilience: Case Study of Samosir Regency, North Sumatra

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Abstract: Samosir Island, located in the center of the Toba Caldera, is characterized by steep slopes and high rainfall, making it highly vulnerable to landslides. This study employs a Geographic Information System (GIS)-based spatial approach to develop a comprehensive landslide susceptibility map of the island. Four conditioning factors—slope gradient, rainfall, land cover, and soil type were classified and weighted according to their influence on slope stability, then integrated through a weighted overlay method. The distinctive contribution of this research lies in its island-specific, multi-parameter GIS analysis for Samosir, a region of global geological significance but with limited prior landslide risk assessment. By providing a scientific basis for hazard evaluation, the study supports not only local disaster risk reduction and land-use planning but also advances broader methodological practices for volcanic and high-rainfall terrains. The results categorize susceptibility into three classes: low, medium, and high. Low-susceptibility areas correspond to flat terrain, dense vegetation, and stable soils; medium-susceptibility zones are found in transitional lowland–hill areas; while high-susceptibility zones are concentrated on steep slopes with sparse or built-up land cover, loose soils, and intense rainfall.

Keywords: GIS; Landslide; Samosir Island; Susceptibility Map; Sumatra

1.0 Introduction

Landslides are among the most destructive and recurrent natural hazards in mountainous and tectonically active regions, posing severe risks to human safety, infrastructure, and ecosystems. Globally, they account for thousands of fatalities and substantial economic losses each year, with developing countries being disproportionately affected (Froude & Petley, 2018). In Southeast Asia, landslide disasters are particularly prevalent due to intense rainfall, rugged topography, and rapid land-use change. Malaysia, for example, has experienced repeated landslide events affecting highways and urban settlements (Roslee et al., 2017; Komoo & Jamaludin, 2019), while similar hazards have been widely documented in Nepal, the Philippines, and Indonesia (Zhou et al., 2016; Haque et al., 2019).

A landslide can be broadly defined as the downslope movement of rock, soil, or debris under the force of gravity (Cruden & Varnes, 1996). Its occurrence is influenced by both natural and anthropogenic drivers. Natural factors such as slope gradient, geological structure, soil properties, and rainfall intensity play critical roles, while human activities such as deforestation, agricultural expansion, and construction on unstable slopes often exacerbate instability (Shano et al., 2020; Reichenbach et al., 2018). The interplay of these elements makes landslides a complex hazard that requires multi-parameter analysis for accurate assessment.

In recent years, Geographic Information Systems (GIS) and remote sensing have become indispensable tools in landslide susceptibility mapping. GIS allows researchers to integrate multiple spatial datasets and apply multi-criteria analysis to classify areas according to their risk levels (Pham et al., 2018; Dou et al., 2019). Compared with traditional field surveys, GIS-based methods provide advantages in terms of efficiency, scale, and visualization, making them highly valuable for disaster risk reduction and land-use planning. Numerous studies across Asia have demonstrated the utility of GIS in landslide hazard assessments. In Malaysia, for instance, researchers have combined slope, lithology, rainfall, and land cover to identify hazard-prone areas (Roslee et al., 2017; Saadatkhah et al., 2020). In Nepal and Bhutan, rainfall-induced landslides have been modeled using logistic regression and random forest approaches, highlighting the importance of soil type and geomorphology (Chen et al., 2017). In Indonesia, studies conducted in Java and Sumatra have shown that integrating topographic, climatic, and anthropogenic parameters enhances the reliability of susceptibility maps (Dahal et al., 2018; Saputra et al., 2021). Collectively, these findings underscore that multi-parameter integration strengthens the accuracy of hazard prediction.

Despite these advances, limited research has focused specifically on Samosir Island, a resurgent dome within the Toba Caldera that is geologically unique and of global significance. The island's steep slopes, deeply weathered volcanic soils, and high annual rainfall create inherently unstable conditions, yet systematic susceptibility mapping remains scarce. Most existing studies in Indonesia either concentrate on other regions or apply generalized models without tailoring parameters to the local context. To address this gap, the present study applies a GIS-based spatial approach to develop a detailed landslide susceptibility map of Samosir Island, integrating four critical parameters: slope gradient, rainfall, land cover, and soil type. The resulting analysis provides essential insights for disaster risk reduction, sustainable land-use planning, and the broader application of GIS in volcanic island environments.

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2.0 Study Area

Samosir Island is a large volcanic island situated in the center of Lake Toba, North Sumatra, Indonesia (Figure 1), between approximately 2.40°–2.80° N latitude and 98.60°–99.10° E longitude (WGS 1984). Covering an area of about 630 km², it is the world's largest island within an island and forms part of the resurgent dome system of the Toba Caldera. The island rises to around 1,630 m above sea level and is characterized by steep caldera walls, rolling uplands, and deeply weathered volcanic soils. These geomorphological features, combined with high annual rainfall exceeding 2,500 mm (BMKG, 2022), make the landscape particularly prone to slope instability.

Samosir Island has a population of approximately 130,000 (BPS, 2021), with most settlements concentrated along the lakeshore and valleys where the terrain is relatively gentle. The local economy relies primarily on agriculture, including rice, maize, coffee, and horticultural crops, along with livestock farming. In recent decades, tourism has emerged as a key growth sector, driven by the island's cultural significance as the homeland of the Batak Toba people and its designation as a priority destination within Indonesia's national tourism development strategy (Harahap et al., 2019; Lumbantobing & Sipayung, 2020). Infrastructure expansion—including new roads, accommodations, and tourism facilities has accelerated land-use change, particularly on hilly terrain, thereby increasing vulnerability to environmental hazards such as landslides.

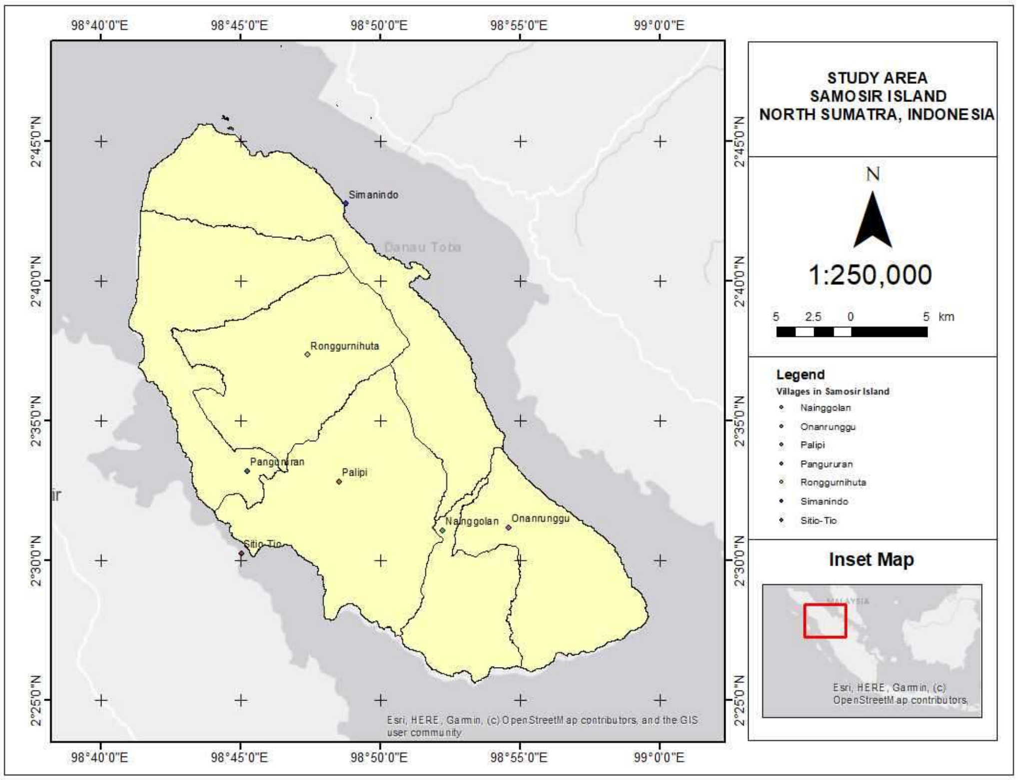

Figure 1. Study Area

Samosir has increasingly been recognized as a landslide hotspot in North Sumatra. Hazard screening studies classify the island as highly susceptible, while GIS-based mapping shows that nearly 35% of its terrain falls into the "high" to "very high" susceptibility categories (Saragih et al., 2022). Historical records and disaster reports confirm that landslides have repeatedly affected communities and infrastructure over the past decade (Figure 2). For instance, slope failures in 2018 blocked the Pangururan–Ronggur Nihuta road (Medcom, 2018), while in 2019 and 2021, landslides in Simanindo District disrupted sections of the Tomok–Tanjungan and Sigarantung–Huta Ginjang corridors (Tagar, 2019; Tagar, 2021). More recently, in November 2023, combined floods and landslides caused one fatality, 100 injuries, and damage to more than 100 houses, bridges, and roads across the island (AHA Centre, 2023). In 2024, further incidents severed inter-village connections in Parlondut (Pangururan) and threatened the main Simanindo–Pangururan road (Kompas, 2024).

These recurring events demonstrate the convergence of natural susceptibility and human-driven vulnerability on Samosir. Local government records, including the Satu Data Samosir disaster inventory, document multiple landslide points across villages between 2015 and 2024 (Satu Data Samosir, 2022). The severity and frequency of these events, coupled with the island's role as a major tourism and cultural hub, underscore the urgency of updated landslide susceptibility mapping. This study therefore focuses on Samosir Island to provide a GIS-based spatial assessment that can inform disaster risk reduction, infrastructure planning, and sustainable land management in this geologically significant and hazard-prone region.

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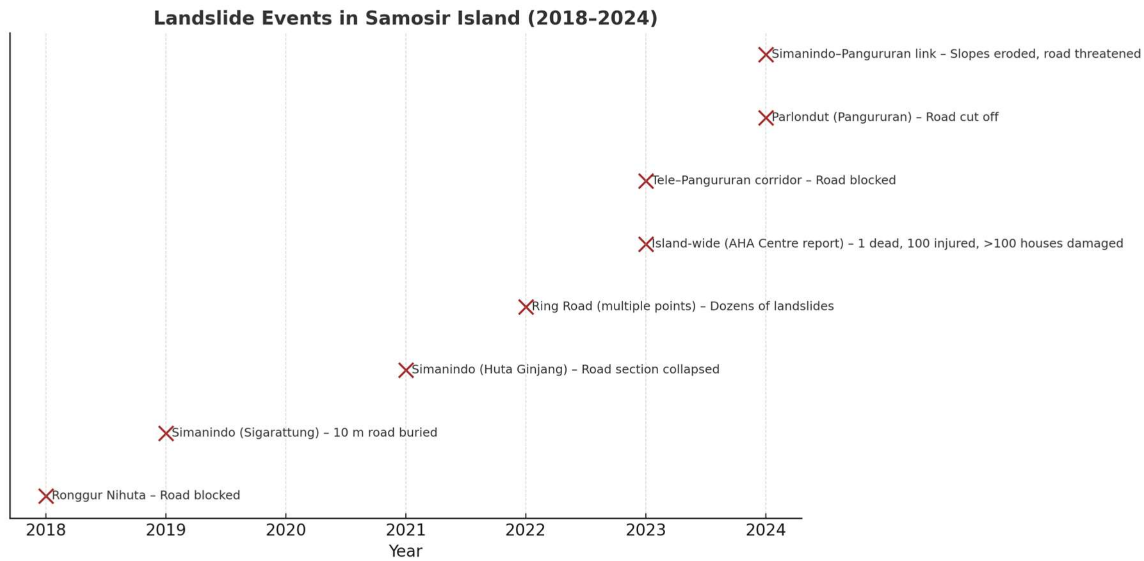

Figure 2. Landslide Events in Samosir Island

3.0 Materials and Methodology

3.1 Materials

To conduct landslide hazard zonation mapping for Samosir Island, this study integrated multiple geospatial datasets from reputable national and international sources. These datasets represent key conditioning factors influencing slope stability—topography, rainfall, soil type, and land cover. Each dataset was selected based on its reliability, spatial resolution, and relevance to tropical volcanic environments.

Data sources used in this study include:

1. Digital Elevation Model (DEM): The Indonesian Digital Elevation Model (DEMNAS) was obtained from the Geoportal of Badan Informasi Geospasial (BIG). DEMNAS has a spatial resolution of 8.25 m and was generated through the integration of Interferometric Synthetic Aperture Radar (IfSAR), TerraSAR-X, and photogrammetric data, corrected and mosaicked by BIG. This dataset was used to derive slope gradients and other topographic parameters.
2. Rainfall Data: Rainfall records were sourced from the Badan Meteorologi, Klimatologi, dan Geofisika (BMKG). The dataset represents mean annual precipitation (mm/year), derived from daily station measurements aggregated to annual values for the period 2015–2020. This temporal scale was selected to capture long-term rainfall intensity patterns relevant to landslide occurrence.
3. Soil Data: Soil information was obtained from the FAO Harmonized World Soil Database (HWSD) at a 1:1,000,000 scale. The database provides soil texture, composition, and classification, which are critical for assessing slope material strength and stability in volcanic regions.
4. Land Cover Map: Land cover data were obtained from the ESRI Land Cover Dataset (2021), with 10 m spatial resolution, derived from Sentinel-2 satellite imagery using deep learning classification methods. This dataset was used to differentiate vegetation cover, agricultural land, and built-up areas, enabling evaluation of their influence on slope stability.

Software:

1. ArcGIS 10.4 was employed as the primary platform for spatial analysis, including data processing, reclassification, weighted overlay, and map layout design.

3.2 Methodology

This study applies a GIS-based multi-criteria analysis to generate a Landslide Hazard Zonation Map for Samosir Island, integrating topographic, land cover, rainfall, and soil data. The workflow comprises three phases: data preparation, data processing, and result generation (Figure 3).

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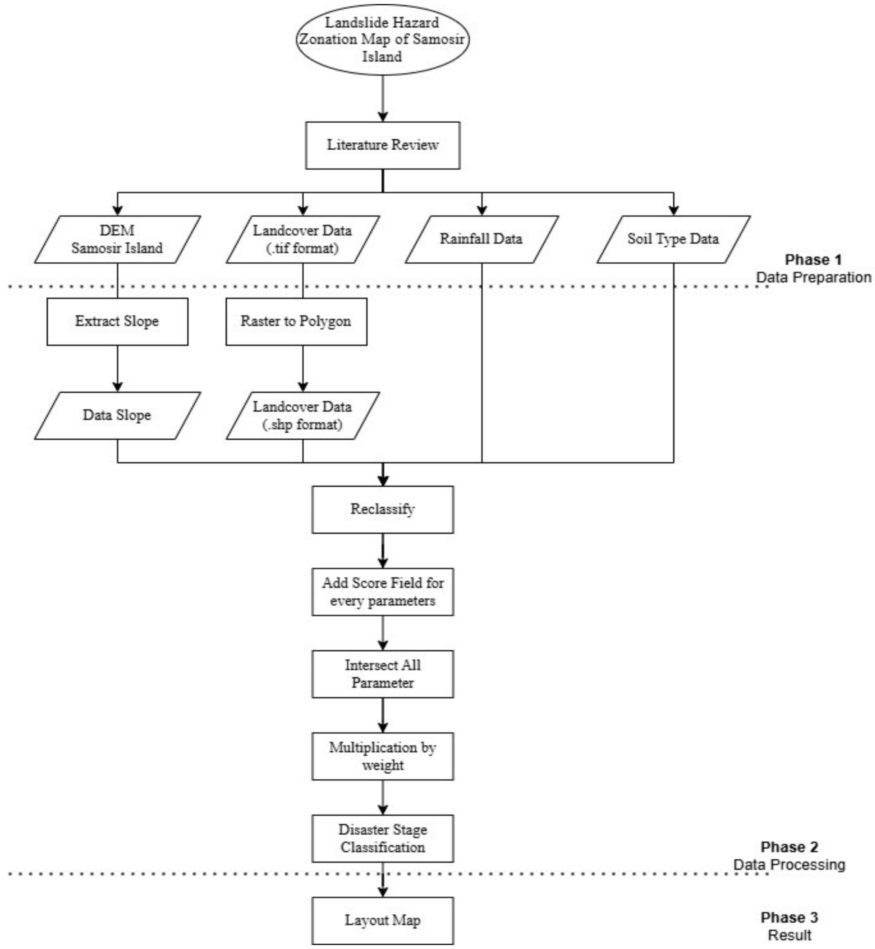

Figure 3. Workflow of Study

The data preparation phase involved assembling, standardizing, and preprocessing four core spatial datasets representing the key conditioning factors for landslide susceptibility analysis on Samosir Island: Digital Elevation Model (DEM), rainfall intensity, land use/land cover, and soil type. The DEM was processed to derive slope gradient values, a critical factor in landslide initiation. Rainfall data, obtained from the Meteorological, Climatological, and Geophysical Agency, were used to classify precipitation intensity zones. Land cover data from ESRI were categorized into classes reflecting varying degrees of slope stability, while soil type information from the Food and Agriculture Organization (FAO) database provided insights into the geotechnical properties influencing slope behavior. All datasets were converted into GIS-compatible formats, reprojected into a uniform coordinate system, resampled to a consistent spatial resolution, and prepared for integration in the weighted overlay analysis.

The slope gradient parameter was generated from the DEM of Samosir Island, provided in GeoTIFF (.tif) format. The DEM was imported into ArcGIS using the Add Data function, after which slope values were derived using the Slope tool in the 3D Analyst toolbox. In this process, the DEM file was set as the input raster, the output file name and storage location were specified, the output measurement was set to Percent Rise, and the Z-Factor was maintained at 1 to preserve the proportional relationship between vertical and horizontal units (both expressed in meters).

Once the slope raster was generated, it was reclassified to group continuous slope values into discrete susceptibility categories. This was carried out using the Reclassify function in the Spatial Analyst toolbox. The classification thresholds and corresponding susceptibility scores followed the criteria outlined in Table 1, adapted from Fina Faizana et al. (2015). In this scheme, slopes greater than 25° were assigned the highest hazard scores, while flat to gently sloping areas received the lowest scores. The reclassified slope layer was then incorporated into the weighted overlay analysis with the highest assigned weight, reflecting its dominant influence on landslide occurrence.

Table 1. Slope Parameter Scoring Classification

Slope Range (% Rise)	Class	Score
0% – 2%	Very Low	1
2% – 15%	Low	2
15% – 25%	Moderate	3
25% – 40%	Steep	4
> 40%	Very Steep	5

The land cover dataset, obtained from ESRI in GeoTIFF (.tif) format, was imported into ArcGIS using the Add Data function. To enable vector-based processing and facilitate integration with other thematic layers, the raster dataset was converted to polygon features

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using the Raster to Polygon tool in the Conversion toolbox. In this step, the input raster was set as the land cover file, the output shapefile name and storage location were defined, the Value field was selected to represent land cover classes, and the Simplify Polygon option was enabled to generate smoother polygon boundaries.

The resulting polygon dataset was then refined using the Dissolve function in the Geoprocessing menu. Polygons sharing the same land cover classification code (GRIDCODE) were merged to form single, continuous units, reducing data fragmentation. An attribute enhancement procedure followed, whereby a new field titled LandCover_Name (Text data type) was added to the attribute table. This field was manually populated with descriptive class names such as Forest, Built-up Area, Plantation, Rice Field, Grassland, and Water Body based on the corresponding classification codes. The processed land cover shapefile was subsequently reclassified into susceptibility scores according to the criteria described in Table 2 (adapted from Fina Faizana et al., 2015) and prepared for integration into the weighted overlay analysis.

Table 2. Landcover Parameter Scoring Classification

Land Cover	Score
Water	1
Forest, Trees	2
Paddy field, Plantation	3
Shrubs	4
Built Area	5

Rainfall intensity data were obtained from the Badan Meteorologi, Klimatologi, dan Geofisika (BMKG) and expressed as annual precipitation (mm/year). High-intensity rainfall elevates pore water pressure within soil layers, thereby reducing shear strength and increasing the likelihood of slope failure. Rainfall classes and corresponding susceptibility scores were assigned following Fina Faizana et al. (2015) (Table 2), with zones receiving more than 3,000 mm/year given higher hazard scores and areas with lower rainfall assigned proportionally lower scores. The reclassified rainfall layer was then weighted according to its relative significance in the landslide hazard model.

Table 3. Rainfall Scoring Classification

Rainfall (mm/year)	Class	Score
2001 – 2500	Low	1
2501 – 3000	Moderate	2
3001 – 3500	High	3
>3501	Very High	4

Soil type information was obtained from the Food and Agriculture Organization (FAO) global soil database, which classifies soils based on texture, composition, and genesis. On Samosir Island, volcanic ash-derived latosols and other weathered volcanic soils are of particular concern, as they often exhibit low cohesion and high-water retention, making them prone to slope failure under saturated conditions. Susceptibility scores were assigned following the classification criteria of Fina Faizana et al. (2015) (Table 4), where soils with lower shear strength and higher permeability were given higher hazard scores. This reclassified soil type layer was assigned the lowest weight in the Weighted Overlay analysis, reflecting its relative influence compared with the other parameters.

Table 4. Soil Type Scoring Classification

Soil Type	Class	Score
Aluvial, Latosol, Grumasol	Low	1
Mediteran	Moderate	2
Amdosol	High	3

All datasets were reprojected to a common coordinate reference system (UTM Zone 47N, WGS 84 datum) and standardized to a uniform spatial resolution prior to analysis. This harmonization ensured accurate overlay operations and consistent spatial referencing across all conditioning factors. The Weighted Overlay analysis was then performed by integrating the reclassified rainfall layer with the slope gradient, land cover, and soil type layers (Table 5). Each parameter was assigned a weight reflecting its relative influence on landslide occurrence:

Table 5. Parameter Weighted Overlay

Parameter	Weight
Slope gradient	4
Rainfall intensity	3
Land cover	2
Soil Type	1

The reclassified scores for each parameter were multiplied by their respective weights and summed to generate a composite total score for each spatial unit, representing the Landslide Susceptibility Index (LSI). The LSI values were then classified into three susceptibility categories—Low, Moderate, and High—using class intervals calculated with the following formula:

$$\boldsymbol{Class\ Interval} = \frac{\boldsymbol{Nmax - Nmin}}{\boldsymbol{Nclass}}$$

Where, Nmax = Maximum Value, Nmin = Minimum Value, Nclass = Number of Classes

The final Landslide Hazard Zonation Map was designed to present susceptibility classes in a clear, accessible, and visually interpretable format for planners, engineers, and local authorities. A scale of 1:250,000 was selected to provide an appropriate balance between spatial detail and regional coverage, enabling effective visualization of hazard patterns across the entirety of Samosir Island. A color-coded scheme was applied to represent the three susceptibility categories: light green for Low, yellow for Moderate, and red for High. This follows cartographic best practices, ensuring intuitive interpretation, with warmer colors signifying higher hazard potential The map explicitly delineates administrative boundaries and highlights six key villages—Simanindo, Ronggurnihuta, Pangururan, Palipi, Nainggolan, and Onan Runggu—to provide local context and facilitate targeted risk assessment and planning.

Essential cartographic elements were incorporated to enhance interpretability and usability, including a title, legend (explaining susceptibility classes and symbols), north arrow, and scale bar. An inset map was added to show the geographic position of Samosir Island within the broader North Sumatra region. Additional annotations specify data sources (DEMNAS DEM, BMKG rainfall data, ESRI land cover, and FAO soil type datasets), as well as the map creator and institutional affiliation (Universiti Utara Malaysia – UUM). This structured layout ensures that the map functions not only as a scientific product but also as a practical decision-support tool for disaster risk reduction, infrastructure planning, and community preparedness initiatives on Samosir Island.

4.0 Results

This study produced a landslide susceptibility map of Samosir Island for 2021 using a GIS-based weighted overlay method. The analysis integrated four key conditioning factors: slope gradient, land cover, rainfall, and soil type. Susceptibility was classified into Low, Moderate, and High categories based on predefined thresholds and weight assignments drawn from established literature and adapted to the local geomorphological context.

Samosir Island, located within the Toba Caldera, is characterized by rugged, hilly to mountainous terrain combined with rapid infrastructure development and land-use changes. This setting makes landslide susceptibility mapping an essential tool for risk reduction and spatial planning.

The resulting map reveals a clear spatial pattern of susceptibility (Figure 4):

- Low Susceptibility zones (≈8,806.33 ha) are concentrated in flatter areas such as valley bottoms and lakeshores. These areas benefit from gentle slopes and intact vegetation cover, both of which enhance slope stability.
- Moderate Susceptibility zones (≈36,193.02 ha) are the most widespread, typically found in mid-slope agricultural areas, mixed vegetation zones, and moderately steep terrain. Although less critical than high-risk zones, these areas remain vulnerable under extreme rainfall or poor land management.
- High Susceptibility zones (≈19,551.46 ha; 30.28% of the island) are concentrated along steep caldera slopes, road cuttings, and hillside settlements where steep gradients, intense rainfall, and vegetation disturbance combine to create severe hazards.

Among all parameters, slope gradient emerged as the most influential factor. Very steep slopes (>40%) are almost entirely classified as High Susceptibility, particularly along the eastern and western caldera walls, where road construction and agricultural clearing have reduced stability. Steep slopes (25–40%) are mostly categorized as Moderate to High Susceptibility, with risk levels increasing in areas of vegetation removal or expansion of built-up land, especially along the ring road and in hilly tourism development zones. Moderate slopes (15–25%) are generally associated with Moderate Susceptibility, though they can shift upward under conditions of heavy rainfall and saturated latosol soils. In contrast, gentle slopes (2–15%) and flat areas (0–2%) mostly fall into Low Susceptibility zones, except where riverbank erosion or construction-related slope cutting has destabilized the ground.

Land cover further highlights the interplay between natural and anthropogenic factors. Forested areas in the central highlands and mid-elevation zones largely correspond to Low and Moderate Susceptibility classes due to stabilizing root systems. However, pockets of deforestation often replaced by plantations or grasslands, shift many steep slopes into High Susceptibility categories. Plantations, while offering partial erosion protection, lack the deep-rooted cohesion of natural forests and are commonly linked to High Susceptibility when established on steep terrain. Grasslands and bare ground pose particular concern: the former provide limited stabilization on slopes above 15%, while the latter, though less extensive, represent the most hazardous cover type when overlapping with steep gradients. Built-up areas along lakeshores and transport corridors are critical hotspots where slope instability directly threatens settlements and infrastructure. In contrast, rice fields on valley floors and flatter terrain generally fall into the Low Susceptibility class, though they remain vulnerable to flooding and failures triggered by nearby hillslopes.

Soil and rainfall conditions add further context. Latosols, the dominant volcanic soils of Samosir, are clay-rich and moisture-retentive but lose shear strength when saturated, making them unstable on steep, deforested slopes. Rainfall distribution also plays a decisive role: BMKG data divide the island into two precipitation zones, 2,500–3,000 mm/year and 3,000–3,500 mm/year. The higher rainfall zone, covering much of the western, northern, and central highlands, overlaps extensively with steep slopes and disturbed land cover—creating the highest susceptibility areas due to the combined effects of intense precipitation, runoff, and soil saturation. The southeastern part of the island, with lower rainfall, exhibits comparatively lower susceptibility, though localized risks remain where steep slopes or land-cover disturbance occurs.

Overall, the findings demonstrate that landslide susceptibility in Samosir results from both natural and human drivers. Steep slopes and heavy rainfall establish a baseline hazard potential, while land-cover disturbance—particularly deforestation, agricultural expansion, and infrastructure development serves as the most significant anthropogenic trigger. The integrated analysis highlights the importance of preserving forest cover, enforcing slope-sensitive land-use planning, and prioritizing revegetation in high-risk bare ground areas as essential strategies for reducing landslide risk.

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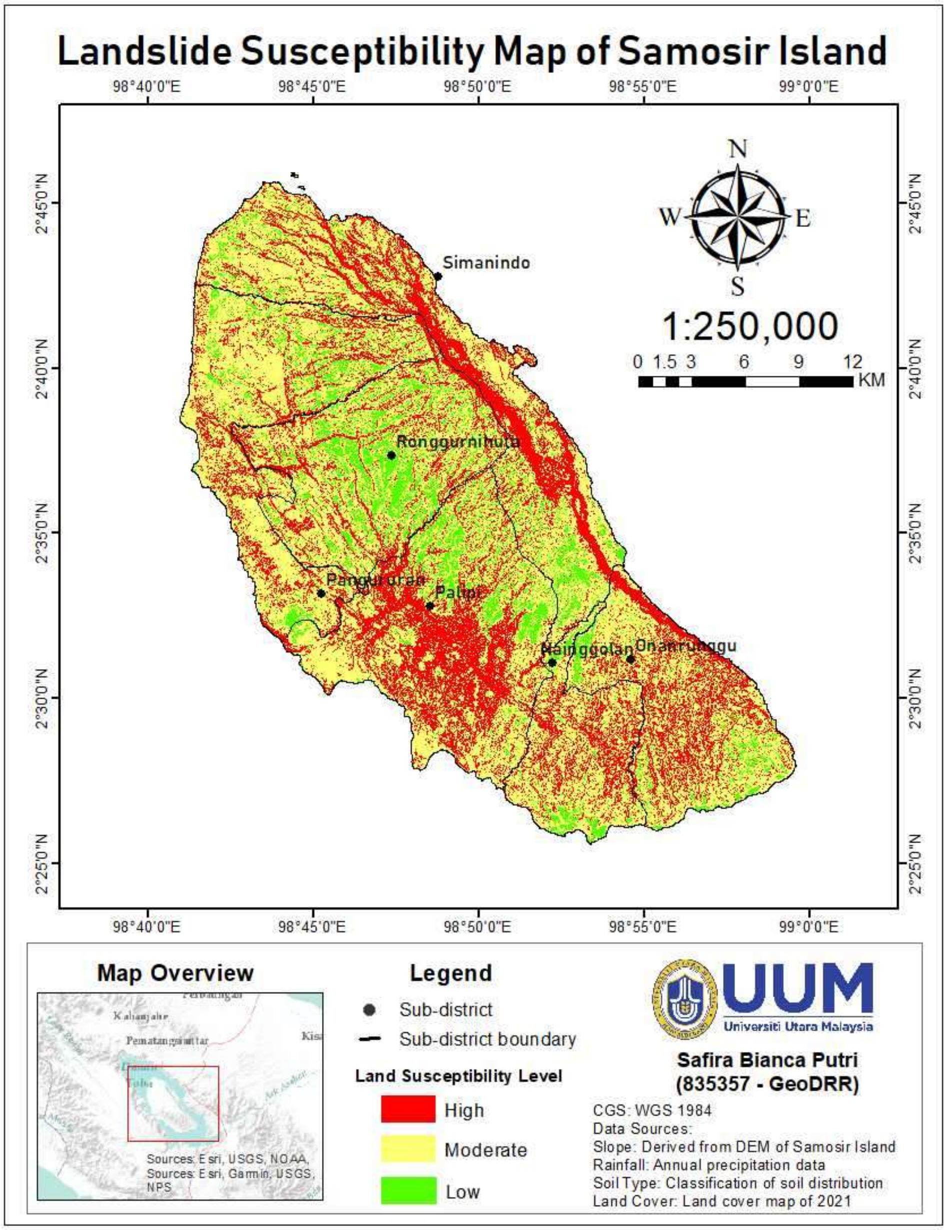

Figure 4. Landslide Susceptibility Map of Samosir Island.

5.0 Discussion

The Landslide Susceptibility Map produced in this study identifies 8,806.33 ha as low susceptibility, 36,193.02 ha as moderate susceptibility, and 19,551.46 ha as high susceptibility. High-susceptibility zones, accounting for 30.28% of the island, are predominantly concentrated along slopes steeper than 25°, particularly on the eastern and western caldera walls. These include vulnerable road segments and hillside settlements in Pangururan, Palipi, and parts of Nainggolan, where bare land, built-up zones, and intensively cultivated slopes are exposed to more than 3,000 mm of annual rainfall. Moderate-susceptibility zones are distributed across mid-slope areas and rolling terrain in Simanindo, Ronggurnihuta, and parts of Onan Runggu, while low-susceptibility zones are concentrated in flatter valley floors and coastal plains of Nainggolan and Onan Runggu.

These results are broadly consistent with previous research in volcanic and high-rainfall regions. Saputra et al. (2021) identified steep slopes and high rainfall as dominant drivers of landslides in North Sumatra, while Saragih et al. (2022) mapped 34.81% of Samosir Island as high susceptibility, closely aligning with the 30.28% found here. Comparable studies in Malaysia have similarly highlighted slope gradient, rainfall, and land cover as the most influential parameters (Roslee et al., 2017; Saadatkhah et al., 2020). Meanwhile, studies employing statistical and machine learning models—such as Dou et al. (2019) in Japan—have produced more refined hazard classifications. The slightly broader distribution of high-susceptibility zones in this study may reflect the weighted overlay approach, which, while effective, is more subjective than data-driven algorithms. Additionally, the unique resurgent dome morphology and deeply weathered volcanic soils of Samosir create slope instability patterns distinct from other volcanic regions.

The implications of these findings are significant for disaster risk management and spatial planning in Samosir Regency and North Sumatra Province. High-susceptibility areas require strict land-use regulation, slope stabilization measures (e.g., retaining walls and bioengineering with deep-rooted vegetation), and real-time monitoring and early warning systems. Moderate-susceptibility zones call for regulated agricultural expansion, improved drainage in road development, and seasonal community awareness campaigns, while low-susceptibility areas should be preserved as safe development zones and considered for relocation of households from more hazardous slopes.

Integrating this hazard information into the Rencana Tata Ruang Wilayah (RTRW, or spatial planning) of Samosir Regency is essential to ensure zoning regulations align with susceptibility patterns. At the provincial level, the maps can complement North Sumatra's disaster risk reduction strategies and BNPB's InaRISK platform, supporting evidence-based planning, infrastructure prioritization, and resource allocation for slope stabilization projects. Local communities also have an important role in this process. Through village-level disaster groups (Destana) and mobile reporting applications, residents can monitor slope conditions, identify early signs of instability, and report minor landslide incidents. Incentives such as training, recognition, or integration into contingency planning will help sustain participation.

Regular updates of susceptibility maps are also critical. A cycle of three to five years is recommended to account for new infrastructure, land-use changes, and shifts in rainfall intensity. Immediate updates should be triggered by extreme rainfall events, rapid deforestation or construction in hazard-prone areas, or the availability of higher-resolution geospatial datasets such as LiDAR or Sentinel-2 land cover products. By integrating updated maps into planning and preparedness, local government can make informed decisions to protect vulnerable communities and assets.

In summary, this study confirms that nearly one-third of Samosir Island is at high risk of landslides, in line with previous susceptibility studies, while also reflecting the island's unique geomorphological context. The GIS-based maps provide a valuable decision-support tool for aligning spatial planning, infrastructure development, and disaster risk reduction strategies, thereby strengthening Samosir's resilience against future landslide hazards.

6.0 Conclusions

This study developed a GIS-based Landslide Susceptibility Map for Samosir Island by integrating slope gradient, rainfall, land cover, and soil type using the Weighted Overlay method. The analysis classified the island into Low (8,806.33 ha; 13.64%), Moderate (36,193.02 ha; 56.08%), and High (19,551.46 ha; 30.28%) susceptibility zones. High-risk areas are concentrated along steep, rainfall-intense caldera slopes, while low-risk zones are found in flatter valleys and coastal terrain.

This research presents the first comprehensive, island-focused landslide hazard assessment for Samosir, extending beyond the broader regional and national analyses conducted previously. From an academic perspective, it contributes to the growing body of work on GIS-based susceptibility mapping in tropical volcanic settings and provides a reference point for future studies employing more advanced modeling approaches.

The findings also hold practical significance for Samosir Regency and North Sumatra. By aligning susceptibility maps with spatial planning (RTRW) and disaster risk reduction strategies, local authorities can restrict unsafe development, prioritize slope stabilization, and designate safe areas for sustainable growth. For communities, the maps highlight priority zones for monitoring, reporting, and preparedness, enabling residents to play an active role in reducing landslide risk. With regular updates every three to five years—or following major rainfall events and land-use changes—this susceptibility map can serve as both a dynamic academic reference and a practical tool for disaster resilience.

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Conflicts of Interest: The authors declare that there are no conflicts of interest.

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