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GIS BASED ON ANALYSIS OF EARTHQUAKE HAZARD LEVEL USING THE PGA IN SIBERUT - MENTAWAI ISLANDS REGENCY FOR SUSTAINABILITY IN DISASTER MITIGATION

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Abstract: The research aims to investigate and map the distribution of epicentre depth, magnitude, and Peak Ground Acceleration (PGA) values against earthquake hazards as well as evaluate the numerical parameters that influence the magnitude of earthquake hazard values. This research uses the Geographic Information System (GIS) and kriging analysis as well as algebra to create an earthquake hazard map. The parameters used include the spatial distribution of epicentres in the ocean, epicentre depth, and PGA values. In addition, statistical analyses were conducted to identify variables affecting the spatial distribution of earthquake hazards. The research results show that the research area on Siberut Island, which is part of the Mentawai Islands has a scattered earthquake distribution. Epicentre depths ranged from 6.10 km to 107.60 km with an average depth of 30.13 km, indicating that most of the earthquakes were shallow. The magnitude of the earthquakes ranged from 3.50 to 7.60 Mw with an average of 4.63 Mw. PGA values ranged from 89.57 gal to 283.17 gal with the highest values found in areas with shallow epicentres and high earthquake intensities. This research provides important contributions for policymakers in island spatial planning, sustainable development, earthquake, and tsunami hazard mitigation.

Keywords: Earthquake hazards, Siberut Island, epicentre depth, PGA, GIS.

Introduction

An earthquake is a natural disaster that causes much loss of property and human lives. Earthquake often cause significant psychological impacts on victims, especially in areas located at the meeting point of several tectonic plates, where the frequency of earthquakes tends to be higher and the sense of uncertainty further exacerbates the mental trauma they experience (Mase *et al*., 2018; Nato *et al*., 2022; Covi *et al*., 2023; Jena *et al*., 2023). An earthquake is also a natural event that is very difficult to predict, so instances of earthquakes are crucial for further research (Huang *et al*., 2011; Darzi *et al*., 2022).

Indonesia is a country at high risk of earthquakes as it is located in the tropics, between three global plate confluences (the Indo–Australian plate moving north, the Eurasian plate moving south, and the Pacific plate migrating west). Because of the impact of this plate movement, the Indonesian region faces a significant risk of tectonic earthquakes (Cummins *et al*., 2020). Indonesia is vulnerable to volcanic earthquakes because it is traversed by two world mountain routes, namely the Pacific and Mediterranean circumferences, where Siberut Island-Mentawai Islands Regency is one area prone to earthquakes. The propensity for earthquakes in the areas is also because Siberut Island is located near the meeting point of the Eurasian and Indo-Australian plates and is passed by two mountain passes, part of the ring of fire.

Earthquakes in Siberut Island can originate on land or in the ocean. The earthquake that hit Siberut Island caused widespread property damage, including residential buildings, utilities, and infrastructure (Putra & Mutmainah, 2018). The quake on Siberut Island also traumatised the locals. This is visible when an earthquake occurs, as many community members evacuate their homes to a safer location, specifically a higher ground (Arlym *et al*., 2018). Many people will attempt to transport as many belongings as possible while carrying their children. Previous scholars researched earthquake hazards using spatial models but in tiny volumes (Wang *et al*., 2017; Tirpáková *et al*., 2023). In this research, the author created an earthquake hazard map using a GIS and parameters such as the spatial distribution of epicentres scattered in the ocean, epicentre depth, and the PGA values, as well as using kriging and algebra analysis to create earthquake hazard maps. Statistical analysis was employed to identify the variables that significantly impact the spatial distribution of earthquake hazards in the research location.

Environmental sustainability is also an important concern in efforts to mitigate the impact of earthquakes, especially in vulnerable areas such as Siberut Island. Every time an earthquake occurs, not only material losses and lives are of concern, but also the resulting environmental impacts. Earthquakes can cause damage to local ecosystems such as forest collapse, landslides, and coastal damage that can disrupt the sustainability of local natural resources. Therefore, spatial planning based on earthquake hazard maps using technology such as GIS is very important. This map will not only help develop earthquake-resistant infrastructure but also maintain environmental sustainability by ensuring that development is carried out in locations with minimal risk of earthquakes.

In addition, according to Greenal and Anilkumar (2024), developing green infrastructure and using eco-friendly technology in the post-earthquake recovery will be an integral part of efforts to maintain environmental sustainability in disaster-affected areas. Implementing an environment-based approach to recovery is hoped to reduce the negative impacts of disasters on ecosystems and increase community resilience and adaptation in dealing with future disasters.

The research aims to investigate and map the distribution of epicentre depth, magnitude, and PGA to earthquake hazards while examining numerical parameters that affect the magnitude of earthquake hazard values. The findings of this research are of the utmost importance to policymakers, especially in island spatial planning, sustainable development, and earthquake and tsunami hazard mitigation, as referenced in Mase *et al*. (2018) and Zhou *et al*. (2023).

Methods

The research was conducted on Siberut Island, part of the Mentawai group. These islands are about 210 km west of Padang, the capital of West Sumatra Province. Padang, the provincial capital of West Sumatra is around 210 km away. Figure 1 shows more information.

Earthquake data from the United States Geological Survey (USGS) from 1927 to 2023 was one of several research materials and methodologies utilised to assess the risk of earthquakes in the research location. These details come in the form of point coordinates for the earthquake that describes the event's magnitude, depth, and epicentre. These data, which show the distribution of earthquakes in the research region were created by converting digital elevation model data. To determine the spatial distribution of earthquake events in the research location from 1927 to 2023, data on earthquake events collected from the USGS were processed using Excel and ArcGIS 10.3 software. USGS seismic event data is analysed to determine the PGA value and the earthquake's magnitude (Qian & Han, 2013; Zhou *et al*., 2023; An *et al*., 2023). The formula below is utilised to ascertain the PGA spatial distribution.

$$log\, log\, A = 0{,}5Mw + 0{,}0036D + \sum d_i s_i - logX_{eq} - 0{,}003X_{eq} + e + \varepsilon$$

where:

A	=	Maximum ground acceleration (gal)
Mw	=	Moment magnitude of earthquake (SR)
D	=	Earthquake depth (km)
X_{eq}	=	Hypocentre distance (km)
d	=	Distance from the epicentre of the earthquake to the location (km)
s	=	Dummy variable for fault type (S = 1)
e	=	Regression coefficient (0.6)
ε	=	Standard deviation (0.24)

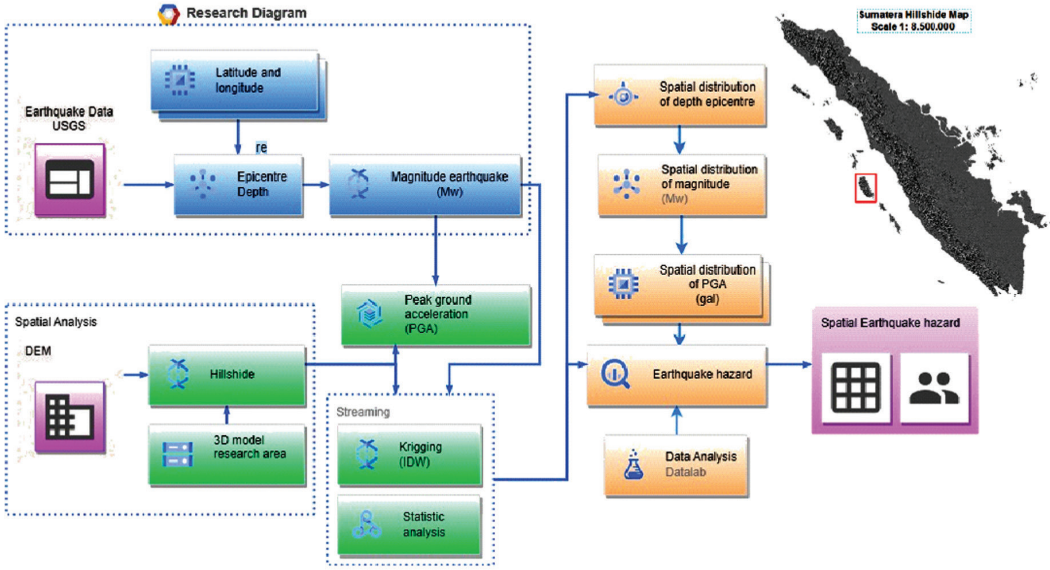


Figure 1: Research flow chart (Insert: Research location)

A formulation was used to determine the earthquake magnitude distribution:

$$M_w = 5.12 + 1.16\log(L) - 0.2\log(S) + e; \sigma_e = 0.26$$

where e is the error term or model error, Mw is the earthquake moment magnitude, L is the fault length in km, and S is the slide rate in millimetres per year. Regression theory states that the variable e is a random variable with a mean value of 0 and a standard deviation of 0.26 at the level of sample scattering (Tirpáková *et al*., 2023; Liu *et al*., 2023). Inverse Distance Weighted (IDW) was utilised as an analysis tool in conjunction with the kriging method to establish the interpolation of earthquake distribution, magnitude, and depth in the research location (Harman *et al*., 2016; Doyle *et al*., 2020; Dewata & Putra, 2021; Ozkaya *et al*., 2023). The formulation that follows is used for interpolation:

$$z = 1 + \frac{\sum_i^n = 1\, wiZi}{\sum_i^n = 1\, wi} = \frac{\sum_i^n = 1\, zi\,/D^p}{1/D_i^p}$$

With this interpolation method, the value of the unknown observation is represented by z and a weight function determines the importance of each control point. Zi represents the value of the observation at each control point while the total number of control points employed is denoted by n. The nearest neighbourhood of the interpolation point can also be used to get this number. n is the seismic distribution parameter typically employed in most calculations because all grid cell calculations necessitate looking across all control points. The distance, p is an actual positive value known as the weighting exponent, between the observed control point (i) and the interpolation point.

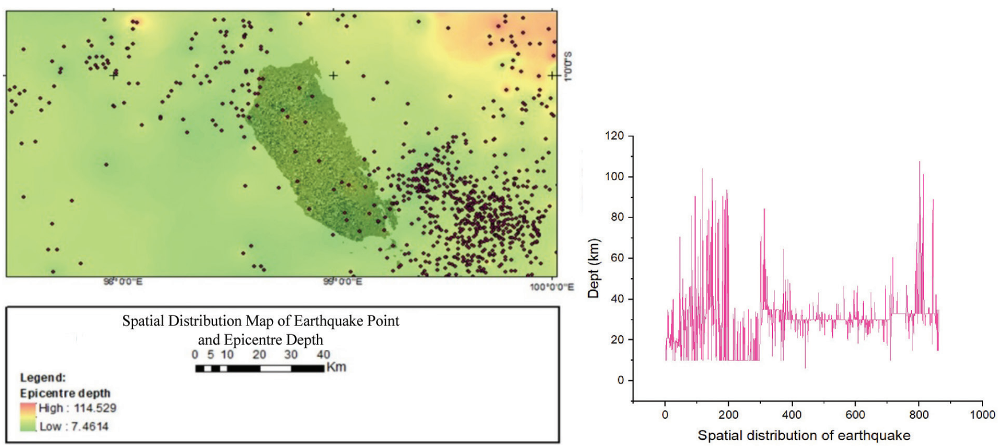
Inverse Distance Weighting (IDW) is the interpolation technique used when p is set to 1 while Inverse Square Distance Weighting (ISDW) is the approach used when p is equal to 2 (Sing & Verma, 2019; Neissi *et al*., 2020; Shao *et al*., 2024). The radially symmetric and Euclidean distances to each scatter point determine the weighting function, as shown in Huang *et al*. (2011), Triyatno *et al*. (2020), and Darzi *et al*. (2022). Consequently, the interpolation surface exhibits a degree of symmetry at every point. It moves toward the average value of the scatter points inside the interval between the points. Algebraic analysis between epicentre depth, magnitude, and PGA maps was done to create an earthquake hazard map.

Results

Data Analysis Results

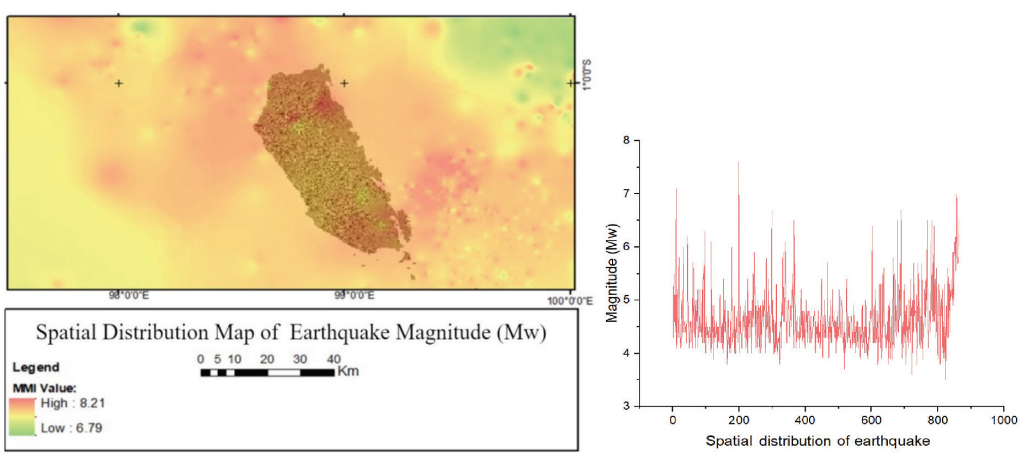
The research location has a dispersed distribution of earthquakes. However, Siberut archipelagos southeast still has the most earthquake distribution pattern with an epicentre depth of 6.10 km to 107.60 km. See the following Figure 2 (a) and (b) for further information.

With an average epidendrum depth of 30.13 km, regarded as a shallow earthquake, the above figure illustrates that most earthquakes occurred southeast of the Siberut archipelago. Very few earthquakes have this distribution or intensity and the northeastern region of the Siberut archipelago is home to earthquakes with deep epicentres. This demonstrates that Siberut Island earthquakes are often shallow. The magnitude of an earthquake's hazard rating is influenced by its magnitude. More information on the magnitude of the earthquake in the research location is included in the following Figure 3 (a) and (b) for further information.



(a) (b)

Figure 2: (a) Earthquake spatial and (b) graph of distribution and epicentre depth

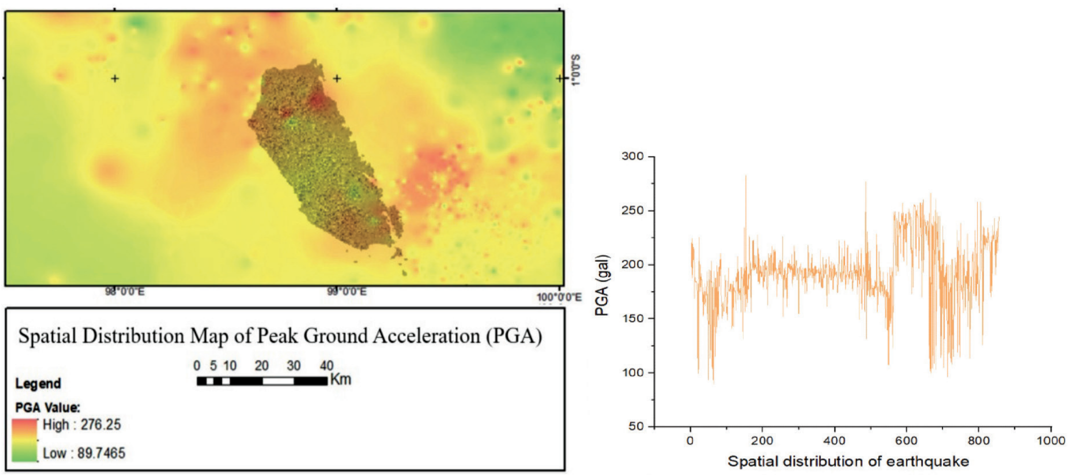


(a) (b)

Figure 3: (a) Earthquake spatial and (b) spatial distribution and graphic of Mw

The distribution of earthquake magnitudes in Siberut Island is depicted in the above figures. The average magnitude of the earthquakes in this region was 4.63 Mw, ranging from 3.50 Mw to 7.60 Mw. The earthquakes mostly happened below sea level and were evenly spaced throughout the region. The islands' northeastern sector saw the fewest earthquakes while the northern and western sections saw the highest number of seismic events. This shows that the largest-magnitude earthquakes can produce tsunamis in the area and often have shallow epicentre depths. The magnitude, depth, and distance of the epicentre from the observation point of the earthquake all affect the peak ground acceleration value that is included in Figure 4 (a) and (b).

In the research location, both on land and in the ocean, the PGA values are distributed in the centre, as the above figures illustrate. The PGA values range from 89.57 gal to 283.17 gal with the largest being the most significant. Shallow depths and vigorous earthquake intensity are typically associated with larger PGA values. Conversely, PGA values are low in regions where the epicentre depth is 107.14 km. This is because the PGA value is influenced by both the strength of the earthquake and the depth of its epicentre. The PGA value in a region is also determined by its constituent materials.



(a) (b)

Figure 4: (a) Earthquake spatial and (b) spatial distribution and graphic of the PGA

The PGA value would be high in areas where the component materials are still forming. The high PGA value also influences the magnitude of earthquakes the community perceives, which is included in Figure 5.

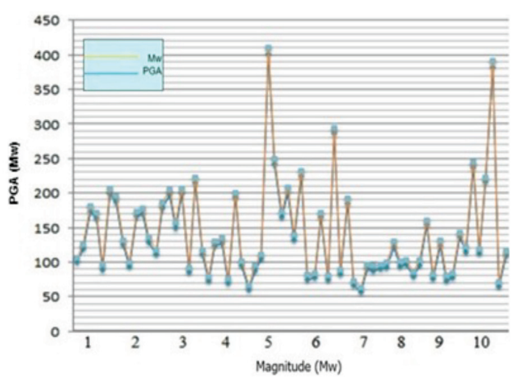


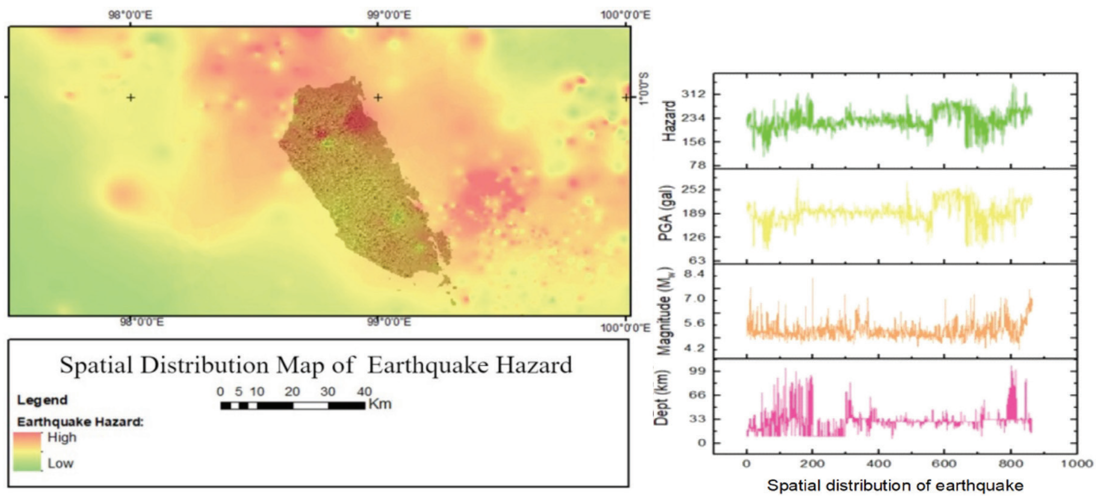
Figure 5: Relationship between PGA (gal) value and Mw (Data analysis in 2024)

The PGA value and earthquake magnitude in Siberut Island are shown in the above figures. A high PGA value will result in strong earthquake vibrations felt by the population and losses from earthquakes, as demonstrated by cases where a high PGA value accompanies a high earthquake magnitude value. The principal factors influencing the seismic risk in Siberut Island are volume, epicentre depth, and the significance of the PGA value, which is included in Figure 6 (a) and (b) for further information.

Figure 6 displays the earthquake risk distribution in Siberut Island on land and at sea. The southern and northern regions of Siberut Island pose the highest risk of earthquakes. The southern region includes West Siberut, Muntei, Madobak, and Matotonan while the northern region is Sikabaluan on North Siberut Island. Due to frequent earthquakes in these regions, Siberut Island has a high seismic hazard ranking. Additionally, the area is at high risk of earthquakes because shallow earthquakes are defined as those that occur less than 30 km deep. However, the significance of the seismic hazard value on Siberut Island is not greatly impacted by the magnitude of the earthquake. Damage to buildings, including residential structures, facilities, and infrastructure is significantly influenced by an earthquake's size. Living near the coast, where there are marshes and coastal alluvial plains behind beaches means that the magnitude of an earthquake also affects the strength of the vibrations felt by the local community. As a result, communities who live in coastal areas frequently experience fear when an earthquake occurs. The community is affected by strong earthquake vibrations because of the components of coastal areas that are not yet solid in alluvial plains and swamp areas beyond the shore.

Descriptive statistical analysis and multiple regression were used to assess the extent of the impact of epicentre depth, magnitude, and PGA on earthquake hazards. The accompanying Table 1 provides additional information.

Table 1 displays the magnitude, PGA values, minimum, maximum, and mean values of the earthquake's epicentre depth, which



(a) (b)

Figure 6: (a) Earthquake spatial and (b) graph of epicentre depth, Mw, and PGA value

Table 1: Analysis statistic descriptive

	N	Minimum	Maximum	Mean	Std. Deviation
Depth	863	6.10	107.60	30.13	14.90
Magnitude	863	3.50	7.60	4.63	0.52
PGA	863	89.57	283.17	193.19	29.68
Valid N (listwise)	**863**				

Source: Data analysis in 2024

influences the magnitude of the seismic hazard value in the research location. The mean value of the earthquake epicentre depth is 30.13 km, the maximum value is 107.60 km, and the minimum value is 6.10 km. This demonstrates that shallow and moderate earthquakes can occur in the research location with a depth epicentre of less than 60 km deep. The lowest earthquake magnitude is 3.50 Mw, 7.60 Mw is the highest, and 4.63 Mw is the mean.

This demonstrates that tremors of varying magnitudes take place in the research region. The smallest PGA in the research region was 89.57 gal, the maximum PGA was 283.17 gal, and the mean PGA was 193.19 gal. This shows that there could be mild to moderate damage caused by PGA values in the research location. The distribution of each epicentre depth data, magnitude, and PGA effect earthquake hazards in the research location, as shown in Figure 7 (a), (b), (c), and (d) for further information.

Epicentre depth, magnitude, and PGA can influence the magnitude of earthquake hazards in the research region. The above figures show a normal distribution for epicentre, magnitude, PGA, and earthquake hazards data. Figure 8 provides further information about how each variable influences the earthquake hazard's magnitude.

Figure 8 shows the impact of the depth of epicentre (with a significant value of 0.025), earthquake magnitude (with a significant value of 0.03), and PGA value (with a significant

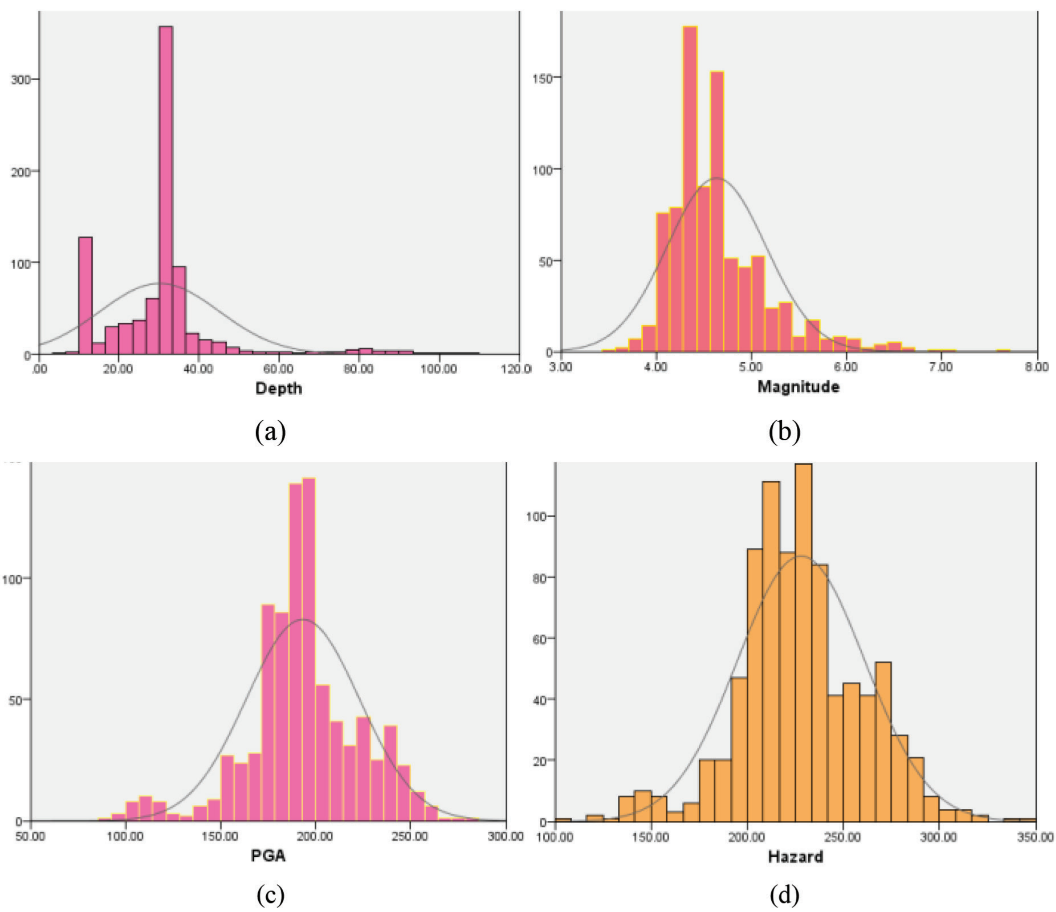
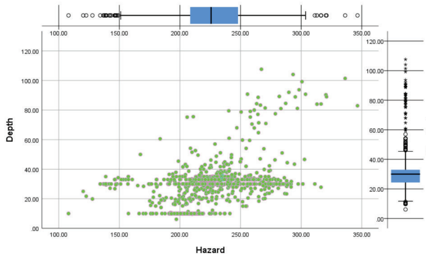
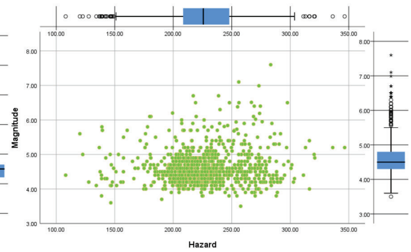


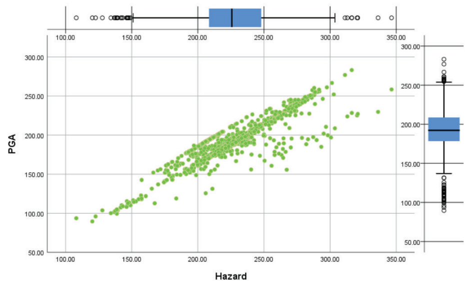
Figure 7: (a) Distribution data of epicentre depth, (b) magnitude, (c) PGA value, and (d) data on earthquake hazards



(a)



(b)



(c)

Figure 8: (a) The effect of epicentre depth value on earthquake hazard, (b) the effect of Mw on earthquake hazard, and (c) the effect of PGA value on earthquake hazard

value of 0.021) on earthquakes. These findings suggest that the hazards of earthquakes in the research area are substantially affected by the epicentre's depth, magnitude, and PGA.

Discussion

The few earthquakes on Siberut Island have their epicentres on land and most events happen under the sea surface or over oceanic regions. Because of their epicentres' location between 3 km and 114.52 km deep, earthquakes that struck Siberut Island can be assumed to have been shallow to moderate in nature (Covi *et al*., 2023; Peng *et al*., 2023). Earthquakes with deep epicentres are generally found in the northeastern part of or near Sumatra Island and the northwestern part of Siberut Island. The PGA value and the likelihood of earthquakes on Siberut Island are determined by the epicentre's depth and spatial distribution, as noted by Wang *et al*. (2017) and Nato *et al*. (2022). High earthquake intensity zones will have a high earthquake hazard, whereas regions with a deep epicentre of 11.52 km will have modest earthquake hazard and PGA values (Ji *et al*., 2022; Ferreira *et al*., 2022; Shao *et al*., 2024). The epicentre and severity of the earthquake largely define the magnitude of the PGA value that happens on Siberut Island; high PGA values are produced in locations with the highest earthquake event intensity (Nato *et al*., 2022; Zhou *et al*., 2023; An *et al*., 2023). The depth of the epicentre also affects the PGA value. A shallow core will provide a high PGA value in these places. Locations with deep quake epicentres such as the northeastern region of Siberut Island, which has a heart of 114.52 km will result in low PGA values.

The constituent materials in a region have a significant impact on the PGA value as well. Coastal alluvial plains and swamps behind beaches are examples of areas with unfinished materials that have higher PGA values than areas with hard rocks, particularly in the middle of Siberut Island. The PGA values have been shown in multiple studies (Wang *et al*., 2017; Jena *et al*., 2023; Zhou *et al*., 2023) to significantly influence the severity of earthquakes a community experiences. For example, the magnitude of the earthquake that struck Siberut Island varied from 3.50 Mw to 7.60 Mw. The 6.79 Mw earthquake was felt by the local community and had the potential to cause minor structural damage such as plaster coming off walls in homes with concrete foundations. The vibrations were noticeably louder and more pronounced at 7 Mw.

The community claims that well-constructed structures sustain minimal damage, whereas poorly constructed buildings develop wall cracks (Qian & Han, 2013; Øystad-Larsen *et al*., 2017; Nato *et al*., 2022). The magnitude 8 Mw earthquake rattled the population so much that many left their houses to seek shelter from falling buildings and tsunamis. In coastal alluvial plains and wetlands behind the coast, where soil layer pressure is prevalent, fluctuations in groundwater levels are typical when damage to structures reaches this degree. This is particularly true for building walls with loose plaster and cracks (Ferreira *et al*., 2022; Jena *et al*., 2023; Tirpáková *et al*., 2023).

The volume, intensity, and relevance of the PGA value and the earthquake's epicentre are the main factors influencing the magnitude of the seismic hazard value on Siberut Island. Siberut Island's northern and southern regions have the highest earthquake hazards, according to the mapping of the spatial distribution of earthquake hazards in the Siberut area. This is because most earthquake events occur in the south or southeast, typically having shallow epicentres of roughly three kilometres.

A tsunami will typically be caused by an earthquake of significant size that has its epicentre in Magathrast, which is the western portion of Siberut Island (Wang *et al*., 2017; Ji *et al*., 2022; Kang *et al*., 2023). The ocean has the highest earthquake risk. As a result, early warning systems and education about earthquake and tsunami disasters are required for communities residing along the coast of Siberut Island. It is important to recognise that a large-magnitude earthquake on the island could cause a tsunami (Peng *et al*., 2023; Yang *et al*., 2023). Communities living along the coast can lessen the loss of life and property from earthquake and tsunami disasters by educating themselves on mitigating these natural disasters. As can be observed in plain areas with generally flat slopes, swamps will experience a significant earthquake impact compared to the middle section of Siberut Island, which has volcanic rock. The epicentre, magnitude, and PGA values affect the earthquake hazard in the research location. Since soft rocks are present, earthquake vibrations in swampy plain locations with high PGA values typically last longer.

For environmental sustainability, the community and local government need to carry out comprehensive efforts to mitigate the dangers of earthquakes and tsunamis on Siberut Island. One of the main steps is strengthening infrastructure and spatial planning based on seismic risk, especially in coastal and lowland areas with high PGA values that are vulnerable to earthquakes. Hill *et al.* (2024) added that building earthquake-resistant buildings and designing good drainage systems in areas with soft ground conditions such as alluvial plains and swamps will greatly help in reducing damage caused by earthquakes.

In addition, research by Marois and Mitsch (2015) and Putra *et al*. (2023) showed that environmental restoration through planting natural vegetation such as mangroves along the coast can help reduce the impact of tsunamis and maintain the stability of coastal ecosystems. Wise land management by paying attention to the geological characteristics of the area and climate change is also very important to support the long-term resilience of Siberut Island. Enforcement of environmentally friendly and seismic risk-based development regulations must be a top priority to protect the ecosystem and environmental sustainability in the area. A combination of structural and non-structural mitigation can provide better protection while preserving existing ecosystems. The recommendations for the government are outlined in Table 2.

This research highlights the importance of strengthening disaster mitigation strategies on Siberut Island, especially since earthquakes

Table 2: Practical recommendations for the government

No.	Recommendation	Description
1	Strengthening earthquake-resistant infrastructure	Construct and reinforce public infrastructure and housing with earthquake-resistant designs, especially in coastal areas.
2	Developing early warning systems	Implement integrated earthquake and tsunami early warning systems with effective communication mechanisms for the community.
3	Public education and training	Conduct educational programs, evacuation drills, and increase community awareness regarding earthquake and tsunami risks.
4	Risk-based spatial planning	Plan spatial arrangements by considering seismic risks and zoning to protect vulnerable areas from future development.
5	Coastal ecosystem restoration and protection	Restore coastal ecosystems such as mangrove planting to protect coastal areas from the impacts of tsunamis.
6	Seismic research and monitoring development	Support continuous seismic research and monitoring to acquire accurate data and strengthen mitigation efforts.
7	Inter-agency collaboration	Facilitate coordination between government, disaster management agencies, and the scientific community for data-driven policies.

in this area have the potential to cause infrastructure damage and threaten the safety of communities, especially in coastal areas. These recommendations include not only strengthening infrastructure and early warning systems, but also risk-based spatial planning, community education, and ecosystem restoration that can increase the island's resilience to disasters. Through collaboration between the government, disaster management agencies, and the scientific community, data-based mitigation efforts can be implemented effectively.

Conclusions

The research highlights the distribution of seismic hazards across the Siberut Archipelago with the southeastern region showing the most concentrated pattern of earthquake events. These events range in depth from 6.10 km to 107.60 km with an average depth of approximately 30.13 km, classified as shallow. Earthquake magnitudes range from 3.50 Mw to 7.60 Mw with an average of 4.63 Mw. Most earthquakes occur beneath the sea, impacting both coastal and inland areas. Shallow earthquakes pose significant risks, especially in regions with high PGA values. These areas, often characterised by soft materials such as alluvial plains and swamps, experience intensified seismic vibrations. The southern and northern regions of Siberut Island are identified as having the highest seismic risks due to frequent shallow earthquakes with epicentres around 3 km deep, which increases the likelihood of structural damage and tsunami events. The magnitude, epicentre depth, and PGA values significantly influence the level of seismic hazards with soft coastal materials exacerbating the intensity of the vibrations felt by the community. To mitigate these risks, the research offers several key recommendations.

First, the government should strengthen infrastructure to make it earthquake-resistant, particularly in coastal areas. Second, integrated early warning systems for earthquakes and tsunamis should be developed and implemented. Public education and training programs are also essential to enhance community preparedness for these hazards. Additionally, spatial planning should prioritise seismic risks, protect vulnerable areas, and avoid future development in high-risk zones. Restoring coastal ecosystems such as mangroves can serve as natural barriers against tsunamis. Ongoing seismic research and monitoring are crucial for ensuring that mitigation efforts are guided by accurate, real-time data. Collaboration between government agencies, disaster management organisations, and the scientific community is essential for creating effective, data-driven policies. This multifaceted approach will significantly enhance the resilience of Siberut Island to earthquakes and related disasters.

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Conflict of Interest Statement

The authors declare that they have no conflict of interest.

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