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Landslide Risk Mapping for Sustainable Tourism Development: A Case Study in Kalibaru Watershed, Indonesia

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ABSTRACT

The development of sustainable tourism in landslide-prone areas required a detailed understanding of environmental risks to ensure safety and resilience. This study aimed to generate a comprehensive landslide risk map to support sustainable tourism development in the Kalibaru Watershed, located in the Raung Volcano region of Indonesia. This study employed the Spatial Multi-Criteria Evaluation (SMCE) method using spatial data and GIS software to map landslide risk based on three main components: hazard, vulnerability, and capacity. The results classified landslide risks in the Kalibaru Watershed into three categories: high risk (21,682 hectares), medium risk (28,113 hectares), and low risk (22,742 hectares). The findings revealed that the highest risk areas were concentrated on the middle and upper slopes of the watershed, particularly within the Glenmore and Kalibaru sub-districts, where a combination of steep terrain, soil characteristics, and heavy rainfall exacerbated landslide susceptibility. This risk map provided valuable insights for stakeholders involved in sustainable tourism planning, offering a strategic tool for developing safe, environmentally-conscious, and disaster-resilient tourism infrastructure. The implementation of this map aimed to raise awareness among local communities and policymakers about the potential landslide risks and encouraged the adoption of effective mitigation measures, fostering a more sustainable and disaster-aware tourism model in the region.

INTRODUCTION

Indonesia is an archipelagic country situated at the convergence of three tectonic plates: the Indo-Australian, Eurasian, and Pacific plates, forming a chain of active volcanoes known as the "Ring of Fire" (Bachri et al., 2023; Thouret et al., 2007; Virkhansa et al., 2019). This geologic condition results in Indonesia having 129 active volcanoes (13% of the world's active volcanoes), one of which is Mount Raung. Mount Raung is located within the United Nations Educational, Scientific, and Cultural Organization (UNESCO) Global Geopark Ijen, situated on the border between Bondowoso and Banyuwangi Regencies, East Java, Indonesia (Sabila & Abdurrachman, 2020). Mount Raung has been active since 1580 and remains so to this day. Historical eruption records indicate that Mount Raung is characterized by explosive eruptions, primarily producing volcanic ash and pyroclastic flows (Fatkhuroyan & Wati, 2017). Several paroxysmal eruptions have been recorded, notably in 1586, 1597, 1638, 1890, 1953, and 1956, with eruption columns reaching up to 12 kilometers in height and ashfall spreading up to a radius of 200 kilometers, affecting areas as far as Bali and Surabaya (Moktikanana et al., 2024). The eruption history of Mount Raung shows the shortest interval between eruptions to be 1 year, while the most extended interval is 15 years (Moktikanana et al., 2024; Moktikanana & Harijoko, 2022). Due to its high eruption frequency, it is regarded as one of the most active volcanoes in Java.

The eruptive activity of Mount Raung poses both primary and secondary hazards. Primary hazards include volcanic ash and pyroclastic flows, which can cause direct damage to infrastructure, the environment, and the social life of communities around the volcano. Secondary hazards include the collapse of lava domes, landslides, rain-triggered lahars, and flash floods (Moktikanana & Harijoko, 2022; Sauqi & Abdurrachman, 2018). Mount Raung is situated in an area prone to landslides. Landslides around the Mount Raung area are often triggered by volcanic and geological activities (Kaneko et al., 2019). Strong volcanic tremors can destabilize slopes, while geological activities, such as soil layer shifts, can accelerate the landslide process (Irawan et al., 2024). Landslides are also caused by heavy rainfall, which erodes the soil surface on the slopes surrounding Mount Raung, leading to mass soil movement (Stevany et al., 2016).

The Kalibaru Watershed, located on the slopes of Mount Raung in Banyuwangi Regency, is one of the river basin areas with a high susceptibility to landslides. The volcanic activity of Mount Raung in recent years has significantly contributed to the instability of the Kalibaru River Watershed, primarily due to pyroclastic flows and loosely deposited volcanic material along the river's course (Erwanto & Pratiwi, 2023; Sujarwo et al., 2021). This unconsolidated material is highly prone to mass soil movement, especially during periods of heavy rainfall. Based on its morphogenetic characteristics, the Kalibaru Watershed is primarily influenced by volcanic processes, with continuous eruptions of Mount Raung supplying fresh volcanic material, thereby increasing the potential for geological hazards (Kaneko et al., 2018; Sujarwo et al., 2021). The loose volcanic material not only heightens the risk of landslides but also reduces the soil's carrying capacity on the slopes, exacerbating risks for settlements and infrastructure surrounding the watershed. In particular, the upper reaches of the Kalibaru Watershed, with its tightly contoured terrain and steep slopes, present a significant landslide threat (Ipmawan et al., 2014; Moktikanana et al., 2021). These steep slopes increase gravitational pressure on the unstable volcanic material, triggering landslides and rockfalls during vibrations caused by volcanic activity or external factors such as earthquakes or heavy rainfall.

In addition to being prone to landslides, Banyuwangi Regency, particularly the areas surrounding Mount Raung, boasts stunning natural beauty with majestic mountain views, offering great potential for development as an attractive natural tourism destination. This natural beauty could become a draw for both local and international tourists, especially those seeking adventure and nature exploration experiences. However, to realize this potential optimally, it is crucial to consider safety aspects and disaster mitigation, given that the areas around Mount Raung are regions with a high potential for natural disasters, particularly landslides (Bachri et al., 2024). The intensive volcanic activity of Mount Raung has resulted in steep slopes with loose volcanic deposits, increasing the risk of landslides in various locations, especially in disaster-prone areas (Suprapto et al., 2015). To ensure sustainable tourism development, it is essential to conduct a detailed and comprehensive mapping of areas at risk of disasters, particularly landslides (Mastika et al., 2023). This mapping will help identify areas with a high risk of landslides, which can serve as a reference for planning and constructing tourism infrastructure. With accurate information regarding disaster risks, the government and tourism management authorities can develop appropriate mitigation strategies.

However, despite the attention given to the tourism potential around Mount Raung, research that integrates landslide risk mapping with sustainable tourism development remains highly limited. Previous studies have primarily focused on either geological aspects or tourism in isolation, without considering the relationship between disaster risk and sustainable tourism management. For example, research on multi-hazard detection using a geomorphological approach (Irawan et al., 2024), landslide hazard mapping (Bachri et al., 2024), and landslide potential analysis using geographic information systems and the analytical hierarchy process (Prasindya et al., 2020). This research did not map the landslide disaster risks by taking into account the multidimensional factors, including hazards, vulnerabilities, and the capacities of the local communities and government to respond to disasters.

This study is designed to address the identified research gap. The novelty of this research lies in the integration of the three main components, including hazard, vulnerability, and capacity, into a comprehensive spatial model for landslide risk mapping, which has not been holistically applied in the Kalibaru region, specifically in the slopes of Mount Raung, before. This study not only produces risk maps based on spatial data but also directly links the results of risk mapping with practical strategies for sustainable tourism development and disaster mitigation. Thus, the findings of this research can serve as a practical reference for managing and developing disaster mitigation-based tourism destinations in landslide-prone areas and can be replicated in other regions with similar characteristics.

RESEARCH METHODS

Research Location

This study was conducted within the ecological boundaries of the Kalibaru Watershed (DAS), which is administratively located in Banyuwangi Regency. The selection of this location was based on the series of eruptions from Mount Raung, which resulted in sector collapse, creating a landslide disaster risk. The study location map is shown in Figure 1.

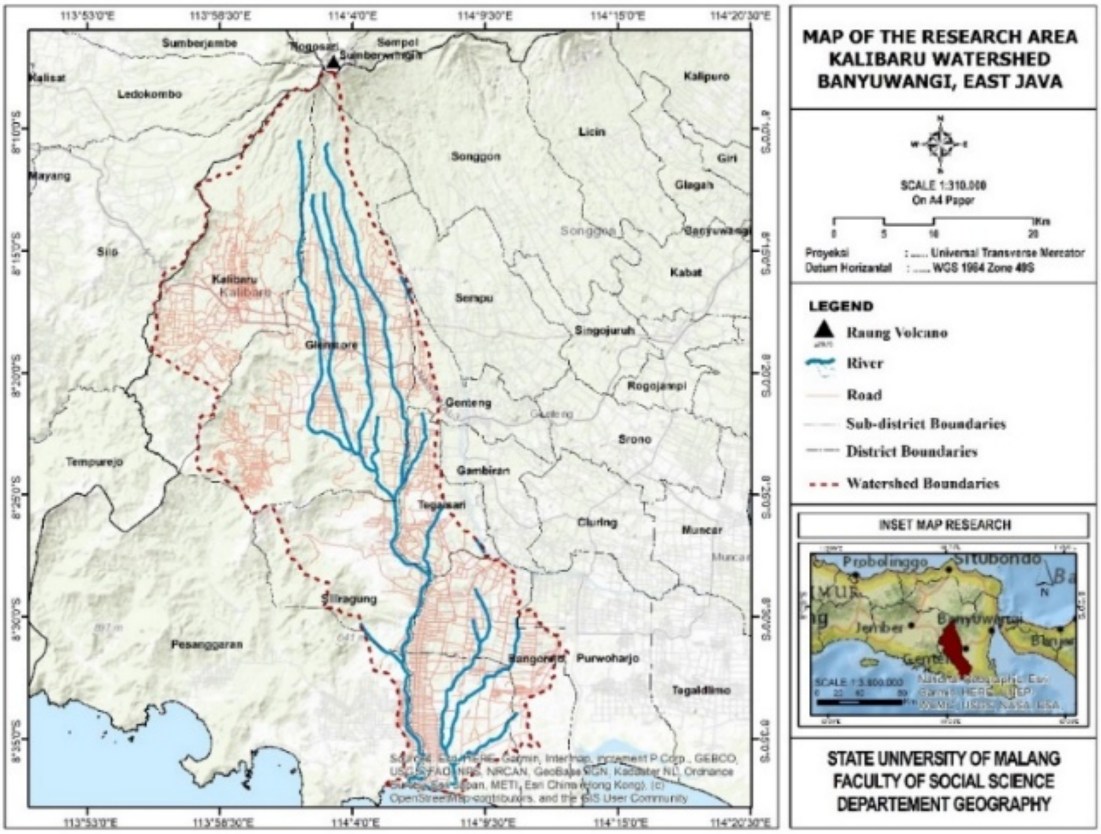


Figure 1. Research Location (Source: Data Processing, 2024)

Data Collection

This research used primary and secondary data. Primary data were obtained from field surveys, including the validation of landslide points, land use type validation, and soil sampling as indicators of soil texture conditions. Secondary data were collected from various institutions to produce vulnerability and capacity maps. The stages of the research, including sources and processing data, are presented in Table 1.

Table 1. Research Stages

Stages		Sources	Processing Techniques
a. Landslide Hazard Mapping			
Landform Identification	Morphology	• DEMNAS Resolution 8.1 m	Interpretation and analysis of hillshade slope, contours
	Morphogenesis	• DEMNAS Resolution 8.1m • Geological Map Banyuwangi Sheet Scale 1:50,000	Interpretation of landforms based on the origin of processes associated with geological materials
	Morphoarrangement	• DEMNAS Resolution 8.1 m • Geological Map of Banyuwangi Sheet Scale 1:50,000	Interpretation using hillshade, slope analysis
	Morphochronology	• DEMNAS Resolusi 8.1 m • Geological Map Banyuwangi Sheet Scale 1:50,000 • Digital Map of Soil Types DPUPR Banyuwangi Regency	Analysis of geological material aspects and soil types
Rainfall		• Rainfall Data Banyuwangi Regency, East Java Natural Resources Agency	Interpretation of average rainfall data for 2012-2023 using Inverse Distance Weighted (IDW) method
Land Use		Sentinel 2A	Interpretation of land use data using the CART method
Landslide Parameters		• DEMNAS Resolution 8.1 m	Analysis of Slope, TWI, TPI, SPI, Distance to River using ArcGIS tools
		• Geological Map Banyuwangi	Lithology analysis
		• Ina-Geoportal	Road Distance Analysis
Soil Samples		• Laboratory Test	Analysis of texture, structure, cole index and soil color
b. Landslide Vulnerability Parameters			
		Social Vulnerability	
Population Density		• Central Statistics Agency for Glenmore, Tegalsari, Siliragung, and Bangorejo Districts in Figures 2018-2023	Analysis of social vulnerability aspects using AHP (Analytical Hierachical Process) with weighting or scoring analysis.
Toddler Population (0-4 years old)			
Elderly Population (60+)			
Physical Vulnerability			
Built-up Area (Ha)		• Researcher's Data Analysis	Analysis of physical vulnerability aspects using AHP (Analytical Hierachical Process) with weighting or scoring analysis.
Road Network		• Ina-Geoportal Banyuwangi Regency RBI 1:25,000 Year 2023	
Protected Forest		• Central Statistics Agency for Glenmore, Tegalsari, Siliragung, and Bangorejo Districts in Figures 2018-2023	
		Environmental Vulnerability	
Natural Forest		• Central Statistics Agency for Glenmore, Tegalsari, Siliragung, and Bangorejo Districts in Figures 2018-2023	Analysis of environmental vulnerability aspects using AHP (Analytical Hierachical Process) with weighting or scoring analysis.
Mangrove Plantation		• Central Statistics Agency for Glenmore, Tegalsari, Siliragung, and Bangorejo Districts in Figures 2018-2023	
Scrub		• Researcher's Data Analysis	
c. Landslide Capacity Parameter			
Total Health Facilities		• Central Statistics Agency for Glenmore, Tegalsari, Siliragung, and Bangorejo Districts in Figures 2018-2023	Capacity aspect analysis using AHP (Analytical Hierachical Process) with weighting or scoring analysis.
Number of Medical Personnel			
Acquisition of Assistance			
Disaster Socialization and Simulation			

The Hazard parameters were analyzed using the SMCE (Spatial Multi-Criteria Evaluation) method due to its high accuracy level, supported by the ILWIS (Integrated Land and Water information System) software. There were ten landslide causative factors, including topographic, geological, hydrological, and anthropogenic aspects. Topography included the Topographic Position Index (TPI) and slope. Geological parameters included regional lithology. The hydrological aspect utilized data on distance from rivers, rainfall data, the Topographic Wetness Index (TWI), and the Stream Power Index (SPI), while anthropogenic aspects included data on soil type, land use, and distance from roads.

The Topographic Position Index (TPI) was used to analyze the elevation differences between valleys, slopes, ridges, and crests (Bachri et al., 2019; Irawan et al., 2021). The Topographic Wetness Index (TWI) indicated the presence of water content as a slope composition due to hydrological accumulation, which could affect slope stability (Singh et al., 2021). The Stream Power Index (SPI) was used to analyze the high erosion rates (Bachri et al., 2019; Singh et al., 2021).

The disaster vulnerability parameters were obtained through the scoring of various data types based on BNPB Regulation No. 02 of 2012 concerning General Guidelines for Disaster Risk Assessment. The vulnerability parameters are presented in Table 2.

Table 2. Vulnerability Parameters

No	District	Vulnerability								
		Social Vulnerability			Physical Vulnerability		Environmental Vulnerability			
		Population Density (km2 / person)	Toddler Population (0-4)	Elderly Population (+60) (People)	Built-up Area (Ha)	Road Network (Total)	Protection Forest (Ha)	Natural Forest (Ha)	Mangrove Plantation (Ha)	Shrubs (Ha)
1	Kalibaru	167	2228	4252	843	557	1255	5048	0	1679
2	Glenmore	186	4808	12417	1232	475	4016	4428	0	368
3	Tegalsari	830	3622	7796	1263	127	0	0	0	0
4	Siliragung	535	3047	7714	1440	153	3837	12	0	1317
5	Bangorejo	497	4452	10409	2150	196	0	423	0	386

(Source: Central Statistics Agency, 2024)

The disaster capacity parameters were obtained through scoring data on the total number of health facilities, medical personnel, aid acquisition, disaster socialization, and simulation. The capacity parameters are presented in Table 3.

Table 3. Capacity Parameters

No	District	Capacity			
		Health Capacity		Disaster Emergency Response Capacity	
		Health Facilities	Medical Personnel	Acquisition of Assistance	Disaster Socialization and Simulation
1	Kalibaru	10	55	Available	Available
2	Glenmore	18	63	Available	None
3	Tegalsari	9	57	Available	None
4	Siliragung	7	30	Available	None
5	Bangorejo	15	75	Available	Available

(Source: Central Statistics Agency, 2024)

Data Analysis

Each landslide risk indicator parameter was then analyzed using different methods. Hazard or threat indicators were analyzed using the SMCE (Spatial Multi-Criteria Evaluation) method supported by ILWIS (Integrated Land and Water Information System) software. The final result of the data processing produced composite maps of several landslide hazard areas. These maps were then subjected to accuracy testing using the Receiver Operating Characteristic (ROC) curve and the Relative Density Index (R-Index) with the formula:

$$R = \frac{nx}{Nx} \Sigma \left(\frac{nx}{Nx}\right) x\ 100\% \quad (1)$$

where nx is the number of landslide events and Nx is the number of pixels in category x. Accuracy testing with ROC and AUC was conducted using the ArcSDM toolbox. Vulnerability and capacity mapping were conducted using a weighting or scoring analysis technique, primarily supported by GIS in ArcGIS software. Each vulnerability parameter was calculated according to the formula listed in BNPB Regulation No. 02 of 2012, while capacity calculation is presented in Table 4.

Table 4. Capacity Parameters Calculation

Capacity Component	Term Frequency	Capacity Class					
		High	Value	Medium	Value	Low	Value
Health workers	20	<10 people	5	10 - 20 people	3	>20 people	1
Health facilities	20	<10 people	5	10 - 20 people	3	>20 people	1
Disaster socialization	20	None	3	-	-	Available	1
Acquisition of assistance	20	None	3	-	-	Available	1

(Source: Central Statistics Agency, 2024)

Subsequently, hazard, vulnerability, and capacity indicators were calculated to obtain a disaster risk map using ArcGIS software, applying the following formula:

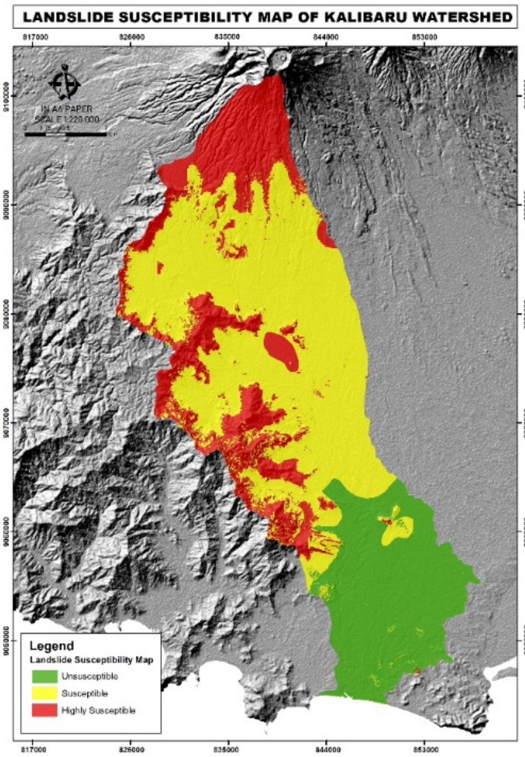
$$R = \mathrm{H} \times \frac{V}{C} \quad (1)$$

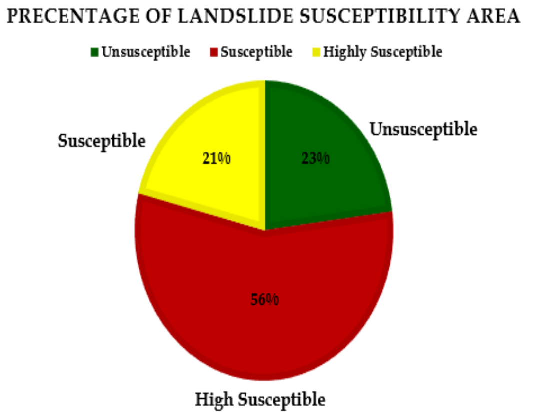
where R represents risk, H represents hazard or threat, V represents vulnerability, and C represents capacity to deal with disasters.

RESULTS AND DISCUSSION

Landslide Hazard in Kalibaru Watershed

The landslide hazard levels in the Kalibaru Watershed were classified into three categories: low, medium, and high (Figure 2). The low-threat level covered an area of 166.79 km², predominantly in the lower slope areas of the watershed, specifically within the Bangorejo and Siliragung Districts. These regions feature flat topography, typical of coastal areas, where the risk of landslides to residential zones is relatively minimal. Furthermore, these districts have a higher population density compared to other areas, with Bangorejo recording 497 people per km² and Siliragung at 535 people per km². The primary land use in these areas is residential, and the relatively low gradient of the slopes minimizes the risk of landslides, especially in the downstream areas where most of the social activities occur.





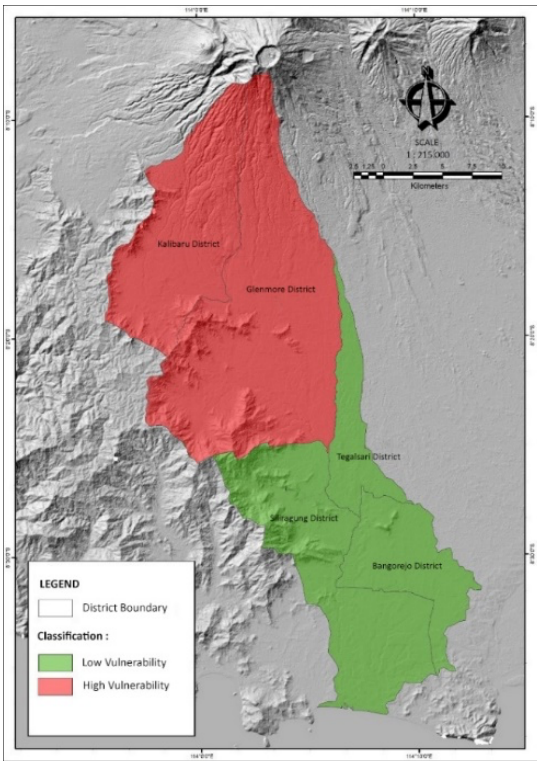
Landslide Classification in Kalibaru Watershed	Area (km²)
Unsusceptible	166.79
Susceptible	407.99
Highly Susceptible	151.62

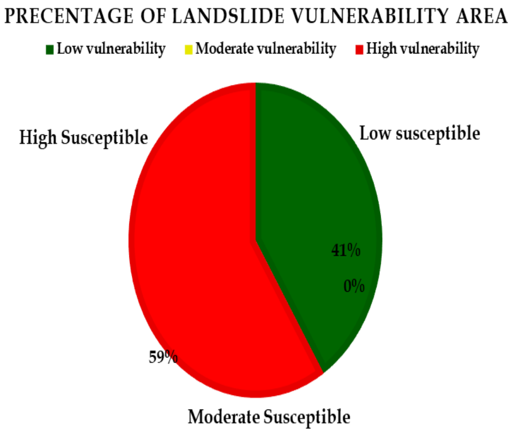
Figure 2. Landslide Hazard Map of Kalibaru Watershed (Source: Data Analysis, 2024)

The medium-threat level predominantly covered the mid-slope area, totaling 407.99 km². This area is characterized by undulating hills and moderate slopes that contribute to a higher frequency of landslides, as confirmed by previous studies (Irawan et al., 2023; Wang et al., 2015). These regions have landforms shaped by volcanic processes, which are especially prone to erosion, particularly under high rainfall conditions. In contrast, the high-threat level was found primarily in the steepest and most vulnerable regions on the upper slopes of the watershed. These areas, covering 151.62 km², include structural landforms associated with geological formations that promote soil instability. Through the Spatial Multi-Criteria Evaluation (SMCE) method, using ILWIS software, high-risk zones were identified, with a Topographic Position Index (TPI) value reaching 42.2, indicating ridges and mountain hills highly susceptible to landslides due to their steep terrain and loose volcanic material. These zones are particularly vulnerable to frequent soil displacement, which exacerbates the risk of landslides.

Landslide Vulnerability in Kalibaru Watershed

Landslide vulnerability across the Kalibaru Watershed varied significantly. Low vulnerability was found in the Bangorejo, Siliragung, and parts of the Tegalsari Districts, while high vulnerability was more prevalent in the Kalibaru and Glenmore Districts (Figure 3). The low-vulnerability areas, spanning 29.471 hectares or 41% of the total study area, are characterized by relatively stable and low-risk zones. In contrast, the high-vulnerability areas covered 59.396 hectares, accounting for 59% of the region, primarily due to high environmental vulnerability and physical factors that make these areas more susceptible to landslide events.





Landslide Classification in Kalibaru Watershed	Area (Ha)
Low vulnerability	29.471
Moderate vulnerability	0
Highly vulnerability	59.369

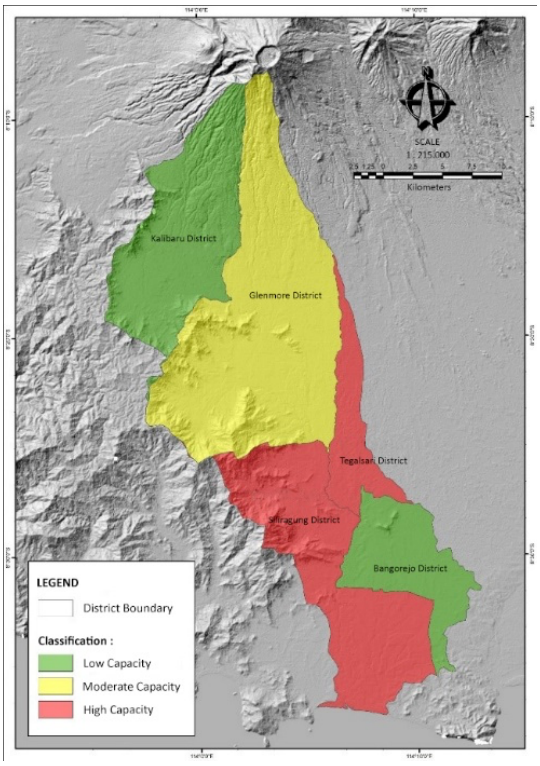
Figure 3. Landslide Vulnerability Map of Kalibaru Watershed (Source: Data Analysis, 2024)

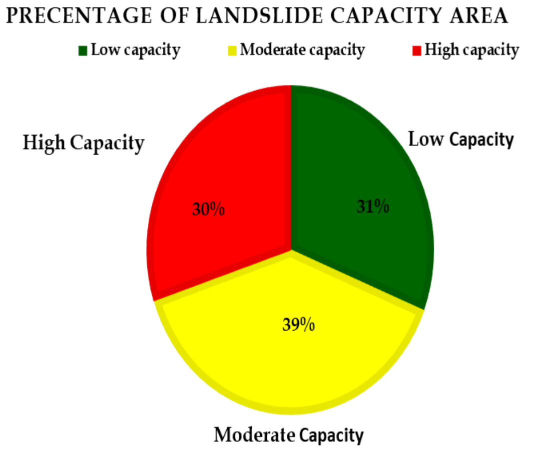
Despite the low vulnerability in certain districts, social vulnerability was consistently high throughout the entire watershed, driven by the dense population residing on steep slopes. The high population density in these areas further exacerbates the vulnerability, as these communities are more susceptible to the effects of landslides. Additionally, the high population density in landslide-prone areas can severely impact emergency response times and disaster management efficiency, underscoring the need for comprehensive preparedness measures. As discussed (Nabila et al., 2020), addressing social vulnerability requires improving social services and meeting the basic needs of communities, which is essential for effective risk mitigation. Thus, the areas with high vulnerability demand an integrated approach that considers both social and environmental factors in managing landslide risks.

Landslide Capacity in Kalibaru Watershed

Disaster capacity is a crucial component in understanding the ability of communities to mitigate and respond to landslide risks. The capacity mapping results (Figure 4) revealed that districts such as Siliragung and parts of Tegalsari, covering 21.682 hectares, exhibited high disaster capacity. This high capacity is attributed to the presence of adequate mitigation infrastructure, effective early warning systems, and a high level of public awareness regarding landslide risks. The capacity of these districts allows for more effective emergency responses and better community preparedness.

Conversely, areas like Glenmore, which cover 28.113 hectares, had medium disaster capacity. While mitigation efforts are ongoing, these areas still face challenges in terms of evacuation planning, community Education, and improving disaster preparedness. Low disaster capacity was found in the upper slopes and downstream areas, including Kalibaru and Bangorejo, where mitigation infrastructure is limited, and access to assistance during emergencies is challenging. These areas are in urgent need of capacity building, with a particular focus on improving infrastructure, educating the public, and enhancing disaster response systems.





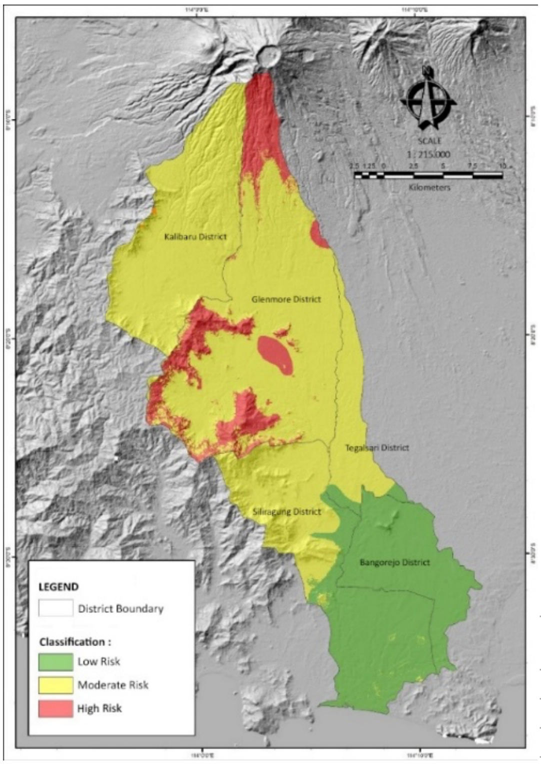
Landslide Classification in Kalibaru Watershed	Area (Ha)
Low capacity	22.742
Moderate capacity	28.113
Highly capacity	21.682

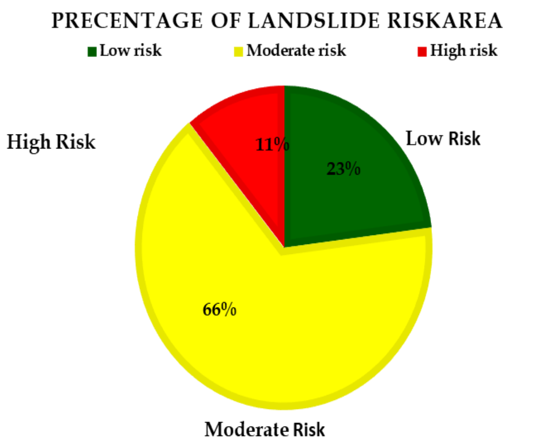
Figure 4. Landslide Capacity Map of Kalibaru Watershed (Source: Data Analysis, 2024)

Landslide Risk in Kalibaru Watershed

The landslide risk map (Figure 5) provided a comprehensive overview of the varying levels of risk across the Kalibaru Watershed. Low landslide risk was observed in the downstream areas, primarily in Bangorejo District, covering 22.742 hectares. This low-risk classification was due to the area's relatively low hazard, vulnerability, and capacity indicators. However, moderate landslide risk was found across 28.113 hectares of the watershed. While these areas showed moderate threat and vulnerability levels, the low disaster response capacity, particularly in the upstream regions, increased the overall risk.

High landslide risk areas were primarily found on the upper northern slopes and parts of the middle slopes, particularly within the Glenmore District. These high-risk zones, covering 21.682 hectares, are characterized by volcanic landforms highly susceptible to erosion. The middle slopes also feature structural landforms that form a weathering zone, which increases water retention in the soil, thereby exacerbating slope instability. Soil landslides are the most common type in these high-risk areas, driven by a combination of geological, morphological, and volcanic factors. Loose volcanic material, particularly during periods of high rainfall, significantly accelerates landslide occurrence (Ipmawan et al., 2018; Moktikanana et al., 2021).





Landslide Classification in Kalibaru Watershed	Area (Ha)
Low risk	22.742
Moderate risk	28.113
Highly risk	21.682

Figure 5. Landslide Risk Map of Kalibaru Watershed (Source: Data Analysis, 2024)

The results of the landslide disaster risk analysis in the Kalibaru Watershed were subsequently verified using the ROC curve, which was implemented through the Area Under Curve (AUC) metric with the ArcGIS tool. Figure 6 shows that the graph has an AUC value of 0.893. This value is close to 1, indicating that the model used in this study to assess landslide disaster risk in the Kalibaru watershed area possesses good accuracy.

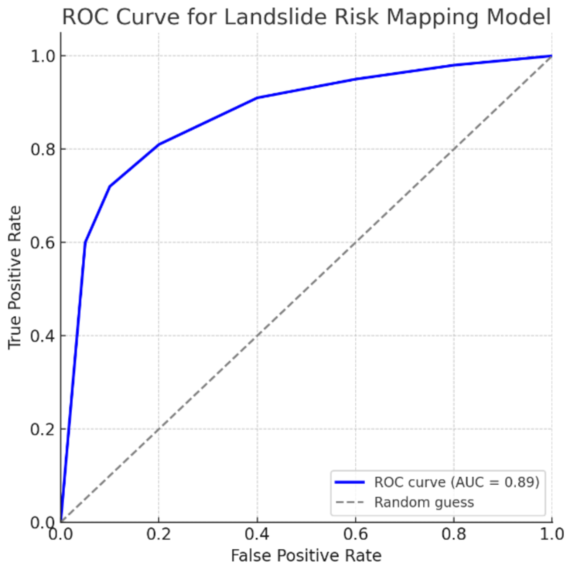


Figure 6. ROC Curve for Landslide Risk Map

An inventory of landslide occurrence points identified 46 landslide locations throughout the Kalibaru Watershed, predominantly in steep regions with structural and volcanic landforms. This data emphasizes the urgent need for comprehensive disaster risk management strategies. While the risk of landslides in densely populated areas is relatively low, the high-risk zones present significant challenges, especially for tourism and agricultural activities. Most tourism facilities are located in the upper watershed areas, which are out of reach of the general public. The lack of disaster awareness in tourist areas, such as the absence of warning signs or evacuation routes, puts both visitors and the local population at risk. Increasing disaster response capacity, particularly in tourism management, and educating visitors about the potential risks are essential steps for minimizing damage from landslides.

The landslide risk in the Kalibaru Watershed mostly occurred in the middle and upper slope areas, particularly in Glenmore and Kalibaru Districts. This high risk was caused by a combination of significant natural hazards and high environmental vulnerability, especially in areas prone to erosion and volcanic rock weathering. The soil in these regions tended to be loose, which increased the risk of landslides during periods of heavy rainfall. If not properly managed, this could result in destructive landslides that disrupt social and economic activities, particularly in areas with high tourism activity. Tourism in these regions was highly vulnerable to disruption from landslides due to its dependence on slope stability and safe accessibility. The impact of such disasters could not only disrupt tourism activities but also harm the local economy, which relied heavily on the tourism sector.

The results of landslide risk mapping in the Kalibaru Watershed demonstrate a spatial pattern consistent with previous studies in volcanic regions. Similar to the findings of (J. F. Irawan et al., 2023; Wang et al., 2016), which reported that hilly areas with moderate to steep slopes tend to have a higher frequency of landslides, this study also identified that high-risk zones are concentrated on the middle to upper slopes of Mount Raung, where the terrain is steep. These findings are in line with (Prasindya et al., 2020), who mapped landslide potential in Songgon Sub-district (on the western slope of Mount Raung), which identified three classes of landslide susceptibility.

Based on the mapping results, most tourist areas were located in middle to upper slope regions, which were categorized as having moderate to high landslide hazard. This indicated that landslide risk management needed to be an integral part of sustainable tourism development plans (Cao et al., 2021; Sarkar et al., 2022). Effective mitigation strategies had to be implemented, including the installation of landslide warning signs, provision of safe evacuation routes, and enhancement of landslide-retaining infrastructure designed to match the region's geomorphological conditions (Khusnani et al., 2023; Lan Huong et al., 2022). The use of modern technology, such as early warning systems, was also crucial to improve the preparedness of the local community and tourists (Mustiadi & Listyalina, 2019; Rahmadya, 2018). The implementation of clear and structured evacuation routes, along with educating tourists about disaster risks, would not only reduce potential losses from landslides but also increase tourists' sense of security, thereby boosting confidence in these tourist destinations.

Sustainable tourism development in the region needed to adhere to environmental conservation principles, especially in maintaining soil and slope stability around Mount Raung. Uncontrolled tourism activities, such as infrastructure development without considering the morphological conditions and environmental capacity, could exacerbate vulnerability to landslides (Bachri et al., 2019). Therefore, tourism development strategies had to align with environmental conservation efforts. One approach that could be taken is through green engineering, a conservation method involving the planting of deep-rooted vegetation in landslide-prone areas. This vegetation served as a natural barrier that could help reinforce the soil structure, reduce erosion, and, at the same time, maintain the aesthetic appeal of the natural tourist destinations.

Moreover, sustainable tourism development also had to actively involve local communities, particularly in areas with low capacity, such as Kalibaru and Bangorejo Districts. Community empowerment was crucial in disaster risk management efforts, as local residents had indigenous knowledge that could be part of the solution (Thouret et al., 2022; Torani et al., 2019). Emergency response training programs, the construction of environmentally friendly infrastructure, and community-based tourism management were some of the initiatives that could help increase local community involvement. By involving the community in risk mitigation efforts, not only would disaster resilience improve, but a sense of ownership and shared responsibility in maintaining tourism sustainability would also be created.

In the framework of sustainable tourism development, a risk-based approach had to be integrated into every stage of tourism planning and management. Landslide risk management in the Kalibaru Watershed demonstrated that the success of sustainable tourism development heavily depended on a deep understanding of the geomorphological conditions and the appropriate implementation of disaster mitigation. Therefore, tourism development around Mount Raung needed to be based not only on the principles of natural resource conservation but also on ensuring adequate protection for the local community and tourists from natural disaster threats like landslides. Integrating risk management into tourism development would ensure the sustainability of these destinations while protecting the environment and the livelihoods of the local community.

The results of this study can be used as a comprehensive reference and practical guideline for various stakeholders, including policymakers, local governments, tourism managers, and disaster management agencies. The integrated landslide risk maps and the underlying analysis offer valuable insights for identifying priority areas, supporting spatial planning, and determining the most appropriate locations for tourism development that are safe from potential landslides. In addition, these findings can be used to inform the preparation of risk mitigation strategies, early warning systems, and community Education programs to increase preparedness and resilience. By utilizing the outcomes of this research, stakeholders can develop tourism infrastructure and activities that not only attract visitors but also prioritize safety, environmental sustainability, and disaster risk reduction. Ultimately, this integrated approach supports the creation of sustainable and disaster-resilient tourism destinations, which can also be replicated in other regions with similar hazard characteristics.

CONCLUSION

The research on landslide risk mapping in the Kalibaru Watershed highlights the critical need for integrating disaster risk management into sustainable tourism development. The study revealed that the highest landslide risks were present in the middle and upper slope areas, particularly in Glenmore and Kalibaru Districts, where a combination of natural hazards and high environmental vulnerability contributed to the elevated risk. Tourism activities in these regions were especially vulnerable to disruption due to the dependence on slope stability and safe access.

To ensure sustainable tourism in these high-risk areas, effective mitigation strategies are essential. These include the installation of landslide warning systems, the provision of clear evacuation routes, and the enhancement of landslide-retaining infrastructure that takes into account the complex geomorphological conditions of the region. Additionally, modern technology, such as early warning systems and community Education on disaster preparedness, is crucial to minimizing the impact of landslides and boosting tourists' confidence in the safety of these destinations.

Moreover, sustainable tourism development must be aligned with environmental conservation efforts. This involves maintaining soil and slope stability through green engineering methods, such as the planting of strong vegetation in landslide-prone areas, which serves to reduce erosion while preserving the natural appeal of the destinations. The active involvement of local communities, especially in areas with lower capacity like Kalibaru and Bangorejo Districts, is also vital in ensuring successful disaster risk management and tourism sustainability. Empowering communities through training and participation in risk mitigation initiatives fosters resilience and shared responsibility.

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