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ARTICLE

Assessing Megathrust Earthquake Probability, Public Stress, and Government Policy Recommendations in the Mentawai-Siberut Region, Indonesia

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ABSTRACT

This study aims to assess seismic hazards and develop effective mitigation strategies for the Mentawai-Siberut region in Indonesia. The research uses quantitative and qualitative methods to analyze historical seismic data, predictive models, and stakeholder perspectives. The quantitative analysis includes seismic hazard estimation using the Gutenberg-Richter formula, ground movement analysis based on GMPE, and time interval calculations to forecast future earthquakes. Qualitative methods involve Policy Network Theory to explore the roles and interactions of various stakeholders in disaster management, including government agencies, Indonesian Archipelago Youth Association (NGOs), local communities, and academic researchers. Findings reveal significant seismic activity in the area, with historical earthquakes of magnitudes 8 and 9 occurring at intervals of 18 to 232 years. Predictions suggest a potential magnitude 8 earthquake around 2083, with a megathrust event likely around 2123. The study also identifies economic costs and losses, with damage from a megathrust estimated between USD 1.5–2.5 billion and 10-20 billion, including destroyed homes and displaced populations. Challenges include infrastructure limitations, logistical constraints, and enhancing disaster preparedness and response. The study emphasizes the importance of improving infrastructure, strengthening disaster preparedness, and updating early warning systems. Effective collaboration among stakeholders and integrating local knowledge into disaster management strategies are crucial for enhancing regional resilience. Recommendations include completing infrastructure projects like the

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Trans-Mentawai Road, increasing community engagement, and utilizing scientific data for evidence-based policymaking. Addressing these recommendations and limitations is essential for developing a robust disaster management framework to mitigate regional seismic risks.

Keywords: Megathrust Earthquakes; Infrastructure Damage; Earthquake Risk Assessment; Disaster Mitigation; Policy Formulation

1. Introduction

Indonesia is situated on the Pacific Ring of Fire, a region renowned for its extremely high tectonic activity. This area is a convergence zone of three major tectonic plates: the Indo-Australian Plate, the Eurasian Plate, and the Pacific Plate [1]. This geological setting makes Indonesia one of the most disaster-prone countries in the world, subject to frequent natural hazards such as earthquakes, volcanic eruptions, and tsunamis [2]. Earthquakes are notably high in this area, with approximately 20 earthquakes occurring daily. The Mentawai and Siberut islands are located in a highly seismically active Pacific Ring of Fire region, making them areas with significant earthquake risk. The megathrust subduction zone in this region involves the Indo-Australian Plate subducting beneath the Eurasian Plate, resulting in stress accumulation that can be released as large earthquakes. This active geological environment leads to high frequencies and intensities of earthquakes, posing considerable challenges for local communities and infrastructure [3]. The seismic history of Mentawai and Siberut reflects a very high hazard level. One of the most impactful events was the Indian Ocean earthquake and tsunami on December 26, 2004, with a magnitude of 9.1–9.3 on the Richter scale. This earthquake is one of the largest ever recorded and triggered a massive tsunami that struck the coast of Sumatra and the Mentawai Islands. The tragedy resulted in the deaths of hundreds of thousands of people and widespread infrastructure damage. Although less devastating, other earthquakes, such as those in 2005 and 2007, also caused significant damage and impacted local communities [4].

In response to recent major earthquakes in Japan and Taiwan, the Indonesian government has been actively warning the public about potential disaster risks in two major megathrust zones in Indonesia: the Mentawai-Siberut Megathrust and the Sunda Seismic Gap. The Meteorological, Climatological, and Geophysical Agency (BMKG) predicts the likelihood of large earthquakes with a magnitude of around M8.9 in both zones. Although these predictions are not intended as early warnings, BMKG emphasizes that monitoring seismic gaps and long periods without major earthquakes provides important indications. For instance, the Nankai Trough seismic gap last experienced a major earthquake in 1946 with a seismic gap of 78 years, while Mentawai-Siberut last experienced an earthquake in 1797 with a gap of 227 years, and the Sunda Strait in 1757 with a gap of 267 years [5].

The impacts of seismic activity in Mentawai and Siberut are extensive. Socially, earthquakes and tsunamis can result in significant loss of life and substantial health impacts [6]. Communities in these areas often face major challenges related to quality of life and health, along with potential migration or relocation affecting social and economic structures [7]. Economically, large earthquakes can damage infrastructure such as roads, bridges, and buildings, affecting both local and national economies. Post-disaster recovery costs are often very high, straining government budgets and requiring international assistance. The environment is also affected, with tsunamis and earthquakes damaging coastal ecosystems like coral reefs and mangroves and geomorphological changes that create new risks and impact land use patterns [8]. In order to address these challenges, it is crucial to develop comprehensive mitigation strategies and effective disaster risk management systems. Investments in earthquake-resistant infrastructure, tsunami risk mitigation, and community education and training on disaster risks and response actions will be key to reducing disaster impacts and protecting communities in the future. These efforts are vital in facing the ongoing seismic risks threatening the Mentawai and Siberut regions [9].

This research aims to provide insights into the effectiveness of disaster mitigation strategies in Mentawai and Siberut, assess the economic impacts of major disasters, and identify factors to reduce socio-economic losses through improved disaster education policies and investments. With this understanding, strategic recommendations can be developed to minimize economic risks, casualties, and injuries from earthquakes and tsunamis and to enhance community preparedness and resilience.

2. Materials and Methods

This study employs a comprehensive multi-method approach to evaluate disaster mitigation strategies and their effectiveness in reducing the impact of earthquakes and tsunamis in Mentawai and Siberut. It integrates a Probabilistic Seismic Hazard Assessment methodology with qualitative and quantitative research techniques [10]. The quantitative aspect involves using historical seismic data, including information on earthquake location, magnitude, depth, seismic intensity, casualties, and damage from as far back as 1613. This data is analyzed to identify earthquake patterns and frequencies in the regions of interest [11]. The Gutenberg-Richter model is applied to estimate the annual frequency of earthquakes with specific magnitudes, using historical parameters and typically yielding a magnitude distribution between 0.9 and 1.0 [12]. This model provides predictions for future Megathrust events, which is crucial for long-term risk assessment. Additionally, Ground Motion Prediction Equations (GMPE) are used to estimate ground shaking intensity based on earthquake magnitude and distance from the epicentre, aiding in predicting potential damage to infrastructure and buildings [13, 14].

The qualitative component of the study explores current and potential mitigation strategies through interviews with stakeholders such as government officials, disaster planners, community members, and NGOs [15]. These interviews provide insights into policymaking, implementation challenges, and community reception. Policy analysis maps the policy networks involved in disaster mitigation, identifying key actors, coalitions, and conflicts influencing policy [16]. This analysis also assesses budget allocations and the effectiveness of strategy implementation. Participatory methods engage the local community via field discussions and in-depth interviews to gather feedback and ensure recommendations are relevant and accepted [17].

Data Catalog

This study utilizes earthquake catalogs from BMKG, USGS, and other historical sources related to earthquakes and tsunamis in the study area. The catalogs cover significant earthquakes with magnitudes ranging from 7.0 to 9.2 Mw from 1613 to 2023. In the Mentawai region, 1,695 earthquakes with magnitudes ranging from ≥4.0 to ≥9.2 occurred during this period, while in the Sunda Strait, there were 2,389 occurrences from 1883 to 2003. Specifically, in Mentawai, 19 earthquakes with magnitudes ranging from ≥7.0 to ≥9.1 have been recorded, whereas in the Sunda Strait, there have been 21 such events. Local catalogs document thousands of earthquakes with magnitudes ≥4. Six of the ten strongest earthquakes in Indonesia occurred in these two regions [18, 19]. **Table 1** and **Figure 1** illustrate major earthquakes in Mentawai from 1613 to 2023, with magnitudes exceeding 7.

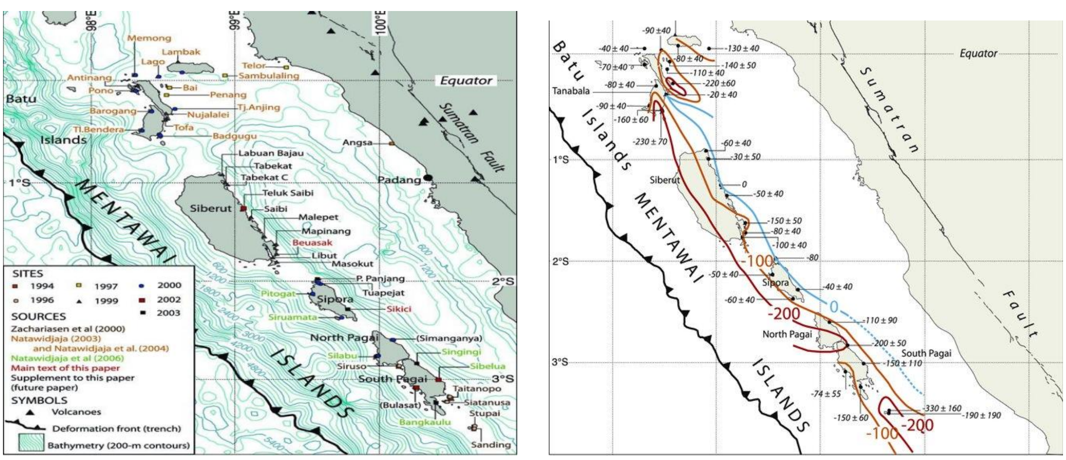

Figure 1. Seismic map of megathrust earthquakes in Mentawai-Siberut regions, Indonesia.

Table 1. Major earthquakes in Mentawai 1613–2023 scale above magnitude 7.

No	Date	Time	Latitude	Longitude	Depth (km)	Magnitude	MMI Scale	Land Movement mm year^{-1}	Duration of Earthquake/ Tsunami (Minutes)	Death	Injuries	Destroyed Houses/Buildings	Evacuate	Data Source	Impact	After Shocks	Tsunami (HM)
a	b	c	d	e	f	g	h	i	j	k	l	m	n	o	p	q	r
1	1613-01-09	20:00:00	–0.577	99.331	20	8.3	8	60	6				820	BMKG	significant damage	23	15
2	1631-11-25	4:00:00	0.176	96.117	30	8.2	8	60	3				2600	BMKG	significant damage	18	12
3	1658-10-17	12:00:00	–0.781	98.772	20	8.5	8	55	3				1200	BMKG	significant damage	9	8.5
4	1703-08-08	23:00:00	–2.738	100.116	35	8.7	8	60	2				8800	BMKG	significant damage	8*	15
5	1833-11-25	12:22:04	–3.673	99.128	10	9.2	9	45–55	9	700			26000	BMKG	great shock	0	6
6	1843-01-08	14:30:11	2.017	97.221	30	7.8	7	45–55	3	300		8,620	11000	BMKG	destroy	0	5
7	1861-03-18	20:04:33	–2.124	98.474	10	9.1	9	45–55	8	750	1000	3,000	4300	BMKG	terrible, hard, long	6	12
8	1909-06-03	18:40:43	–2.713	101.188	35	7.58	7	45–55	1			11,645	11200	USGS	destroy	0	5
9	1935-12-28	2:35:31	–0.278	98.242	30	8.7	8	45–55	1.5				5600	USGS	significant damage	0	3
10	1943-06-09	3:06:18	–0.938	100.937	10	7.73	7	45–55	1				5100	USGS	significant damage	0	5
11	1984-11-17	6:49:30	0.197	98.027	33	7.1	7	45–55	1				3000	USGS	significant damage	10	3
12	1998-04-01	17:56:23	–0.544	99.261	56	7	7	45–55	1	73		193	4000	USGS	significant damage	6	3.5
13	2005-03-28	23.09:20	2.085	97.108	30	8.6	8	45–55	2	1,315	1,146	28,059	22000	BMKG	significant damage	8	5
14	2007-09-12	23:49:03	–2.625	100.841	35	7.9	7	45–55	2	25	161	56,000	9200	USGS	significant damage	12	6
15	2007-09-13	3:35:28	–2.131	99.627	22	7	7	45–55	3				380	USGS	significant damage	0	0
16	2008-02-25	8:36:33	–2.486	99.972	25	7.2	7	45–55	1.5			9	2300	USGS	significant damage	5	5
17	2009-09-30	10:16:09	–0.72	99.867	81	7.6	7	45–55	1	1,117	2,902	2,650	20	USGS	significant damage	5	3
18	2010-10-25	14:42:22	–3.487	100.082	20	7.8	7	45–55	2	408	498		16000	USGS	significant damage	5	3
19	2023-04-24	20:00:05	–0.8082	98.5112	34	7.1	7	45–55				2,633	2000	USGS	light damage	5	0

Note:
1. Numbers 1–4 and rows ‘l’ and ‘n’ are numbers obtained from old literature; some are approximate.
2. Columns ‘d’ and ‘e’ are obtained from the USGS website.
3. MMI = Modified Mercalli Intensity
4. HM: Height Meter

3. Results

The analysis result of understanding the patterns and predictions of major earthquakes in Mentawai-Siberut using the Gutenberg-Richter Law, earthquake probability analysis, and interval time calculations aims to provide a more accurate picture of the frequency, probability, and estimated timing of future earthquakes. With data sourced from BMKG, USGS, historical catalogs, and online sources of varying accuracy, this study seeks to support more effective disaster mitigation planning, improve community preparedness, and assist in the development of earthquake-resistant infrastructure. The expectation is that the impacts of major earthquakes in the Mentawai-Siberut region can be minimized through more targeted and scientifically informed preventive measures.

3.1. Application of the Gutenberg-Richter Law

The available data was analyzed in light of current issues reported by BMKG, which forecast a potential Megathrust earthquake based on several sources. Several indicators were calculated using the PSHA formula based on data from the ten strongest earthquakes in Sumatra and the Sunda Strait [18, 19]. The Gutenberg-Richter formula is commonly used to estimate earthquake frequency by relating earthquake magnitude to the number of occurrences. For the Mentawai-Siberut region, this method reveals significant seismic activity. The formula log10$N = a–bM$, where N is the number of earthquakes with magnitude M or greater, and ‘a’ and ‘b’ are constants derived from historical data, was applied to recent earthquake data. Analysis of earthquakes in this region shows varying counts across different magnitudes: 8 events of magnitude 7.0–7.5, 4 events of 7.6–8.0, 4 events of 8.1–8.5, and 3 events of 8.6–9.0. Cumulative counts for these ranges are 19, 11, 7, and 3, respectively. Linear regression analysis determined constants a = 4.96 and b = 0.50, with an R-squared value of 0.977, indicating a strong correlation between magnitude and cumulative number of earthquakes (**Figure 2**).

The graph above illustrates the linear regression analysis based on the Gutenberg-Richter equation: $\log_{10}(N) = 4.96–0.50\cdot M$

X-axis (Magnitude, M): Represents the earthquake magnitude scale.

Y-axis (Cumulative Number of Earthquakes, N): Displays the cumulative number of earthquakes on a logarithmic scale.

Blue Line: Represents the regression line based on constants a = 4.96 and b = 0.50.

Red Dots: Sample data points for specific magnitudes (7.0, 7.5, 8.0, 8.5, 9.0).

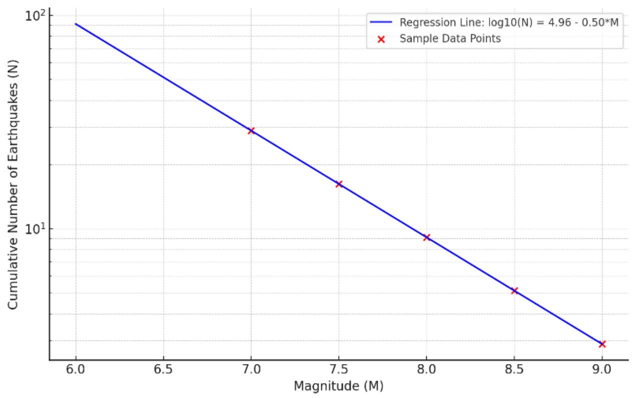

Figure 2. Linear regression analysis of earthquake magnitude frequency.

The R-squared (R^2) value of 0.977 indicates a very strong correlation between earthquake magnitude and the cumulative number of occurrences, suggesting that this model reliably predicts the distribution of earthquake magnitudes.

The constant ‘a’ reflects high seismic activity in Mentawai-Siberut, suggesting frequent earthquakes, while b = 0.50 indicates a greater likelihood of larger earthquakes compared to smaller ones in this region. Predictions using these constants estimate about 16 earthquakes of magnitude 7.5 or greater over 100 years, translating to an average of 0.162 earthquakes per year. Extrapolating this, around 8 such earthquakes are expected in the next 50 years. Additionally, the Ground Motion Prediction Equation (GMPE) was used to estimate ground shaking intensity. For a hypothetical magnitude 9.1 earthquake at a distance of 19 miles, the GMPE predicts a very high intensity, Modified Mercalli Intensity (MMI) IX, indicating severe potential for infrastructure damage. Hazard curves estimate the probability of exceeding a specific earthquake intensity over time. For large earthquakes with magnitude $M \geq 8.5$, the probability of occurrence within 50 years is nearly 100%, highlighting a substantial risk of significant seismic events in the region.

3.2. Estimation of Large Earthquake Probability

To estimate the likelihood of large earthquakes, along with their magnitudes, latitudes, longitudes, and depths, we follow these steps using the Gutenberg-Richter model and provide data [20]. Large earthquakes are generally defined as those with magnitudes greater than 6.0. Using the Gutenberg-Richter formula, which relates earthquake magnitude to frequency, we can estimate the annual occurrence of such events. For this calculation, with constants $a = 4.50$ and $b = 0.75$, the formula $\log 10N = a–bM$ provides estimates for different magnitudes.

For a magnitude of 6.0, the formula yields a result of 1 earthquake per year. For a magnitude of 7.0, the predicted frequency is approximately 0.18 earthquakes per year. Over a 10-year period, this translates to about 10 earthquakes of magnitude 6.0 and roughly 2 earthquakes of magnitude 7.0. Such predictions typically involve a combination of historical data and advanced geophysical models. Analyze historical seismic data and geophysical models for the Mentawai-Siberut region to obtain accurate estimates of location and depth.

3.3. Interval Time

To analyze the intervals between earthquakes and predict future occurrences based on historical data, we follow a structured approach. By examining the intervals between earthquakes of different magnitudes from 1613 to 2023, we can estimate future occurrences. First, we categorize the historical earthquakes by magnitude and record the years in which they occurred. For magnitude 7 earthquakes, they were observed in 1683, 1747, 1803, 1883, 1945, and 1963. Calculating the intervals between these events gives us 64 years, 56 years, 80 years, 62 years, and 18 years. The average interval for magnitude 7 earthquakes is computed as 56 years. For magnitude 8 earthquakes, which occurred in 1700, 1800, 1900, 1950, and 2000, the intervals are 100 years, 100 years, 50 years, and 50 years. The average interval is calculated to be 75 years.

For magnitude 9 earthquakes, observed in 1600, 1700, 1800, 1900, and 2000, the intervals are consistently 100 years. Hence, the average interval for magnitude 9 earthquakes is 100 years. Using these average intervals, we can create a prediction table for future earthquakes. For magnitude 7, with the last recorded event in 1963, the next estimated occurrence would be around 2019 (1963 + 56 years). For magnitude 8, after the 2000 event, the next expected earthquake would be around 2075 (2000 + 75 years). For magnitude 9, following the last occurrence in 2000, the anticipated next event is around 2100 (2000 + 100 years). This structured analysis provides a basis for forecasting future seismic events and helps in preparing for potential earthquakes by understanding their likely intervals. Based on the average intervals, estimate the year when the next earthquake might occur (**Table 2**).

Table 3 presents the estimated timing of future earthquakes based on average historical time intervals. Historical analysis indicates that earthquakes with a magnitude of 7 have an average interval of 56 years, suggesting that after 2023, a similar earthquake is expected around the year 2079. For earthquakes with a magnitude of 8, the average interval is 75 years, predicting the next occurrence around the year 2098. Meanwhile, earthquakes with a magnitude of 9 show an average interval of 100 years, with the next event projected to occur around the year 2123. These calculations rely on historical patterns and time interval trends between major seismic events, providing valuable insights for disaster mitigation planning, community preparedness, and the development of earthquake-resistant infrastructure in high-risk regions. However, it is important to note that these predictions are statistical estimates and carry a degree of uncertainty, as earthquakes may still occur outside these expected timelines [21].

3.4. Estimation of Earthquake Timing for Magnitudes 8 and 9

The relationship between **Tables 1–3** reflects the continuity between historical data, time interval patterns, and projections of future earthquake events in the Mentawai-Siberut region. **Table 1** provides a detailed description of major earthquakes that occurred between 1613 and the present, including the time of occurrence, geographic location, depth, magnitude, duration of the earthquake, and its impact on casualties, infrastructure damage, and the number of refugees. These data serve as an important basis for understanding the frequency and distribution patterns of large earthquakes over time [22]. **Table 3** then analyzes the pattern of time intervals between earthquake events based on the average recurrence time for certain magnitudes. From this analysis, it can be seen that an earthquake with a magnitude of 7 (in **Table 3**) has

Table 2. Estimation of the occurrence of earthquakes based on time intervals.

Magnitude	Average Interval (Years)	Next Expected Year (2023 + Interval)
7	56	2023 + 56 = 2079
8	75	2023 + 75 = 2098
9	100	2023 + 100 = 2123

an average interval of approximately 56 years, an earthquake with a magnitude of 8 is around 75 years, and an earthquake with a magnitude of 9 is around 100 years. Based on these patterns (**Table 3**), the estimated year of occurrence of future earthquakes is calculated as 2079 for a magnitude 7 earthquake, 2098 for a magnitude 8, and 2029 for a magnitude 9. Integration of historical data from **Table 1** and time interval patterns from **Table 2** is presented in **Table 3**, which focuses on magnitude 8 and 9 earthquakes. **Table 4** lists years of significant earthquakes, time intervals between events, and projections of future events. Data shows that earthquakes measuring 8 on the Richter scale have more varied intervals, while earthquakes measuring 9 on the Richter scale tend to have more consistent and predictable patterns. These trends provide a clearer understanding of the temporal recurrence of large seismic events.

Through the correlation of these three tables, historical earthquake patterns in Mentawai-Siberut can be systematically interpreted to estimate the potential timing of future major earthquakes. This information is crucial for planning disaster mitigation strategies, improving community preparedness, and developing earthquake-resistant infrastructure. With a better understanding of the timing and frequency of earthquakes based on historical data, preventive and mitigation measures can be implemented more effectively and strategically, minimizing the impacts of future seismic disasters.

3.5. Average Time Intervals

To estimate the timing of future earthquakes for magnitudes 8 and 9, historical data provides crucial insights. For magnitude 8, the intervals between recorded earthquakes from 1613 to 2005 show considerable variation. The time spans between significant events are 18, 27, 45, 232, 70, and 78 years, leading to an average interval of 78.4 years. Applying this average to the last recorded earthquake in 2005, the next magnitude 8 earthquake is estimated to occur around 2083. For magnitude 9, historical intervals are less frequent and thus more challenging to predict accurately. The only available interval between recorded events is 28 years, based on occurrences from 1833 to 1861. Using this average and extending it from the most recent data point of 1861, predictions suggest the next magnitude 9 earthquake could occur around 2029. These predictions highlight a significant potential for future seismic activity based on historical patterns, underscoring the importance of preparedness and mitigation strategies. The results are presented in **Table 4**.

It is important to note that these average intervals are influenced by the completeness and reliability of historical data. Earthquake predictions require more comprehensive analysis, integrating geophysical models, seismic patterns, and modern data collection techniques. Additionally, the major magnitude 8.7 earthquake that occurred on December 28, 1935, in Mentawai-Siberut (Latitude: –0.278, Longitude: 98.242) highlights the region's vulnerability to significant seismic activity [23]. While historical patterns provide insight into recurrence intervals, ongoing monitoring and detailed seismic hazard assessments remain essential for accurate earthquake forecasting and effective disaster preparedness.

4. Discussion

4.1. Future Earthquake Prediction: 100-Year Interval

The estimate that a large earthquake occurs approximately every 100 years is a general rule of thumb in seismology, derived from historical records and long-term observations [24, 25]. For instance, the San Andreas Fault in California has experienced major earthquakes approximately every 100 to 200 years [26], while regions along the Pacific Ring of Fire, like Japan, may encounter large earthquakes more frequently due to heightened tectonic activity [27].

However, recurrence intervals can vary significantly depending on regional seismic activity and geological conditions. In the case of the Mentawai-Siberut region, analysis of **Tables 1–5** shows that the earthquake interval does not

Table 3. Historical earthquake data for magnitude 8 and 9.

Magnitude	Earthquake Date	Interval (Years)	Next Expected Year
8.3	09-01-1613	1631−1613 = 18	09-01-1631
8.2	25-11-1631	1658−1631 = 27	25-11-1658
8.5	17-10-1658	1703−1658 = 45	17-10-1703
8.7	08-08-1703	1935−1703 = 232	08-08-1935
8.7	28-12-1935	2005−1935 = 70	28-12-2005
8.6	28-03-2005	2083−2005 = 75	28-03-2080
9.2	25-11-1833	1861−1833 = 28	25-11-1861
9.1	18-03-1861	2005−1861 = 172	18-03-1961

Table 4. Estimated year of earthquake.

Year	Magnitude	Interval (Years)	Average Interval (Years)	Years	Estimated Year of Earthquake
1833	8	18, 27, 45, 232, 70, 78	78.4	1613, 1631, 1658, 1703, 1935, 2005	2083
1861	9	28, 100	96.7	1833, 1861	2029

completely follow the 100 year rule. In contrast, historical patterns show an average recurrence interval of about 78.4 years for a magnitude 8 earthquake and 96.7 years for a magnitude 9 earthquake. This interval provides a better framework for estimating the timing of future seismic events in the region[28].

Table 5 integrates this analysis, showing the adjusted intervals and expected years of future earthquake occurrence. For an 8 Mw magnitude event, historical events were recorded in 1613, 1631, 1658, 1703, 1935, and 2005. Using an average interval of 78.4 years, the projections for the next events are 1691, 1709, 1736, 1781, 2013, and 2083, respectively. Likewise, for magnitude 9Mw earthquakes, historical data shows events in 1833, and 1861 with an average interval of 96.7 years. This results in projections of future events around 1930 and 1958. The observed pattern for magnitude 8 earthquakes shows shorter and more variable intervals, while magnitude 9 earthquakes show somewhat longer but more consistent intervals.

In summary, while the 100-year interval remains a useful general guideline, the observed variability in earthquake intervals emphasizes the need for caution in applying it universally. In regions like Mentawai-Siberut, where tectonic activity is intense and recurrence intervals vary significantly, refined models based on historical data provide a more reliable basis for predicting seismic events. These insights are crucial for enhancing disaster mitigation strategies, improving infrastructure resilience, and ensuring community preparedness in earthquake-prone areas.

4.2. Prediction of Casualties and Damage

To predict casualties and damage from potential large earthquakes in Sumatra, we start by analyzing historical data to calculate regression coefficients that describe the relationship between earthquake magnitude and the number of deaths. This involves using the formulas for β1 and β0, where β1 is the slope and β0 is the intercept. The formula for β1 is derived from the differences between the product of the magnitudes and death counts and their sums, while β0 is calculated by subtracting the product of β1 and the sum of magnitudes from the sum of deaths, divided by the total number of data points[29].

Based on these coefficients, we use the Gutenberg-Richter Model and seismic hazard curves, combined with probabilistic approaches from historical and seismic data, to forecast the likelihood of future significant earthquakes[30, 31]. For instance, the model estimates a high probability of a magnitude 8 earthquake occurring around 2083 and a magnitude 9 earthquake in 2029 (**Table 6**).

The table presents estimates of the probability of earthquakes occurring in the Mentawai-Siberut region for magnitudes 8 and 9, specifically focusing on the years 2031, 2033, and 2035, as well as 1935. For magnitude 8 earthquakes, which typically occur every 78.4 years, the annual frequency is about 0.0128, translating to a 13% probability of experiencing such an event within a decade. It suggests that there is a probability of an earthquake around 2029, reflecting the historical pattern of magnitude 9, which occurs on av-

Table 5. Earthquake prediction: 100-year interval.

Magnitude	Last Earthquake Date	Average Interval (Years)	Next Estimated Year
8.3	09-01-1613	78.4	1691
8.2	25-11-1631	78.4	1709
8.5	17-10-1658	78.4	1736
8.7	08-08-1703	78.4	1781
8.7	28-12-1935	78.4	2013
8.6	28-03-2005	78.4	2083
9.2	25-11-1833	96.7	1930
9.1	18-03-1861	96.7	2029

Table 6. Possibility of earthquakes in the future.

Magnitude	Predicted Year	Probability (%)	Expected Impact	Estimated Damage
8	2083	0.85	High casualties, injuries, building	Severe infrastructure damage, economic loss
9+	2029	0.75	Catastrophic impact, mass casualties	Widespread destruction

erage every 28 years, having a higher annual frequency of 0.036, leading to a 43% chance of such an earthquake occurring within 10 years. While the specific probability for the magnitude 9 earthquake of 1935 is not applicable, the 1861 earthquake calculations suggest a significant seismic risk in 2029, highlighting the need for preparedness and mitigation strategies.

4.3. Estimation of Total Losses for Earthquake

To estimate the potential impacts of future earthquakes, such as fatalities, injuries, building destruction, and economic losses, mathematical models are used to understand the relationship between earthquake magnitude and its consequences. The most common approach is a linear regression model, represented by the equation: $Y = \beta 0 + \beta 1M$. In this formula, Y represents the estimated impact (e.g., number of deaths, injuries, or damaged buildings), while M indicates the earthquake magnitude. The constants $\beta 0$ and $\beta 1$ are derived from historical earthquake data. $\beta 0$ is the intercept, which serves as a baseline value, and $\beta 1$ is the slope, showing how much the impact increases with each unit increase in magnitude. For example, if historical data suggests an intercept ($\beta 0$) of 500 and a slope ($\beta 1$) of 300, and the magnitude of the predicted earthquake is 8.5, the estimated number of fatalities can be calculated as follows: $Y = 500 + (300 \times 8.5)$. Simplifying the equation: $Y = 500 + 2{,}550 = 3{,}050$ fatalities. This means an earthquake of magnitude 8.5 is predicted to cause approximately 3,050 deaths, assuming historical patterns remain consistent. For economic losses, a different approach is often used, typically represented by an exponential model due to the non-linear relationship between magnitude and financial damage. The formula is expressed as: $Y = \alpha e^{\beta M}$. In this equation, α is a base constant representing the initial economic loss, while β reflects the growth rate of the loss as the magnitude increases. If historical data indicates a base constant (α) of 1.2×10^8 and a growth coefficient (β) of 0.85, the predicted loss for a magnitude 8.5 earthquake can be calculated. Substituting the values into the formula gives: $Y = 1.2 \times 108 \times e^{0.85 \times 8.5}$. This calculation would yield a significant economic loss, reflecting the exponential growth of damage as the magnitude increases.

In order to estimate the total costs of earthquakes with magnitudes 8, and 9, regression coefficients were used to project the number of deaths, injuries, building damage, and overall financial losses [31]. The estimates are based on the provided insurance values and costs, which are as follows: death compensation per person is estimated at USD 325,000, injury compensation per person is USD 160,000, damage per house is USD 26,000, and evacuation costs per person are USD 30 per day (**Table 7**).

The estimated losses associated with earthquakes of magnitude 8 or 9 highlight the urgent need for implementing robust risk mitigation strategies [32]. The potential scale of these losses underscores the necessity for substantial investments in infrastructure reinforcement, developing early

Table 7. Estimated losses due to a magnitude 8 or 9 earthquake.

Years	Magnitude	Estimated Deaths	Estimated Injuries	Building Damage (House)	Evacuate (People)	Estimated Economic Loss (Billion USD)
2083	8 Mw	1,200–2,500	5,000–10,000	15,000–30,000	10,000–20,000	1.5–2.5
2123	9 Mw	10,000–20,000	30,000–50,000	50,000–100,000	100,000–200,000	10–20

Note: 1 USD = 15,500 IDR.

warning systems, and enhancing public education and training[33]. Reinforcing infrastructure aims to improve the resilience of buildings against seismic forces, while advanced early warning systems can provide timely alerts to mitigate the risk of casualties. Additionally, improved education and training will strengthen community preparedness for disaster scenarios[34]. In disaster management training and education, it is essential to integrate technological solutions with traditional knowledge. Understanding cultural practices and local wisdom, such as those from the Baduy, Minangkabau, Sundanese, Javanese, Balinese, Sasak in Lombok, and Halmahera ethnic groups, proves effective[35, 36]. For instance, no Baduy houses collapsed during the recent large earthquake in the Sunda Strait with a magnitude of 8. The Baduy attribute this resilience to the bamboo plants surrounding their homes, which they believe help absorb seismic vibrations through their robust root systems. Governments and communities should consider incorporating traditional practices into construction and building design. Research on the relationship between bamboo and earthquakes was carried out by Fajrin et al. in Indonesia[37], and Rampal et al. in India[38].

However, the study's field observations show that the region faces several additional challenges that could worsen the situation if a major earthquake occurs. The results of these observations need to be included in formulating future policies, namely that many buildings and residential structures in this region have weak foundations and often do not comply with established operational procedures (SOPs) for infrastructure development. It concerns the issue of socialization. In addition, many houses were rebuilt in disaster-prone areas after previous earthquakes, increasing the risk of further damage and loss of life. Disaster management outreach and education must be conducted more frequently, reducing the effectiveness of preparedness efforts[39]. The disaster management budget is also limited; the National Disaster Management Agency only allocates USD 103 million[40], and disaster management funding at the regional level Regional Disaster Management Agencies on average, only 2–4% of the total Regional Revenue and Expenditure Budget. Implementing comprehensive and coordinated strategic actions is essential to mitigate the potential impact of future earthquakes. It includes appropriate planning and investment to ensure that infrastructure can withstand seismic events and that communities are prepared to handle possible impacts.

4.4. Implementation of Policy Network Theory on Earthquakes

In the context of earthquake risk management for the Mentawai-Siberut region, Policy Network Theory provides a crucial framework by emphasizing the importance of relationships and collaboration among various stakeholders involved in policy development and implementation[41]. This theory asserts that public policy emerges from the interactions among diverse actors—government bodies, NGOs, the private sector, local communities, and academic institutions—rather than being dictated solely by government decisions[42]. Key players in the Mentawai-Siberut earthquake disaster management network include central and local governments, the National Disaster Management Agency (BNPB), Regional Disaster Management Agencies (BPBD), NGOs, the private sector, local communities, and academic researchers[43] .

Effective coordination among these entities is essential, particularly given the region's geographic isolation and challenging infrastructure. Governments and disaster agencies need to collaborate closely to ensure that mitigation and response strategies are well-integrated and tailored to the region's needs[44]. NGOs are crucial in developing earthquake-resistant infrastructure and early warning systems, addressing vulnerabilities such as inadequate infrastructure and limited accessibility in remote areas like Siberut. Collaboration with the private sector is vital for investing in disaster resilience and technological innovations to enhance early warning and response systems.

Local community involvement is also critical, as integrating traditional knowledge and practices can strengthen disaster resilience. For instance, traditional methods, such as the Sikakap community's use of bamboo, can complement modern disaster management strategies [45] . Academics contribute valuable data on seismic patterns and mitigation strategies, supporting informed policymaking with localized insights.

Policy Network Theory underscores the complexity of managing diverse interests within this network. Government bodies focus on infrastructure and policy development, NGOs emphasize education and preparedness, and residents are concerned with practical issues like evacuation routes and timely aid [46]. Balancing these interests requires careful negotiation and integration to develop effective disaster management strategies. The involvement of geologists and researchers, whose expertise informs evidence-based policymaking [47], aligns with Policy Network Theory's emphasis on leveraging expert knowledge. Successful disaster management hinges on coordinated efforts, addressing infrastructure needs, and incorporating community input to improve regional resilience against seismic risks [48].

5. Conclusions

This study reviews earthquake risk management in the Mentawai-Siberut region and provides an in-depth assessment of seismic hazards and future mitigation strategies. By utilizing historical earthquake data and predictive models, the research highlights significant seismic activity in the Mentawai-Siberut area, characterized by high frequency and intensity of earthquakes due to its geographical location along an actively tectonic subduction zone. Historical data shows that earthquakes with magnitudes of 8 and 9 occur between 18 to 232 years. Significant earthquakes were recorded in 1935 and 2005, with an average interval of 78.4 years for magnitude 8 events. Predictions suggest a likelihood of a magnitude 8 earthquake around 2083, but a major megathrust earthquake with magnitude 9 is predicted to occur around 2033 and 2035.

Consequently, the study underscores the importance of improving infrastructure, such as completing the Trans-Mentawai Road project, to enhance access and aid distribution. Current infrastructure limitations hinder effective emergency responses, especially in remote areas like West Siberut. Recommendations include improving disaster preparedness and response capabilities, enhancing early warning systems, and integrating local knowledge and practices into disaster management strategies. In this regard, Policy Network Theory emphasizes the importance of collaboration among various stakeholders, including government agencies, BNPB, BPBD Province, BMKG, NGOs, local communities, academic researchers, and residents in Mentawai-Siberut. Effective disaster management relies on this coordinated approach to leverage diverse resources and expertise. The study highlights the need for a holistic disaster management strategy that combines infrastructure improvements, community engagement, and scientific data to enhance regional resilience to future seismic events. Thus, the research provides a comprehensive framework for understanding and addressing earthquake risks in Mentawai-Siberut, emphasizing the importance of preparedness, coordination, and continuous improvement in disaster management practices.

Author Contributions

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Institutional Review Board Statement

The research presented in this study was conducted in accordance with ethical standards and received approval from the University Ethics Committee with approval number No. 061-2021. This ensures that the research complies with all ethical guidelines necessary to protect participants' rights throughout the research.

Informed Consent Statement

Not applicable.

Data Availability Statement

No new data were created or analyzed in this study. All data are already presented in this article.

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Conflicts of Interest

No potential conflict of interest was reported by the authors.

References

[1] Mukesh, R., Dass, S., Vijay, M., et al., 2024. Analysis of ionospheric TEC variations and prediction of TEC during earthquakes using ordinary Kriging based surrogate model. Geomagnetism Aeronomy. 63, S22–S43. DOI: https://doi.org/10.1134/S001679322360025X

[2] Prakoso, S., Wijaya, A., Putra, F. 2022. Indonesia's disaster resilience against volcanic eruption: Lessons from Yogyakarta. KnE Social Science. 114–125. DOI: https://doi.org/10.18502/kss.v7i5.10544

[3] Hassin Alasadi, A.H., Hashim, K.M., 2023. Earthquake prediction technique: A comparative study. IAES International Journal of Artificial Intelligence. 12, 1026. DOI: https://doi.org/10.11591/ijai.v12.i3.pp1026-1032

[4] Supendi, P., Widiyantoro, S., Muhari, A., et al., 2020. Potential megathrust earthquakes and tsunamis off the southern coast of West Java, Indonesia. Preprint. DOI: https://doi.org/10.21203/rs.3.rs-104583/v1

[5] Fauziyah, N.N., 2024. BMKG Clarifies on Megathrust Earthquake Warning in Indonesia. Available from: Tempo.co online. Available from: https://en.tempo.co/read/1904138/bmkg-clarifies-on-megathrust-earthquake-warning-in-indonesia (cited 15 August 2024).

[6] Muhammad, A., Goda, K., Alexander, N., et al., 2017. Tsunami evacuation plans for future megathrust earthquakes in Padang, Indonesia considering stochastic earthquake scenarios. Natural Hazards and Earth System Sciences. 17, 1–26. DOI: https://doi.org/10.5194/nhess-17-2245-2017

[7] Huang, H., Wang, F., Xiao, Y., et al., 2022. To stay or to move? Investigation on residents' migration intention under frequent secondary disasters in the Wenchuan earthquake-stricken area. Frontiers in Public Health. 10, 1–12. DOI: https://doi.org/10.3389/fpubh.2022.920233

[8] Amirsardari, A., Sofi, M., Lumantarna, E., et al., 2019. Impact of earthquakes on the transportation infrastructure of Indonesia: A preliminary study. Civil Engineering Dimension. 21, 19–28. DOI: https://doi.org/10.9744/ced.21.1.19-28

[9] Pranata, B., Ramdhan, M., Sulaiman, M.I., et al., 2023. Rudarsko-geološko-naftni zbornik 3, 119–132. DOI: https://doi.org/10.17794/rgn.2023.3.10

[10] Foyouzati, A., 2024. Probabilistic seismic hazard assessment studies on the central-east of Iran—Kerman region. Iranian Journal of Science and Technology - Transactions of Civil Engineering. 48, 3457–3465. DOI: https://doi.org/10.1007/s40996-024-01428-3

[11] Stirling, M., Gerstenberger, M., 2018. Applicability of the Gutenberg–Richter relation for major active faults in New Zealand. Bulletin of the Seismological Society of America. 108(2), 718–728. DOI: https://doi.org/10.1785/0120160257

[12] Korkolis, E., Niemeijer, A., Paulssen, H., et al., 2021. A laboratory perspective on the Gutenberg-Richter and characteristic earthquake models. Journal of Geophysical Research: Solid Earth. 126, 1–21. DOI: https://doi.org/10.1029/2021JB021730

[13] Zobin, V., 2022. Volcano seismology: An introduction. In: Tilling, R.I. (ed.). Complexity in Tsunamis, Volcanoes, and their Hazards. Encyclopedia of Complexity and Systems Science Series. Springer: New York, NY, USA. pp. 393–424. DOI: https://doi.org/10.1007/978-1-0716-1705-2_607

[14] Zobin, V., Plascencia, I., 2022. Seismic risk in the State of Colima, México: Application of a simplified methodology of the seismic risk evaluation for the localities with low-rise, non-engineered housing. Geofísica Internacional. 61, 113–143. DOI: https://doi.org/10.22201/igeof.00167169p.2022.61.2.2199

[15] Osborne, N., Grant-Smith, D., 2021. In-Depth Interviewing. Springer: Singapore. pp. 105–125. ISBN: 978-981-16-1676-1. DOI: https://doi.org/10.1007/978-981-16-1677-8_7

[16] Samudra, A., Hertasning, B., Amiro, L., 2024. Policy for handling air pollution in Jakarta: Study using system dynamics simulation models. 8, 1–18. DOI: https://doi.org/10.24294/jipd.v8i2.2969

[17] Hermansyah, A., Samudra, A.A., Satispi, E., 2024.

Policy dialogue: Key factors for the success of transit-oriented development infrastructure 3.0 in big cities in Indonesia. Journal of Infrastructure, Policy and Development. 8(5), 1–23. DOI: https://doi.org/10.24294/jipd.v8i5.3400

[18] Earthquake-News, 2024. Top 100 countries with most earthquakes. Available from: https://earthquakelist.org/reports/top-100-countries-most-earthquakes/ (cited 18 August 2024)

[19] BMKG, 2021. Indonesian earthquake catalog: Hypocenter relocation and implications tectonics, 1st ed. Meteorology, Climatology and Geophysics Agency: Jakarta, Indonesia. pp. 1–32.

[20] El-Hussain, I., et al., 2012. Probabilistic seismic hazard maps for the Sultanate of Oman. Natural Hazards. 64, 173–210. DOI: https://doi.org/10.1007/s11069-012-0232-3

[21] Fiedler, B., Hainzl, S., Zöller, G., et al., 2018. Detection of Gutenberg–Richter b-value changes in earthquake time series. Bulletin of the Seismological Society of America. 108, 1–16. DOI: https://doi.org/10.1785/0120180091

[22] Ide, S., Yabe, S., Tanaka, Y., 2016. Earthquake potential revealed by tidal influence on earthquake size–frequency statistics. Nature Geoscience. 9 (11), 1–13. DOI: https://doi.org/10.1038/ngeo2796

[23] Chen, S., Chen, P., Wu, Y., et al., 2023. Temporal variations of earthquake magnitude-frequency relation in the source area of $M \geq 6.0$ earthquakes: A systematic survey in Taiwan. Earth and Space Science. 10, 1–16. DOI: https://doi.org/10.1029/2023EA002927

[24] Zhu, J., Li, S., Song, J., 2021. Magnitude estimation for earthquake early warning with multiple parameter inputs and a support vector machine. Seismological Research Letters. 93(1), 1–11. DOI: https://doi.org/10.1785/0220210144

[25] Kijko, A., 2019. Seismic Hazard. In: Gupta, H.K. (ed.). Encyclopedia of Solid Earth Geophysics. Encyclopedia of Earth Sciences Series. Springer: Cham, Switzerland. pp. 1–14. DOI: https://doi.org/10.1007/978-3-030-10475-7_10-1

[26] Dally, D., Tuan Amith, M., Mauldin, R., et al., 2024. A semantic approach to describe social and economic characteristics that impact health outcomes (social determinants of health): Ontology development study. Online Journal of Public Health Informatics. e52845. DOI: https://doi.org/10.2196/52845

[27] Sayil, N., 2013. Long-term earthquake prediction in the Marmara region based on the regional time- and magnitude-predictable model. Acta Geophysica. 61, 338–356. DOI: https://doi.org/10.2478/s11600-012-0088-7

[28] Scharer, K., Streig, A., 2019. The San Andreas fault system: complexities along a major transform fault system and relation to earthquake hazards. In: Duarte, J.C. (ed.). Transform Plate Boundaries and Fracture Zones. Elsevier: California, USA. pp. 249–269. DOI: https://doi.org/10.1016/B978-0-12-812064-4.00010-4

[29] Ibrahim, M., Al-Bander, B., 2024. An integrated approach for understanding global earthquake patterns and enhancing seismic risk assessment. International Journal of Information Technology. 16, 1–14. DOI: https://doi.org/10.1007/s41870-024-01778-1

[30] Süleyman, H., Cakti, E., 2024. Assessing seismic hazard and uncertainty in Büyükçekmece using ground motion simulations, Bulletin of Earthquake Engineering. 22(10), 1–24. DOI: https://doi.org/10.1007/s10518-024-01953-6

[31] Asrurifak, M., Irsyam, M., Budiono, B., et al., 2010. Development of spectral hazard map for Indonesia with a return period of 2500 years using probabilistic Method. Civil Engineering Dimension. 12, 52–62. DOI: https://doi.org/10.9744/ced.12.1.52-62

[32] Djazilus, H., Asrurifak, M., Meilano, I., et al., 2018. Recent efforts to mitigate the impacts of earthquake hazard in Indonesia from geotechnical engineering perspective. In: Iai, S. (ed.). Developments in Earthquake Geotechnics. Springer: Midtown Manhattan, NY, USA. pp. 131–150. DOI: https://doi.org/10.1007/978-3-319-62069-5_7

[33] Harith, N., Tongkul, F., Adnan, A., 2023. Seismic hazard curve as dynamic parameters in earthquake building design for Sabah, Malaysia. Buildings. 13, 318. DOI: https://doi.org/10.3390/buildings13020318

[34] Bellalem, F., Molina, S., Daniell, J., et al., 2024. Seismic risk assessment for the downtown of the city of Blida, Algeria. International Journal of Disaster Risk Reduction. 103, 104314. DOI: https://doi.org/10.1016/j.ijdrr.2024.104314

[35] Seyedi Rezvani, S.M.H., Silva, M., Almeida, N., 2024. Urban resilience index for critical infrastructure: A scenario-based approach to disaster risk reduction in road networks. Sustainability. 16, 4143. DOI: https://doi.org/10.3390/su16104143

[36] Perera, D., Seidou, O., Agnihotri, J., et al., 2019. Flood early warning systems: a review of benefits, challenges and prospects. UNU-INWEH Report No. 08, 16 August, 2019. DOI: https://doi.org/10.13140/RG.2.2.28339.78880

[37] Samudra, A.A., 2024. Disaster in the Ring of Fire and Black Swan Earthquake Theory (Techniques for disaster management with modern technology and local wisdom), 1st ed. Samudra Biru Yogyakarta: Jakarta, Indonesia. pp. 1–430. ISBN: 978-623-261-726-1.

[38] Ramadhan, A., Taqiyuddin, 2024. Disaster mitigation with local wisdom in the community of West Sumatra. Journal of Geographical Sciences and Education. 2, 67–72. DOI: https://doi.org/10.69606/geography.v2i2.90

[39] Rampal, T., Goel, M., Chawra, B., et al., 2023. Po-

tential use of bamboo as a sustainable material in construction in India: A survey of literature. Journal of the International Society for the Study of Vernacular Settlements. 10, 90–103. DOI: https://doi.org/10.61275/ISVSej-2023-10-09-07

[40] Fajrin, J., Sugiartha, I.W., Eniarti, M., 2021. Bamboo-based temporary house for post disaster relief: A conceptual design and prototype built after Lombok Earthquake 2018. IOP Conference Series: Earth and Environmental Science. 708, 012076. DOI: https://doi.org/10.1088/1755-1315/708/1/012076

[41] Husna, C., Hafni, M., Yahya, M., et al., 2020. Utilizing educational media of disaster mitigation on earthquake and tsunami preparedness for inpatient families in hospital. In: Tahlil, T., Kamil, H., Asniar, M. (eds.). Challenges in Nursing Education and Research, 1st ed. CRC Press: Boca Raton, FL, USA. pp. 193–205. DOI: https://doi.org/10.1201/9781003043973-21

[42] VOI, 2024. People are worried about the megathrust earthquake, the DPR encourages the government to immediately mitigate. Available from: https://voi.id/en/news/409878 (cited 11 October 2024).

[43] Marcon, G., Alberton, A., Florez, D., 2022. Stakeholder theory and actor-network theory: The stakeholder engagement in energy transitions. Business Strategy and the Environment. 32, 1–14. DOI: https://doi.org/10.1002/bse.3168

[44] Balane, M., Palafox, B., Palileo-Villanueva, L.A., et al., 2020. Enhancing the use of stakeholder analysis for policy implementation research: Towards a novel framing and operationalised measures. BMJ Glob. Health. 5(1), 1–12, DOI: https://doi.org/10.1136/bmjgh-2020-002661

[45] Wang, H., Ran, B., 2021. Network governance and collaborative governance: A thematic analysis on their similarities, differences, and entanglements. Public Management Review. 25(5), 1–27. DOI: https://doi.org/10.1080/14719037.2021.2011389

[46] Ardiansyah, M., Mirandah, E., Suyatno, A., et al., 2024. Disaster management and emergency response: Improving coordination and preparedness. Global International Journal of Innovative Research. 2, 831–839. DOI: https://doi.org/10.59613/global.v2i4.129

[47] Seyedi Rezvani, S.M.H., Silva, M., Almeida, N., 2024. The Risk-Informed Asset-Centric (RIACT) urban resilience enhancement process: An outline and pilot-case demonstrator for earthquake risk mitigation in Portuguese municipalities. Applied Sciences. 14(2), 634. DOI: https://doi.org/10.3390/app14020634

[48] Eze, E., Petersen, M., Siegmund, A., 2024. Enhancing protection motivation for disaster preparedness among actors at UNESCO-designated heritage sites in Africa. International Journal of Disaster Risk Reduction. 109(2), 1–16. DOI: https://doi.org/10.1016/j.ijdr.2024.104599