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RESEARCH ARTICLE

Identification the Level of Social Vulnerability of the Tsunami Disaster in the Coastal Area of Bengkulu City, Indonesia

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Abstract

This study investigates the spatial dynamics of social vulnerability to tsunami hazards in Bengkulu City by applying the BNPB (2012) framework as a national reference for index-based assessments. Five key social indicators: population density, gender ratio, poverty, disability, and age were analyzed using spatial techniques and secondary socio-demographic data to identify spatial disparities in vulnerability across sub-districts. The findings reveal that Teluk Segara and Ratu Samban Sub-Districts are the most socially vulnerable areas, driven not only by high population density and poverty but also by their low-lying coastal topography, direct exposure to the Indian Ocean, and limited evacuation accessibility. In contrast, inland sub-districts such as Selebar and Singaran Pati demonstrate lower vulnerability levels due to their higher elevation and greater distance from the coast. These spatial variations indicate that social vulnerability in Bengkulu City is strongly influenced by the interaction between socio-economic vulnerability and oceanographic conditions. The study emphasizes the importance of integrating social and oceanographic dimensions into tsunami risk assessments to better reflect site-specific realities and support more effective mitigation planning. Teluk Segara and Ratu Samban Sub-Districts need to be a priority for targeted preparedness efforts, improved evacuation infrastructure, and the restoration of coastal ecosystems is essential to reduce tsunami impacts. The results contribute to advancing integrated coastal disaster risk management in Indonesia by reinforcing the need to link human vulnerability with coastal environmental processes to achieve sustainable and resilient coastal communities.

Keywords: Bengkulu City, Coastal Area, Social Indicators, Social Vulnerability, Tsunami

1. Introduction

Tsunamis are enormous sea waves generated by intense seismic activity, where the source of the earthquake is on the seabed with an epicenter depth of less than 30 km (Wirp et al., 2021). Most tsunamis happen when the seafloor suddenly shifts up or down. However, they can also be triggered by underwater landslides, volcanic eruptions beneath the ocean, or even meteors hitting the Earth (Paris et al., 2014; Satake, 2015). Tsunamis are among the most destructive natural hazards, particularly affecting residents living in coastal areas such as Bengkulu City.

From a geotechnical and oceanographic perspective, Bengkulu is situated along the Sumatra Subduction Zone (SSZ), an active convergent boundary where the Indo-Australian Plate descends beneath the Eurasian Plate. This tectonic zone has repeatedly produced megathrust earthquakes capable of triggering destructive tsunamis (Madden et al., 2021). Historically, Bengkulu has experienced multiple major megathrust earthquakes. The Enggano earthquake in 2000 (Mw 7.9) and the Bengkulu earthquake in 2007 (Mw > 8.0) are recognized as key seismic events influencing the region's hazard profile (Mase et al., 2021). The 2007 rupture has been shown to produce a significant co-seismic slip that generated observable tsunami run-up along the Bengkulu coastline, consistent with numerical tsunami source modeling (Ratnasari et al., 2020). Recent assessments further categorize these events as part of the tectonic activity along the southern segment of the Sunda Subduction Zone, where strain accumulation and seismic coupling are notably high (Triyoso et al., 2024)

Recent research confirms that this segment remains highly active, as evidenced by the 2022 Southern Sumatra tsunami earthquake (MW 7.3), which ruptured the shallow portion of the 2007 fault plane, indicating ongoing seismic potential in the area (Qin et al., 2024; Supendi et al., 2023) . Recent coastal modeling and morphological analyses in Indonesia indicate that the interaction between tectonic activity and coastal topography significantly controls tsunami wave propagation and inundation levels, particularly along open coastal zones such as Bengkulu (Faiez & Fan, 2023; Ondara et al., 2020; Sihombing et al., 2024)

From an oceanographic perspective, the coastal morphology and bathymetry of Bengkulu, marked by steep underwater slopes and direct exposure to the Indian Ocean, intensify the impact of tsunami waves as they move toward land. Simulation study by (Triyoso et al., 2024) and (Fathiyah et al., 2024) estimate that tsunami run-up heights in the region could reach 4-6 meters, with inundation extending several kilometers inland, depending on fault displacement and seabed configuration. Spatial modeling by Fauzi et al., (2022) and local hazard mapping further identifies southern coastal areas, particularly Panjang Beach and Teluk Segara Sub-District, as the most vulnerable areas due to their low elevation and dense urban development.

In addition, seismic hazard analysis indicates that Bengkulu experiences relatively high peak ground acceleration (PGA) values, which can intensify tsunami risk when strong ground shaking precedes wave arrival (Mase and Keawsawasvong, 2022). This combination of complex seafloor morphology, active tectonic setting, and dense coastal settlement underscores the multifaceted nature of tsunami risk in the region. In a broader context, similar vulnerability patterns have also been documented in other Indonesian coastal regions, where rapid urbanization and limited disaster preparedness have intensified exposure to tsunami and coastal flooding hazards (Zamroni et al., 2020; Lamonge et al., 2024)

These findings highlight the importance of integrating social vulnerability indicators with physical hazard assessments to strengthen community-based mitigation strategies and promote more resilient coastal management frameworks (Lamonge et al., 2024). Bengkulu City is divided into nine sub-districts, and seven of them are in the coastal area, namely Muara Bangkahulu, Sungai Serut, Teluk Segara, Ratu Samban, Ratu Agung, Gading Cempaka, and Kampung Melayu (Fauzi et al., 2009). To minimize the risk of tsunamis to the Bengkulu City coastal community, it's crucial to understand the social vulnerability to such disasters. Social vulnerability, referring to the demographic and economic traits that impact a community's resilience to disasters, has not been adequately addressed (Fatemi et al., 2017). Social vulnerability describes the societal characteristics of a community that increase its risk of being affected by harm ((Chen et al., 2013; Maharani et al., 2016). Social vulnerability is also one of the factors that can turn natural hazards into natural disasters (Lin & Hung, 2016). Social vulnerability encompasses multiple dimensions, involving factors such as age, gender, education, income, occupation, housing conditions, resource accessibility, and information (Mah et al., 2023; Saulsberry et al., 2023).

Understanding the interplay between social vulnerability and tsunami hazard dynamics is essential for crafting realistic risk assessments. Communities that suffer from limited information access, weak institutional preparedness, or restricted evacuation capacity are disproportionately exposed to the physical effects of tsunami waves. For example, rapidly propagating waves coupled with high run-up heights can leave very little time for reaction in densely populated or socio-economically disadvantaged neighborhoods, thereby exacerbating the overall disaster impact. Hence, an integrated analysis that links oceanographic and tectonic parameters with indicators of social vulnerability provides a more holistic foundation for tsunami disaster mitigation in coastal Bengkulu. This research contributes to strategies for minimizing the impact of tsunami disasters. The combination of this approach with the social vulnerability of coastal populations can be used as a strategy for disaster risk reduction and comprehensive spatial planning. These findings are expected to inform policymakers, planners, and stakeholders in enhancing community resilience and promoting equitable disaster mitigation efforts.

2. Materials and Methods

2.1 Study Area

This research was conducted in Bengkulu City, which is divided into nine sub-districts: Selebar, Kampung Melayu, Gading Cempaka, Ratu Agung, Ratu Samban, Singaran Pati, Teluk Segara, Sungai Serut, and Muara Bangkahulu. Based on the location of the sub-districts, only two sub-districts in Bengkulu City are not located in coastal areas: Selebar Sub-District and Singaran Pati Sub-District.

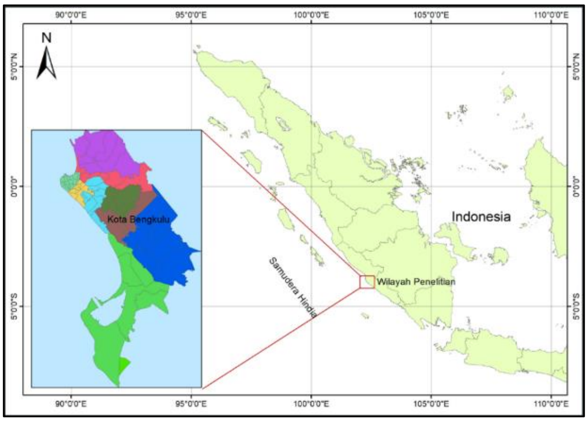

Fig 1. Research Area

2.2 Type of Research and Variables

This study uses a quantitative approach to explore and assess the level of social vulnerability to tsunami hazards in the coastal areas of Bengkulu City. The variables and weighting used in this study are based on Regulation No. 2 of 2012 issued by the Head of BNPB, which outlines the General Guidelines for Disaster Risk Assessment. These five variables are population density, ratio of the elderly and children, ratio of people with disabilities, ratio of women, and ratio of the poor population (BNPB, 2012) These variables were selected because these indicators are core components of the social vulnerability index recommended by BNPB (2012) for national-level disaster risk assessment. The weighting system provides a consistent and nationally recognized framework for assessing social vulnerability. This approach has limitations. It does not fully capture the specific characteristics of coastal communities, such as dependency on marine resources, accessibility to evacuation routes, or coastal geomorphological conditions. Therefore, this study should be viewed as an initial framework for assessing social vulnerability, which can be refined in future research by integrating more locally specific coastal indicators.

2.3. Population, Sample, and Data

The population, which is also a sample, is the Bengkulu City community, consisting of 390.060 people spread across nine sub-districts (BPS Kota Bengkulu, 2023). This study relies on secondary data collected from a variety of sources, as shown in Table 1.

Table 1. Data Source and Usage

No	Data	Source	Use
1	Number of population of each sub-district	Statistics Indonesia (BPS)	Population and sample calculation
2	Population density	Statistics Indonesia (BPS)	Population density calculation
3	Number of population by age group for each sub-district		The ratio of the age group calculation
4	Number of disabled population for each sub-district	Population and Civil Registration Agency (Dinas Dukcapil Kota Bengkulu)	The ratio of the disabled population calculation
5	Number of population by gender for each sub-district		The ratio of gender calculation
6	Number of poor population for each sub-district	Social Office Bengkulu City	The ratio of the poor population calculation

2.4. Research Method

The primary focus of this research is assessing the social vulnerability of communities, not modeling the physical characteristics of tsunami hazards. Therefore, the model emphasizes demographic and socioeconomic factors that influence a community's ability to respond to and recover from disasters. However, the addition of spatial variables in the future is highly recommended for a more comprehensive and accurate tsunami risk assessment.

Determining the weight and class for each variable considered in assessing the social vulnerability of the area is based on Regulation No. 2 of 2012 issued by the Head of BNPB, as shown in Table 2. This weighting is intended to ensure consistency in inter-regional evaluations at the national level, so that the results of vulnerability analysis can be compared and used as a basis for disaster mitigation policies. In Bengkulu City, the interpretation and significance of each vulnerability indicator, especially population density, are highly influenced by local topography and settlement configuration (Fathiyah et al., 2024). Low-lying coastal sub-districts such as Teluk Segara and Ratu Samban are more exposed to tsunami hazards because densely inhabited communities are concentrated along the shoreline, where available evacuation areas are scarce. In such conditions, high population density emerges as a key determinant that heightens social vulnerability by constraining evacuation efficiency and elevating the potential for casualties during tsunami incidents.

In contrast, inland and upland sub-districts such as Selebar and Singaran Pati exhibit comparable levels of population density but are subject to a much lower tsunami hazard. Their higher elevation serves as a natural barrier that mitigates the extent of tsunami inundation, thus lowering the level of physical exposure to tsunami hazards. This spatial variation demonstrates that similar social indicators can reflect different degrees of vulnerability when examined through geographical and environmental contexts.

Table 2. Weight and Score of Social Vulnerability Variables (BNPB, 2012)

Variables	Weight (%)	Class		
		Low	Medium	High
Population Density	60	< 500 people / km²	500 - 1000 people / km²	> 1000 people /km²
Vulnerable Group				
Gender Ratio	10	< 20 %	20 - 40 %	> 40 %
Poor Population Ratio	10			
Disable Population Ratio	10			
Vulnerable Age Group Ratio	10			
Scoring		1	2	3

The Total Value of Social Vulnerability (TVSV) is calculated using the following formula (BNPB, 2012; Nabillah et al., 2020)

$$TVSV = (0.6 * \text{Populaton Density score}) + (0.1 * \text{Gender Ratio Score}) + (0.1 * \text{Poor Population Ratio Score}) + (0.1 * \text{Disable Population Ratio Score}) + (0.1 * \text{Vulnerable Age Group Ratio Score}) \quad (1)$$

Determination of social vulnerability classes total (low, moderate, and high) uses a calculation by dividing interval classes with the following formula:

$$\text{Interval class} = \frac{\text{highest value} - \text{lowest value}}{3} \quad (2)$$

3. Results and Discussion

3.1 Population Density

A key factor in an area's social vulnerability is its population density. According to data from BPS Bengkulu City, scores were obtained for each sub-district in Bengkulu City, as shown in Figure 2.

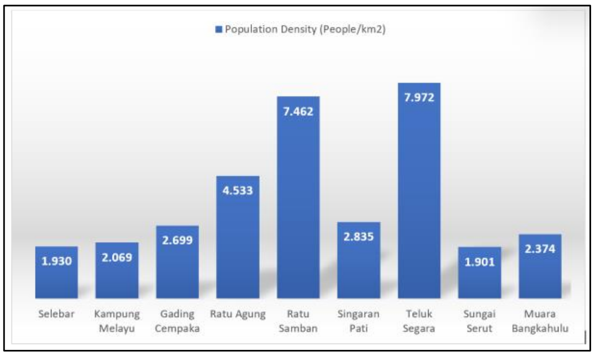

Fig 2. Population Density

The area is characterized by a high population density, with a population exceeding 1,000 people/km². Among all sub-districts, Sungai Serut has the least crowded population, with 1,901 people/km², whereas Teluk Segara is the most densely populated, reaching 7,972 people/km². High population density directly impacts the community's vulnerability to the threat of tsunamis. This high density not only limits evacuation space and access to rescue routes, but also increases the potential number of victims and losses when a disaster occurs.

3.2. Gender Ratio

The calculation of the ratio for gender is the number of females divided by the total population. This calculation was done for every sub-district in Bengkulu City, and the gender ratio scores can be seen in Figure 3.

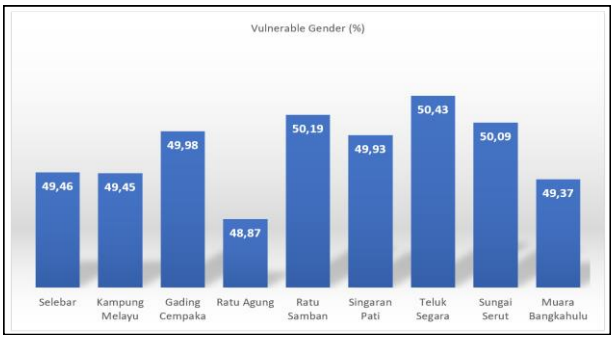

Fig 3. Ratio of Vulnerable Gender

The gender ratio is classified as high because it shows more than 40%. The lowest gender ratio is in Ratu Agung Sub-District, 48,87%, while the highest gender ratio is in Teluk Segara Sub-District, 50,43 %.

3.3. Poor Population Ratio

The poverty ratio is calculated by dividing the number of people living in poverty by the total population. This calculation is carried out for each sub-district in Bengkulu City, and scores were obtained for the poor population ratio as shown in Figure 4.

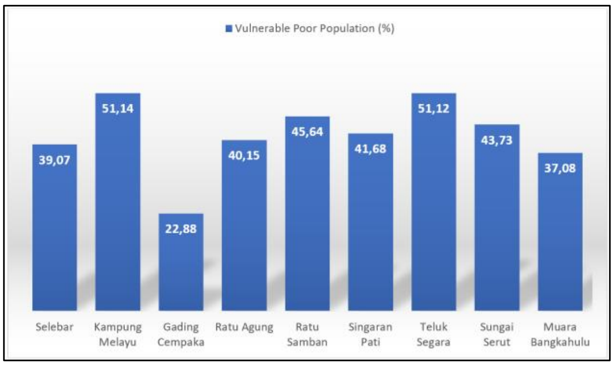

Fig 4. Ratio of Vulnerable Poor Population

The poor population ratio is classified as moderate to high. Three sub-districts are classified as moderate: Selebar, Gading Cempaka, and Muara Bangkahulu, while six sub-districts are classified as high: Kampung Melayu, Ratu Agung, Ratu Samban, Singaran Pati, Teluk Segara, and Sungai Serut. The highest poor population ratio is in Teluk Segara Sub-District, 51,12%, while the lowest poor population ratio is in Gading Cempaka Sub-District, 22,88%.

3.4. Disabled Population Ratio

The calculation of the ratio for the disabled population is the number of disabled individuals divided by the total population. This calculation is carried out for each sub-district in Bengkulu City, and scores were obtained for the disabled population ratio as shown in Figure 5.

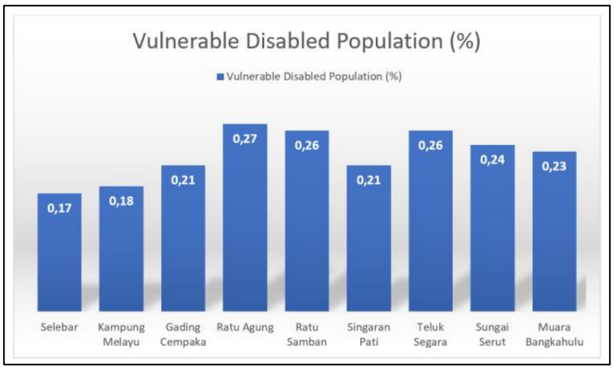

Fig 5. Ratio of Vulnerable Disabled Population

The disabled population ratio is classified as low because it shows less than 20%. The disabled population is dominated by people with mental disabilities. The highest disabled population ratio is in Ratu Agung Sub-District, 0,27%, while the lowest disabled population ratio is in Selebar Sub-District, 0,17%.

3.5. Vulnerable Age Group Ratio

The ratio for vulnerable age groups is determined by adding the population of children aged 0–4 and the elderly (over 60), and dividing that total by the overall population. The vulnerable age ratio for each sub-district in Bengkulu City is classified as low class (<20%). Teluk Segara Sub-District has the highest proportion of the age group at 17.4%, while Kampung Melayu Sub-District has the lowest at 14.9%.

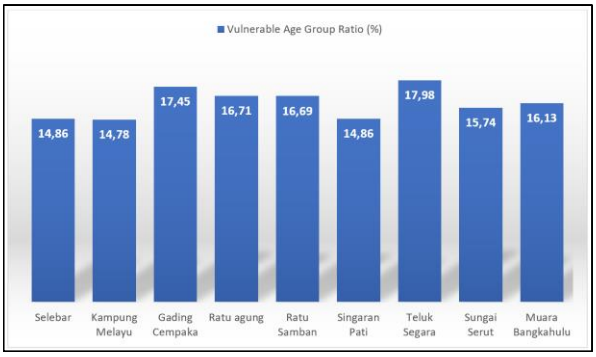

Fig 6. Ratio of Vulnerable Age Group

3.6. Total Value of Social Vulnerability (TVSV)

The TVSV is grouped into three levels, namely low level of vulnerability, moderate level of vulnerability, and high level of vulnerability. Determination interval of TVSV, using Equation (2). The class intervals for each level of social vulnerability can be seen in Table 3.

Table 3. The Class Intervals of Social Vulnerability

No	Vulnerability Score	Vulnerability Level
1	1151.58 – 2366.11	Low
2	2366.12 - 3580.66	Moderate
3	3580.67 - 4795.19	High

The TVSV is calculated using Equation (1). The level of social vulnerability is shown in Table 4 and described in Figure 7.

Table 4. The Level of Social Vulnerability for Each Sub-District in Bengkulu City

No	Sub-District	Population Density (people/ km^2)	Gender Ratio(%)	Poor Population Ratio (%)	Disabled Population Ratio (%)	Vulnerable Age Group Ratio (%)	TVSV	Category
1	Selebar	1.930	49,46	39,07	0,17	14,86	1168,36	Low
2	Kampung Melayu	2.069	49,45	51,14	0,18	14,78	1576,95	Low
3	Gading Cempaka	2.699	49,98	22,88	0,21	17,45	1628,45	Low
4	Ratu Agung	4.533	48,87	40,15	0,27	16,71	2730,40	Moderate
5	Ratu Samban	7.462	50,19	45,64	0,26	16,69	4488,48	High
6	Singaran Pati	2.835	49,93	41,68	0,21	14,86	1711,83	Low
7	Teluk Segara	7.972	50,43	51,12	0,26	17,98	4795,18	High
8	Sungai Serut	1.901	50,09	43,73	0,24	15,74	1151,58	Low
9	Muara Bangkahulu	2.374	49,37	37,08	0,23	16,13	1438,68	Low

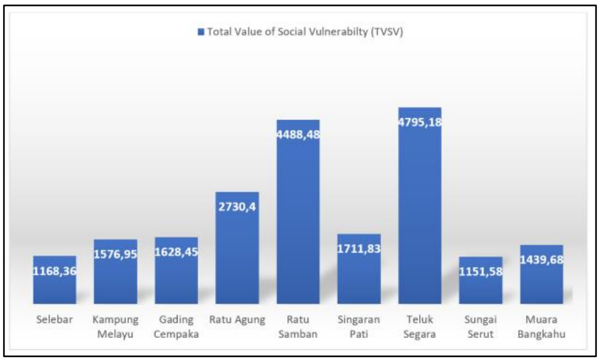

Fig 7. Total Value of Social Vulnerability

The results of the study indicate distinct spatial patterns of social vulnerability in Bengkulu City. Two sub-districts, Teluk Segara and Ratu Samban, show the highest levels of vulnerability, while Ratu Agung falls into the moderate category, and the remaining six sub-districts demonstrate relatively low levels. The high vulnerability observed in Teluk Segara and Ratu Samban is not only the result of high population density and poverty, but is also strongly influenced by their geographic location, topographic characteristics, and limited access to evacuation routes.

Both Teluk Segara and Ratu Samban are situated in low-lying coastal zones directly facing the Indian Ocean. Their flat coastal morphology, low elevation, and limited natural buffers such as mangrove forests or dunes make them particularly exposed to the direct impact of tsunami waves (Lestari et al., 2024). Spatial analysis and field verification show that these sub-districts possess minimal vertical relief and have been repeatedly affected by coastal flooding events in the past. Furthermore, several densely populated neighborhoods are located more than 500 meters from designated evacuation points, which restricts mobility and increases the potential for loss of life during tsunami events (Qüense et al., 2022).

In contrast, inland sub-districts such as Selebar and Singaran Pati are located on higher ground, which provides a natural buffer against wave inundation. Their greater distance from the shoreline and lower concentration of settlements near the coast significantly reduce exposure to tsunami impacts (Hadi & Damayanti, 2019). This difference highlights how topography, settlement distribution, and accessibility play crucial roles in shaping social vulnerability beyond demographic and economic factors as defined by BNPB (2012).

Further analysis suggests that social vulnerability in Bengkulu is spatially mediated, shaped by the interaction between social fragility and oceanographic hazards. Coastal areas with greater exposure often have lower environmental protection capacity due to the degradation of natural buffers (such as mangrove forests and dunes), and the accelerating sea-level rise observed in southern Sumatra (Girl et al., 2024). These processes enable wave energy to penetrate farther inland, intensifying inundation. Additionally, land subsidence, increasingly reported along the coasts of Sumatra and Java, may exacerbate these risks by reducing ground elevation and expanding flood-prone zones in the coming decades.

When compared with other Indonesian coastal cities such as Padang, Cilacap, and Banda Aceh, similar dynamics can be observed, though under different environmental conditions. In Padang and Banda Aceh, high social vulnerability is primarily associated with dense coastal populations and limited evacuation infrastructure (Mauro et al., 2013). Meanwhile, in Cilacap, tsunami run-up modeling has shown that land-use changes and coastal morphology play significant roles in determining hazard exposure (Destrayanti et al., 2023) .

In Bengkulu, population concentration in low-lying coastal sub-districts such as Teluk Segara and Ratu Samban interacts directly with oceanographic hazards, including potential tsunami propagation, the absence of natural protective ecosystems, and the expanding reach of inundation zones driven by rising sea levels. This complex interplay between social and physical drivers demonstrates that tsunami risk in Bengkulu is not solely governed by wave dynamics, but also by the socio-ecological conditions that shape community exposure and resilience.

These findings emphasize the importance of adopting an integrated coastal disaster risk reduction framework that bridges human and environmental dimensions. Effective mitigation should not only focus on physical infrastructure and evacuation systems, but also aim to strengthen community preparedness, restore natural buffers, and align land-use planning with spatial exposure patterns. Such a comprehensive approach reflects the current understanding in coastal risk science that long-term resilience can only be achieved by addressing both human vulnerability and environmental transformation simultaneously.

According to the results of the analysis regarding social vulnerability, Bengkulu City is divided into 3 levels, namely low, moderate, and high, where Teluk Segara and Ratu Samban Sub-Districts are at the high level, Ratu Agung Sub-District is at the moderate level, and the other 6 Sub-Districts: Sungai Serut, Singaran Pati, Selebar, Gading Cempaka, Muara Bangkahulu, and Kampung Melayu, are at the low level. The level of social vulnerability for each sub-district in Bengkulu City is illustrated in Figure 8.

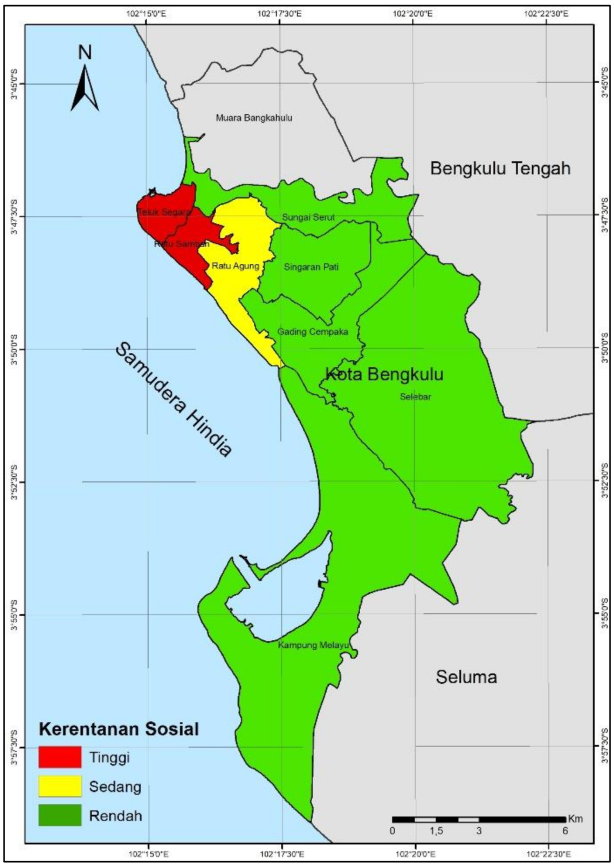

Fig 8. Map of Social Vulnerability Levels in Bengkulu City

4. Conclusion

This study highlights the spatial differentiation of social vulnerability to tsunami hazards across Bengkulu City. Two coastal sub-districts, Teluk Segara and Ratu Samban, emerge as the most vulnerable zones, while Ratu Agung shows moderate vulnerability, and the remaining six sub-districts exhibit relatively lower levels. The high-risk status of Teluk Segara and Ratu Samban is shaped not only by dense population and socioeconomic constraints but also by their low-lying coastal morphology, direct exposure to the Indian Ocean, and limited evacuation accessibility. These geographic and infrastructural conditions amplify the potential impact of tsunami waves and restrict residents' ability to respond effectively during emergencies. The findings emphasize the necessity of integrating social and oceanographic dimensions in assessing tsunami risk. Understanding how social fragility interacts with physical and oceanographic factors provides a more complete picture of vulnerability, enabling the development of targeted preparedness and mitigation strategies. Such insights are particularly valuable for local governments in prioritizing high-risk areas and designing community-based disaster risk reduction programs that enhance both human safety and environmental resilience.

From a policy standpoint, Teluk Segara and Ratu Samban should be treated as priority zones within Bengkulu's disaster management agenda. Efforts such as improving evacuation routes and facilities, restoring natural coastal defenses (e.g., mangroves and dune vegetation), regulating coastal land use, and strengthening community preparedness are essential to reduce disaster impacts and build long-term resilience. Despite its contributions, this study recognizes several limitations. The analysis is primarily based on secondary socio-demographic data and does not yet incorporate physical exposure indicators, such as inundation depth, coastal morphology, or proximity to evacuation infrastructure. Future research should adopt a multidisciplinary and spatially explicit approach—combining physical, social, and environmental variables through geospatial modeling, participatory mapping, and hazard simulations to develop a more comprehensive understanding of coastal vulnerability.

Overall, this research reinforces the importance of an integrated coastal disaster risk management framework in Indonesia, where sustainable resilience depends on recognizing the interconnectedness between human vulnerability and oceanographic processes. Such integration will help coastal cities like Bengkulu move toward more adaptive, inclusive, and science-based mitigation planning.

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