Multi-Hazard Risk Hotspots: A Spatial Analysis for Enhancing Tourism Sustainable-Resilience in Labuan Bajo, Manggarai Barat Regency, Indonesia

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Abstract. Labuan Bajo, a popular tourism destination in Manggarai Barat Regency, Indonesia, faces escalating multi-hazard risks driven by rapid development, land-use change, and climate variability. To address this, we conducted a comprehensive spatial multi-hazard risk assessment encompassing seven hazards: tsunami, earthquake, landslide, flood, extreme weather, drought, and forest/land fire. Following Indonesia's national disaster risk analysis standard (SNI), we integrated hazard, vulnerability, and capacity data within a Geographic Information Systems (GIS) framework. The analysis uniformly classifies the entire region as "high risk," with the highest risk concentrations in coastal zones, tourism infrastructure, and residential corridors. These results highlight the urgent necessity for a cohesive resilience strategy, encompassing multi-hazard-informed spatial planning, improved early warning systems, nature-based solutions, and focused contingency planning. This study provides a scientific basis for policymakers and tourism stakeholders to advance for developing sustainable resilience tourism.
Keywords: multi-hazard risk assessment, resilience tourism, sustainable tourism

1 Introduction

Tourism plays a vital role in the global political and economic landscape, serving as a major driver of growth and foundation for sustainable livelihoods in many destination communities [1,2]. However, the tourism sector is highly sensitive to environmental disturbances and climate change, particularly in regions frequently exposed to natural hazards [3]. Tourism destinations in coastal and island areas around the world are increasingly facing challenges from disasters such as floods, tsunamis, and coastal erosion, underscoring the importance of integrating disaster risk management into tourism planning and policy [3]. Indonesia is recognized as one of the most disaster-prone nations globally because of its position within the Pacific Ring of Fire, rendering it susceptible to numerous natural hazards. Tourism destinations in Eastern Indonesia, such as Labuan Bajo, face the dual challenge of fostering economic growth while addressing diverse disaster risks [4,5].

Manggarai Barat, especially Labuan Bajo, has undergone rapid tourism-driven infrastructure expansion in recent years, marked by the construction of new resorts, ports, and transportation facilities [4,6]. However, this accelerated growth has not been fully supported by spatial planning practices, including the principles for reducing disaster risk. The complex terrain and climatic variability in the area expose it to multiple natural hazards, including landslides, flooding, and seismic events [7].

Research on disaster risk in tourism locations has attracted substantial interest over the last decade, because of the tourism sector's value to the global economy and vulnerability to disaster impacts [7,8]. Labuan Bajo, one of Indonesia's top tourist spots, has seen significant progress in tourism infrastructure. However, it is in an area with a lot of seismic activity and complicated climate hazards, and is at risk for many different types of disasters. Previous studies have shown the need for integrated strategies for disaster risk reduction within tourist regions, especially in places that are prone to disasters, such as Indonesia [9]. Several studies have explored specific disaster risks in Eastern Indonesia; however, a complete understanding of the multi-hazards faced by highly visited tourist locations such as Labuan Bajo, remains insufficient [4,10]. Most prior studies have concentrated on single-hazard analysis; however, the complex geographical characteristics of Labuan Bajo require a multi-hazard assessment method. Moreover, there is a lack of research that spatially combines the examination of tourism infrastructure vulnerability with climate change forecasts within the framework of multiple hazard risk analyses.

This study aims to develop an integrated multi-hazard risk assessment through spatial analysis of the

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Labuan Bajo tourism destination. Specific objectives: (1) to identify the spatial distribution of seven major hazards, (2) to combine these maps into a multi-hazard risk map using an overlay method, and (3) to provide evidence-based recommendations for disaster resilience and sustainable tourism. This study is expected to enhance the implementation of spatial-based techniques for assessing disaster risks in tourism areas in Indonesia. In addition, the results provide a foundation for local governments to design policies to reduce disaster risks that are integrated with sustainable tourism development plans.

2 Material and Method

2.1 Study Area

This research focuses on the Tourist Destination Area (TDA) of Manggarai Barat, encompassing the Key Tourism Areas (KTA) of Labuan Bajo and Taman Nasional Komodo. The Tourist Destination Area (TDA) Manggarai Barat is situated in the western region of Flores Island, East Nusa Tenggara Province, Indonesia. It is bordered by the Flores Sea to the north, Sumba Strait to the south, Sawu Sea to the east, and Flores Sea to the west.

Tourist Destination Area (TDA) Manggarai Barat covers a total area of 3,141.47 km², consisting of 1,545.06 km² of land area and 1,596.41 km² of marine waters. The population density varies significantly across the regency, with the highest concentration in the urban areas of Labuan Bajo functioning as the primary access point to Komodo National Park.

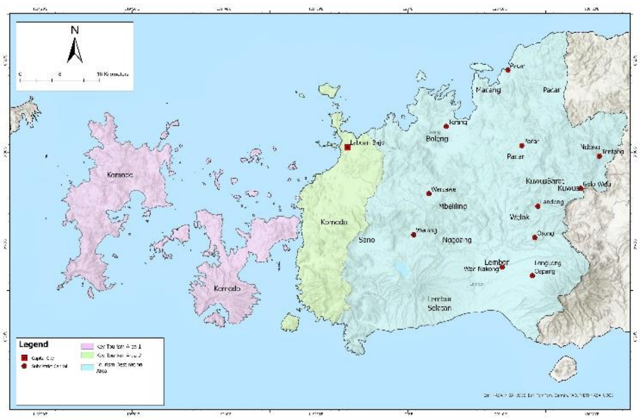


Fig. 1. Research Area

The unique geographical characteristics of the Tourist Destination Area (TDA) Manggarai Barat, which combine coastal areas, hilly terrain, and small islands, creates complex disaster risk patterns. The location of the region within the active Sunda-Banda Arc and its tropical monsoon climate contribute to high vulnerability to various hazards, including tsunamis, earthquakes, and extreme weather. The rapid development of tourism infrastructure in coastal areas, combined with population growth and climate change, has significantly increased disaster exposure levels.

Therefore, a comprehensive disaster risk assessment is crucial for identifying high-risk areas, particularly those containing critical tourism infrastructure and settlement areas that have experienced significant losses according to recorded catastrophic events from the past decade.

2.2 Data and Methodology

This research utilized a single-hazard map incorporating susceptibility parameters for various hazards, including earthquakes, tsunamis, floods, landslides, extreme weather, forest and land fires, and drought, to develop a multi-hazard map. The methodology employed aligns with the assessment standards set forth by the Head of the National Disaster Management Agency (BNPB) Number 2 of 2012, along with the relevant technical guidelines and Indonesian National Standard (SNI). A disaster risk assessment is conducted based on three risk components: hazard, vulnerability, and capacity. The risk index is directly proportional to the hazard and vulnerability indices and inversely proportional to the capacity index. The values of the hazard and vulnerability indices are directly proportional to the risk index because the potential for hazards cannot be eliminated, and vulnerability will inevitably follow. Therefore, the development of government and community capacities is necessary to reduce potential risks.

Table 1. Data and Objective

No	Type of Data	Data Collection Technique	Objective
1	Regional Resilience Index (IKD)	FGDs with local actor	Developing capacity map (C)
2	Community Preparedness Index (IKM)	Village surveys (based on sampling method), interviews, and using InaRISK Personal application	Developing capacity map (C)
3	Tourism Resilience Index (TRI)	Tourism surveys (based on sampling method), and interviews.	Developing capacity map (C)
4	Physical Infrastructure Vulnerability Index	Infrastructure surveys (based on sampling method), interviews,and using InaRISK Personal application.	Developing vulnerability map (V)
5	Social, Economy, and Environmental	Infrastructure surveys (based	Developing vulnerability map (V)

	Vulnerability Index	on sampling method), interviews,and using InaRISK Personal application	
6	Hazard Index	"Walidata" Multi-actor Agency: tsunamis, earthquakes, landslides: (BMKG, Badan Geologi) floods: (BIG, Ministry of Work) extreme weather, droughts: (BMKG), and forest and land fires: (Ministry of Forest)	Developing hazard map (H)

2.2.1 Hazard Assessment

The hazard assessment aimed to identify and analyze the spatial distribution and intensity of potential natural hazards in the Manggarai Barat Regency. The analysis covered seven hazard types: earthquakes, tsunamis, floods, droughts, landslides, forest and land fires, and extreme weather. The assessment followed the general framework of the BNPB Disaster Risk Assessment Guidelines, emphasizing the integration of verified national datasets and standardized spatial processing to ensure consistency across hazard types.

Hazard-related datasets were obtained from official national data custodians "Walidata" and relevant institutions. Seismic and tsunami data were acquired from the Meteorology, Climatology, and Geophysical Agency (BMKG) and the Geological Agency (PVMBG), and include vector data on fault lines, seismic events, and tsunami-prone zones. Flood, drought, and landslide datasets encompassing rainfall distribution, slope gradients, and soil lithology were collected from the Geospatial Information Agency (BIG), PVMBG, and BMKG. Forest and land fire data were provided by LAPAN/BRIN using MODIS and VIIRS imagery, whereas coastal morphology and bathymetric data were obtained from BIG and Sentinel-2A Level-2A imagery (10 m resolution) supplied by the European Space Agency (ESA).

All spatial datasets used in the analysis were converted into raster format to enable quantitative spatial modeling. The raster layers were regenerated to a consistent spatial resolution of 30 m × 30 m to maintain spatial uniformity. Each raster dataset and hazard indicator was normalized to a uniform range of 0 to 1, allowing all variables regardless of their original measurement units to contribute proportionally to the composite hazard analysis. The normalization process followed the general standardization principles recommended by the BNPB Risk Assessment Guidelines. The normalized layers were then integrated through a spatial overlay and map algebra operations to produce continuous hazard intensity surfaces for each hazard type.

All resulting maps were stored in (GeoTIFF) format as standardized hazard layers, forming an analytical foundation for subsequent assessments of vulnerability, capacity, and overall disaster risk. This approach ensures methodological consistency with the technical standards and data protocols applied in Indonesia's national disaster risk assessment framework.

2.2.2 Vulnerability Assessment

Vulnerability assessments are conducted in the form of social vulnerability in the form of population, poverty, and disability data obtained from the latest BPS; in the form of physical vulnerability in the form of public facilities, critical facilities, and settlement data obtained from BIG WebGIS; in the form of economic vulnerability in the form of the latest income in the region obtained from BPS data at the district level; and in the form of environmental vulnerability in the form of land use obtained from the Ministry of Environment and Forestry.

2.2.3 Capacity Assessment

The capacity assessment in this study considered three main components. First, the Regional Resilience Index, is validated by the National Disaster Management Agency. The second component was the Community Readiness Index, which was developed from focus group discussions (FGDs) with local stakeholders to capture community-level preparedness. The third component assessed readiness of the tourism sector, particularly tourism operators, through structured interviews. The results from these three components were standardized and aggregated to represent the overall capacity level of the Manggarai Barat Regency.

2.2.4 Risk Assessment

The risk index was calculated using the following equation. The calculation yielded an index value between zero and one. An index value ranging from 0 to 0.333 signifies a low-risk classification, whereas a value from 0.334 to 0.666 denotes a medium-risk classification. An index value between 0.667 and 1 represents a high-risk classification. The risk index was determined using the following formula:

$$R = \frac{H\ X\ V}{C} \tag{1}$$

R represents Disaster Risk. H (Hazard Threat) refers to the probability of a specific disaster occurring at a defined intensity at a given location. V (vulnerability) denotes the degree of exposure and the potential population impacted in a specific region in the event of a disaster of a certain intensity; C (capacity) refers to the resources available in that area for recovery from a specific disaster. Disaster risk assessment efforts were conducted to mitigate disaster risk through three primary strategies: (1) minimizing hazards, (2) reducing vulnerabilities, and (3) enhancing capacities.

3 Result and discussion

The classification process for the single hazard map was conducted using the fuzzy logic classification method, in accordance with the regulatory document issued by the Head of the National Disaster Management Agency (BNPB) Number 2 of 2012 and the Indonesian National Standards (SNI). Disasters can be categorized into several types: earthquakes, tsunamis, floods, landslides, extreme weather events, forest fires, and droughts. The spatial resolution applied to the single hazard map for each disaster type is a pixel size of 30 by 30 square meters.

3.1 Hazard

The hazard level classes in the (TDA) Manggarai Barat for disaster types such as earthquakes, tsunamis, floods, landslides, extreme weather, forest and land fires, and droughts are shown in Table 2.

Table 2. Hazard potential in TDA Manggarai Barat.

Disaster type	Hazard level	Area	
		Ha	%
Earthquakes	Low	159,205.5	50.8
	Moderate	144,205.7	46.0
	High	10,082.3	3.2
Forest and land fires	Low	114,291.6	36.5
	Moderate	96,356.9	30.7
	High	96,272.8	30.7
Extreme weather	Low	0	0
	Moderate	139,997.1	44.6
	High	172,879.2	55.1
Drought	Low	0	0
	Moderate	0	0
	High	313,493.4	100
Tsunami	Low	604.8	0.2
	Moderate	337.6	0.1
	High	16,395.8	5.2
Floods	Low	11,469.9	3.7
	Moderate	26,419.5	8.4
	High	24,929.4	7.9
Landslides	Low	114,862.2	36.6
	Moderate	86,629.5	27.6
	High	29,800.6	9.5

Table 2 presents the classification of hazard levels in the (TDA) Manggarai Barat based on spatial analysis of the seven hazard types. The results indicate that the majority of the region is dominated by moderate-to-high hazard levels, reflecting the complex environmental conditions and exposure of key settlements and tourism areas. Earthquake and landslide hazards generally fall within the low-to-moderate categories, suggesting that while both hazards are spatially extensive, their potential impacts remain relatively manageable under current conditions. These findings indicate that, although the earthquake threat is widespread, its intensity remains relatively moderate across most parts of the study area [7]. In contrast, flood and tsunami hazards occupy more limited areas but are mostly classified as moderate to high, particularly in zones associated with high population density and tourism infrastructure [11].

Drought and extreme weather hazards dominate the regional hazard profile, with most areas categorized as having high hazard levels, consistent with the dry climatic characteristics of (TDA) Manggarai Barat and its dependence on seasonal rainfall. Meanwhile, forest and land fire hazards were distributed relatively evenly across all hazard classes, indicating that fire risk was not concentrated in a specific land type or subregion.

Overall, the findings highlight that (TDA) Manggarai Barat faces a multi-hazard environment, with overlapping hazard zones that could amplify cumulative disaster impacts. The predominance of moderate to high hazard levels suggests the need for proactive spatial planning and disaster preparedness measures, particularly in tourism and settlement zones where exposure is the greatest.

3.2 Vulnerability

Vulnerability assessment based on the components of social, physical, economic, and environmental vulnerability results in the potential for the population to be exposed and disaster losses. The recapitulation of the vulnerability study for determining the potential population exposed to disasters in the Tourist Destination Area (TDA) of Manggarai Barat is shown in Table 3.

Table 3. Vulnerability assessment in TDA Manggarai Barat.

Disaster Type	Exposed Population (People)	Vulnerable Group			Class
		Vulnearble Age	Poor Resident	Persons with Disabilities	
Earthquakes	282,943	25,345	45,159	2,717	Medium
Forest and land fires	(-)	(-)	(-)	(-)	(-)
Extreme weather	217,360	19,471	34,690	2,087	High
Drought	282,943	25,345	45,159	2,717	High
Tsunami	22,988	2,057	3,670	220	High
Floods	104.438	9,354	16,670	1,002	High
Landslides	77,735	6,961	12,402	749	Low

Based on Table 3, a considerable portion of the population of Manggarai Barat is exposed to multiple hazards, particularly drought, extreme weather, tsunamis, earthquakes, and floods. The exposed groups included residents in densely populated areas, elderly populations, low-income households, and persons with disabilities, all of whom are more likely to experience severe impacts during disaster events.

Earthquake hazards show moderate vulnerability, as many residents live in permanent housing and have relatively good access to public facilities, which helps reduce potential losses. However, extreme weather and drought hazards present a higher vulnerability, reflecting the region's semi-arid conditions, dependence on seasonal rainfall, and limited water infrastructure. These hazards disproportionately affect poor households and communities with restricted access to clean water and emergency resources.

Tsunamis and flood hazards also indicate high vulnerability due to the concentration of settlements and tourism infrastructure in low-lying coastal zones. The high exposure in these areas, combined with limited evacuation routes and early warning systems, increases potential risks to life and property [4]. In contrast, landslide vulnerability is relatively low because steep and elevated areas are less populated and are supported by natural vegetation that stabilizes slopes [7].

Data on forest and land fires are not numerically available in this table. However, based on land cover characteristics and land-clearing activities in the surrounding hilly areas, this hazard is likely to have localized impacts, with vulnerability ranging from moderate to high during the dry season.

Overall, the findings demonstrate that vulnerability in Manggarai Barat is driven not only by physical exposure, but also by socio-economic conditions and uneven access to resources. Strengthening early warning systems, improving public awareness, and integrating spatial risk information into local development planning are essential for enhancing community resilience across hazard-prone areas.

3.3 Capacity

A capacity assessment was performed to demonstrate the region's capability to anticipate, respond to, and recover from disaster events. This approach follows the guidelines of the BNPB, which assesses capacity through three main components: the Community Preparedness Index, the Regional Resilience Index, and Tourism Resilience Index. These indices are subsequently combined to form the Capacity Index, which serves as the basis for multi-hazard risk calculations.

3.3.1 Regional Resilience Index

The Regional Resilience Index was used to describe the institutional and governance capacity of the Manggarai Barat Regency in disaster risk management. This index reflects the strength of disaster management structures, availability of regulations and coordination mechanisms, and incorporation of disaster risk reduction into local planning. Higher index values indicate stronger institutional readiness and coordination at a regional level.

Table 4. Regional resilience index of TDA Manggarai Barat

Priority	Priority Index	Regional Capacity Index	Regional Capacity Level
Policy and Institutional Strengthening	0.7	0.5	Medium
Integrated Assessment of risks and Planning	0.6		
Development of Information Systems,	0.6		

Priority	Priority Index	Regional Capacity Index	Regional Capacity Level
Training, and Logistics			
Thematic Management of Disaster-Prone Zones	0.6		
Enhancing the Efficacy of Disaster Prevention and Mitigation	0.5		
Enhancing Disaster Preparedness and Emergency Management	0.4		
Disaster Recovery System Development	0.3		

The analysis of the Regional Resilience Index indicated that the institutional capacity of the Manggarai Barat area was categorized as moderate, with an average index value of 0.50 (Table 4). This value reflects a gradually improving institutional capability to support disaster management systems, although disparities remain across the priority aspects.

Specifically, the Policy and Institutional Strengthening indicator obtained the highest score of (0.7), which, according to BNPB's classification, falls into the high category. This suggests that policy and institutional strengthening efforts in the Manggarai Barat Regency have been well developed, supported by the presence of the Local Disaster Management Agency (BPBD) and the adoption of local policy instruments such as the Local Disaster Management Plan (RPB) of Manggarai Barat 2023–2027, which serves as the foundation for enhancing the regional disaster management system.

Meanwhile, the Integrated Risk Assessment and Planning (0.6) and Information System Development, Training, and Logistics (0.6) indicators also demonstrated relatively high values (moderate–high category). These results indicate that risk assessment, disaster planning, and the development of disaster information and logistics systems have begun to be implemented in a structured manner at the regional level.

However, several other indicators remained within the moderate-to-low range. The Thematic Management of Disaster-Prone Zones aspect scored (0.6), while Enhancing the Efficacy of Disaster Prevention and Mitigation scored (0.5). These results indicate that, although thematic disaster risk reduction programs have been initiated, their implementation remains confined to project-based activities and has not been fully incorporated into the wider regional development framework.

Lower scores were found for the indicators of Strengthening Disaster Preparedness and Emergency Management (0.45) and Disaster Recovery System Development (0.30). These values reflect a limited capacity in preparedness, emergency response, and post-disaster recovery management. Logistical support and sustainable recovery mechanisms remain suboptimal, particularly in tourism-oriented areas characterized by high economic and population dynamics.

According to the BNPB, the regional resilience index value within the range of 0.4–0.8 represents institutional capacity that has been established but is not yet effective in cross-sectoral implementation. This finding is consistent with the observations of Wibowo et al., who noted that development planning in Labuan Bajo has not yet fully integrated disaster mitigation and climate adaptation strategies [4]. Moreover, inter-agency coordination in managing high-risk tourism zones remains limited, constraining the effectiveness of institutional resilience.

3.3.2 Community Preparedness Index

Community preparedness represents the social aspect of disaster capacity and, indicates how well local communities can anticipate and respond to hazards. The Community Preparedness Index was developed from the indicators of awareness, early warning response, training participation, and availability of emergency resources. The results are summarized in Table 5, which shows the preparedness levels across the TDA Manggarai Barat.

Table 5. Community preparedness index of TDA Manggarai Barat.

Disaster type	Knowledge	Early Warning	Emergency Response	Mobilization	Preparedness Index	Preparedness Level
Earthquakes	0.1	0.1	0.3	0.2	0.1	Low
Forest and land fires	0.1	0.1	0.3	0.3	0.2	Low
Extreme weather	0.2	0.1	0.3	0.3	0.2	Low
Drought	0.2	0.1	0.2	0.3	0.2	Low

Disaster type	Knowledge	Early Warning	Emergency Response	Mobilization	Preparedness Index	Preparedness Level
Tsunami	0.1	0.1	0.4	0.2	0.2	Low
Floods	0.2	0.1	0.3	0.3	0.2	Low
Landslides	0.3	0.1	0.3	0.3	0.2	Low
Multi-Hazard Index	0.2	0.1	0.3	0.3	0.2	Low

The average Community Preparedness Index value of (0.2) indicates that the level of community preparedness in the Labuan Bajo tourism area remains low. The assessed components were knowledge (0.2), early warning systems (0.1), emergency response (0.3), and community mobilization (0.3). The very low scores in the knowledge and early warning components suggest that most residents have a limited understanding of local hazards and insufficient access to disaster information systems. Meanwhile, the response and mobilization components show slightly better yet still low values, indicating that the community capacity to respond effectively during disasters remains limited.

The low value further implies that disaster preparedness has not yet become part of local culture or daily tourism practices. Most tourism stakeholders are not been actively involved in simulation exercises, training programs, or evacuation planning. This finding is consistent with a previous study, which reported that Indonesia's priority tourism destinations face similar challenges, particularly low disaster literacy among local communities and weak coordination between government, community groups, and the private sector in developing community-based preparedness systems [8].

Such conditions exacerbate the socioeconomic risks in the coastal areas of the Manggarai Barat Regency, which serve as both the main tourism hub and the most hazard-prone zones exposed to tsunamis, tidal floods, and coastal erosion. Limited preparedness capacity also contributes to slow post-disaster recovery, as communities lack the adaptive capabilities needed to cope with disruptions. Therefore, improving community preparedness by integrating disaster education into tourism communities, conducting regular evacuation drills, and strengthening community-based early warning systems to enhance resilience at the local level is an urgent priority.

3.3.3 Tourism Resilience Index

The Tourism Resilience Index provides a practical framework for tourism businesses and industry leaders to evaluate their preparedness to sustain operations during and after disasters, offering insights that support strategic actions toward long-term resilience. Table 6 presents a summary of the Tourism Resilience Index results.

Table 6. Tourism resilience index of TDA Manggarai Barat.

Priority	Priority Index	Tourism Capacity Level
Business and Operations Plans	0.8	Medium
Disaster Preparedness Plan	0.4	
Marketing	0.8	
Workforce	0.6	
Source Access and Knowledge	0.8	
Local Resource	0.4	

The Tourism Resilience Index results indicate that the Manggarai Barat Regency has a medium level of tourism resilience, reflecting the limited capacity to maintain and recover operations during crises. Components such as business and operational planning, marketing, resource access, and knowledge show relatively better conditions, suggesting that basic management and promotional systems are in place. However, weaknesses in disaster preparedness, workforce capacity, and local resource utilization highlight the lack of integrated risk management and adaptive capabilities. Overall, the low resilience score implies that while some institutional foundations exist, the tourism sector remains vulnerable and requires stronger coordination, skill development, and community engagement to achieve long-term resilience.

3.3.4 Capacity Index

Capacity reflects the ability of a community or region to anticipate, respond, and recover from hazardous events. Disaster risk assessment, functions as a counterbalance to hazard and vulnerability, where higher capacity indicates greater resilience. This study assessed regional capacity in the Manggarai Barat Regency using composite indicators of institutional readiness, infrastructure, access to basic services, and community preparedness.

A summary of the capacity index and its regional classification are presented in Table 7.

Table 7. Results of disaster capacity studies in TDA Manggarai Barat

Disaster type	Capacity Index	Capacity Class
Earthquakes	0.3	Low
Forest and land fires	0.3	Low
Extreme weather	0.3	Low
Drought	0.3	Low
Tsunami	0.3	Low
Floods	0.3	Low
Landslides	0.3	Low

The analysis results show that the capacity index values in the Manggarai Barat Regency average (0.3), which falls under the low capacity category. These values indicate that the region's ability to anticipate, respond, and recover from disasters remains limited. Conceptually, the capacity index reflects the level of institutional readiness, human resources, and coordination mechanisms in disaster risk management. These low values suggest that these three components have not yet functioned optimally.

The small variation across hazard types indicates that preparedness levels are uniformly low throughout the region. This aligns with the findings from both the Regional Resilience Index and the Community Preparedness Index, which also show moderate to low levels of achievement. Consequently, limited adaptive capacity has become a key factor contributing to higher disaster risk levels in the TDA Manggarai Barat. Therefore, strengthening institutional systems and enhancing community preparedness should be prioritized to improve resilience and reduce potential disaster impacts in the future.

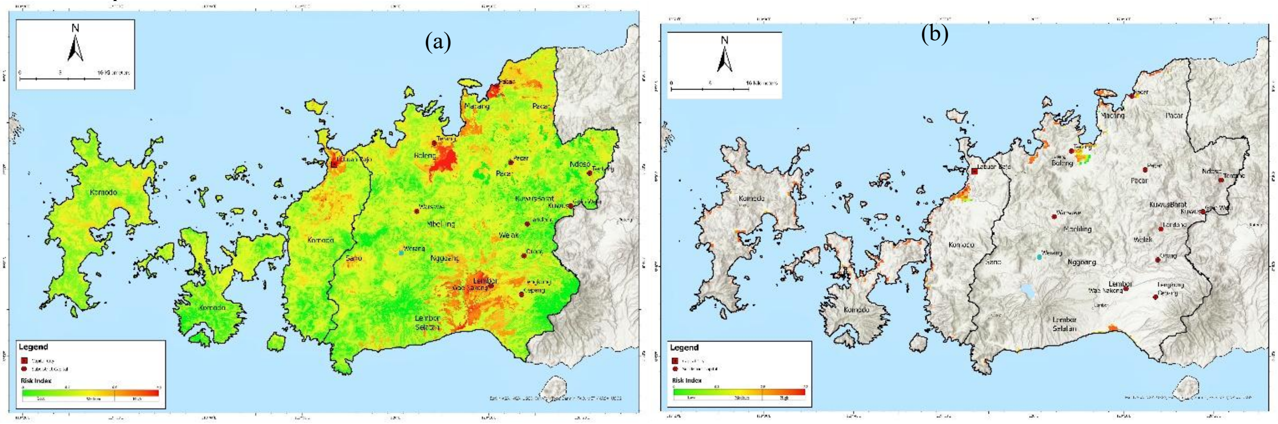
3.4 Risk Index

The disaster risk index for the TDA Manggarai Barat was determined through the integration of hazard, vulnerability, and capacity components using the national standard approach from the BNPB. Each hazard type was analyzed individually to determine the level of potential loss and exposure, followed by the aggregation of all hazard indices into a single multi-hazard risk layer.

Table 8. Results of disaster capacity studies in TDA Manggarai Barat.

Disaster type	Threat Level	Level of Potential Loss	Capacity Level	Risk Level
Earthquakes	High	High	Low	High
Forest and land fires	High	High	Low	High
Extreme weather	High	High	Low	High
Drought	High	High	Low	High
Tsunami	High	High	Low	High
Floods	High	High	Low	High
Landslides	High	High	Low	High

Table 8 summarizes the classification results, showing that all hazard types fell within the high-risk category. This overall high level of risk reflects the wide spatial extent of hazard exposure, combined with significant vulnerability and limited adaptive capacity. Among the assessed hazards, tsunamis, floods, and extreme weather showed the highest relative impact values because of their spatial overlap with dense coastal settlements and tourism infrastructure.



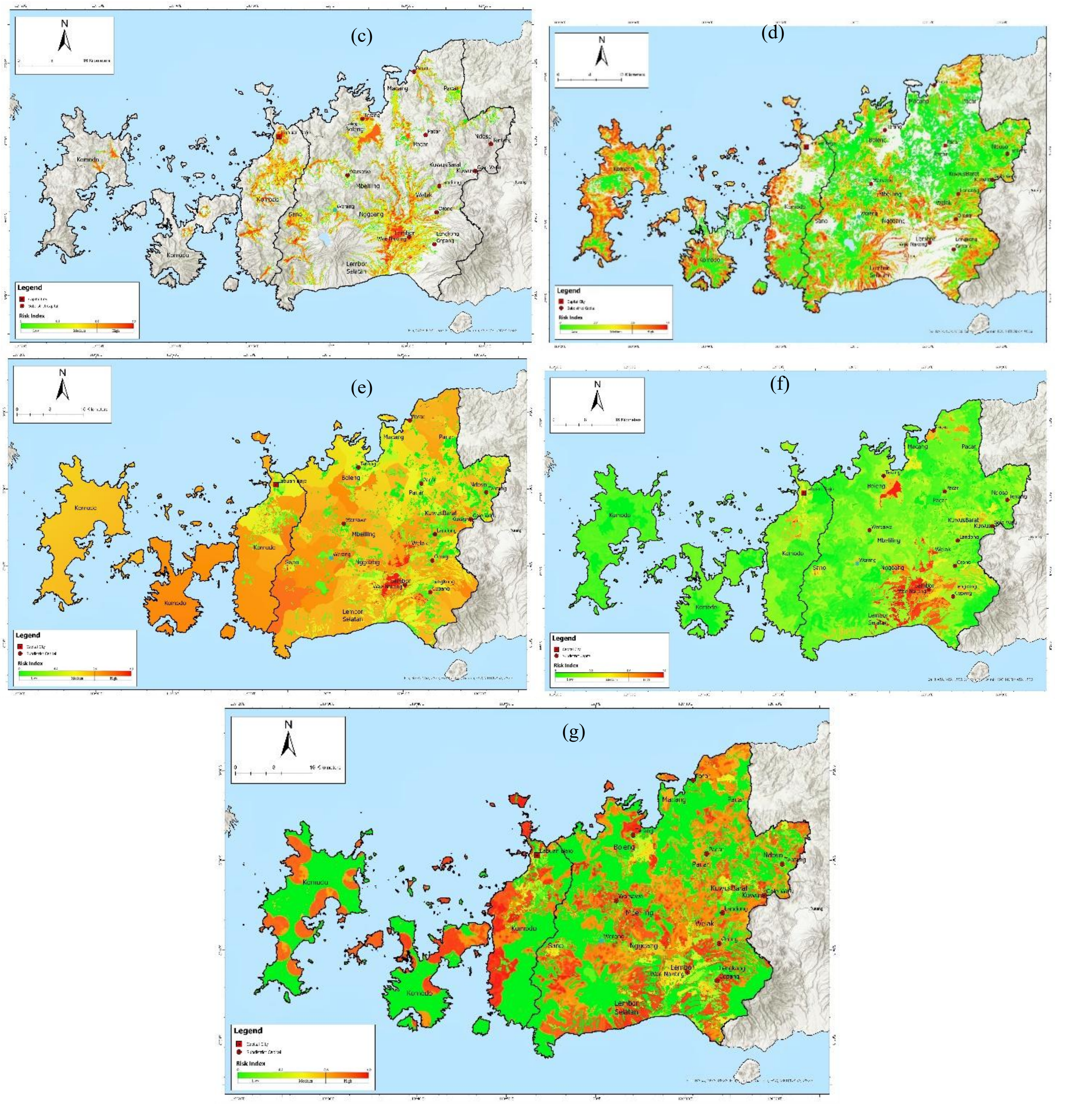


Fig. 2. The Spatial Distribution of Single-Hazard Risk Indices for Manggarai Barat Regency. *Each panel represents the spatial pattern of risk for a specific hazard type: (a) earthquakes, (b) tsunami, (c) floods, (d) landslide, (e) drought, (f) extreme weather, (g) forest and land fire*

The results indicated that all hazard types fell within the high-risk category, although the level of severity varied spatially. Tsunami and flood risks are most dominant in coastal areas, where population density and tourism infrastructure are concentrated. The earthquake risk is widespread across the regency, particularly in the southern zones, owing to the region's tectonic setting. Landslide risk is prevalent in the central hilly areas with steep slopes and agricultural expansion, whereas drought and extreme weather risks tend to affect the eastern and interior regions, impacting water resources and livelihoods. Forest and land fire risks were concentrated in dryland vegetation zones.

The integration of these individual risk layers produced a composite multi-hazard risk index, representing the cumulative risk level across the regency. Figure 3 illustrates the spatial distribution of this composite index, revealing a clear west-east risk gradient. High-risk zones are mainly concentrated in the western and southern coastal areas, where multiple hazards overlap with dense settlements and tourism infrastructure. Moderate-risk zones extend across the central highlands, and low-risk zones dominate the eastern uplands and are characterized by lower exposure and greater vegetation cover.

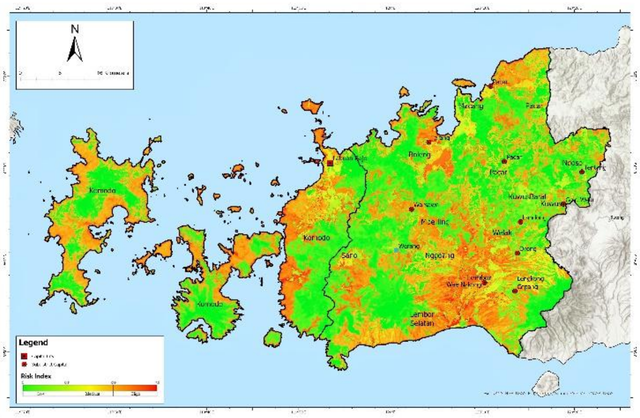


Fig. 3. Spatial Distribution of the Composite Multi-Hazard Risk Index in Manggarai Barat Regency.

This spatial pattern highlights that the Labuan Bajo coastal corridor is the most critical multi-hazard cluster in the regency. The overlap of intensive tourism activities, rapid urban expansion, and limited institutional preparedness amplifies systemic vulnerability. Therefore, integrating multi-hazard information into spatial planning and sustainable tourism policy is essential for reducing risks and strengthening resilience in this high-exposure coastal region.

These findings reveal that the level of disaster risk in Manggarai Barat is influenced not only by the intensity of natural hazards but also by the limitations of adaptive capacity and the ineffectiveness of disaster governance. Previous studies emphasize that regions with low institutional capacity tend to experience higher systemic risks even when hazard intensity remains relatively constant [12,13], and highlight a persistent gap between the rapid growth of the tourism sector and insufficient disaster mitigation preparedness in Labuan Bajo.

Overall, these results indicate that the disaster risk in Manggarai Barat is systemic in nature, emerging from the interaction between natural hazards, socioeconomic vulnerabilities, and weak capacity. Reducing this risk requires strengthening the institutional capacity, implementing inclusive risk governance, and integrating resilience-building strategies into tourism development and spatial planning. Through such an integrated approach, a region can move toward becoming a more resilient, adaptive, and sustainable tourism destination.

4 Conclusions

This study concludes that the TDA Manggarai Barat Regency, particularly the Labuan Bajo tourism area as the main center of tourism activities, faces a high level of multi-hazard risk driven by the combination of intense natural hazards, socio-economic vulnerability, and limited adaptive capacity. Disaster risk in this tourism region is systemic, as it is shaped not only by physical exposure but also by weak institutional coordination and limited community preparedness. To achieve sustainable resilience, integrated disaster risk governance, community-based preparedness initiatives, early warning system enhancement, and implementation of nature-based solutions are essential. Incorporating multi-hazard risk considerations into spatial and tourism development planning is crucial for harmonizing economic growth with environmental safety.

Future studies are encouraged to expand the analytical framework by integrating dynamic spatial modeling with long-term climate change projections and socio-economic scenarios to improve the accuracy of risk prediction. Moreover, assessing the effectiveness of disaster risk governance in the tourism sector and evaluating the long-term socio-economic impacts on local communities would provide valuable insights for adaptive planning. Such interdisciplinary approaches will deepen the understanding of the complex relationships among natural hazards, social vulnerability, and sustainable tourism development in high-risk regions, such as Labuan Bajo.

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