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Building Distribution and Spatial Constraints from Perspectives of Tsunami Inundation at a Small Island Context: A Study Case of Sabang-Aceh, 20 Years after the 2004 Aceh Tsunami

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ABSTRACT In the aftermath of the devastating 2004 Indian Ocean tsunami, the Indonesian government implemented disaster mitigation measures through improved spatial planning, particularly in settlement areas. These efforts focused on reconstruction and sustainable development strategies to enhance safety while aligning with national and regional regulations. Sabang City, located in a tsunami-prone region, was also affected by the 2004 tsunami, necessitating further evaluation of its building resilience and spatial planning. This study aims to assess the spatial distribution of buildings in Sabang City to evaluate their suitability in tsunami-prone areas and their potential for residential development. A field survey was conducted between February and June 2023, identifying and classifying 14,104 building units based on the HAZUS methodology developed by FEMA (Federal Emergency Management Agency, USA). The buildings were categorized into six structural types: Reinforced Concrete (C1-La, C1-Lb, C1-M), Concrete Frame with Unreinforced Masonry (C3-L), Steel Frame (S1-M), and Wood Frame (W1-L). Spatial analysis examined settlement patterns in relation to land capability and disaster mitigation requirements. Findings reveal significant constraints in land development for residential purposes, particularly in tsunami-prone and low-capability areas. Of the total surveyed buildings, 6,726 units (47.7%) are located in low-capability zones, primarily influenced by the dominance of protected forests and buffer zones that restrict land availability. Moreover, Sabang's rugged topography, characterized by steep slopes and hilly terrain, exacerbates land development challenges. These findings underscore the urgent need for strategic interventions, including relocating settlements from high-risk tsunami zones, updating spatial planning policies, and integrating tsunami risk assessments into urban development strategies. Strengthening these measures will enhance urban resilience and promote sustainable growth in Sabang City.

KEYWORDS Spatial Planning, Rapid Visual Screening (RVS), HAZUS Typology, Land Development, Settlement Suitability

1 INTRODUCTION

Residential areas are significant in spatial planning (Regional Spatial Planning). Economic and population growth push residential development into outer and non-residential zones (Malik and Dewancker, 2018). However, this expansion affects environmental capacity and its ability to adapt to extreme conditions like disasters. For instance, tsunami disaster that struck Aceh Province on December 26, 2004, was one of the deadliest natural events in modern history (Grezio et al., 2010; Heidarzadeh et al., 2021; Jihad et al., 2021; Small and Melgar, 2023; Swaroop et al., 2020). The waves wiped out most of the land and caused massive destruction, severely impacting infrastructure, the economy, and coastal communities. Due to this event, 139,195 homes were destroyed or damaged, along with 669 government buildings, 3,145 educational facilities, and 517 health centers (BRR (Reconstruction and Rehabilitation Agency), 2006). The tsunami waves reached up to 100 feet (~30 meters), with inundation heights of 9 meters in Banda Aceh City, 5 meters in Krueng Raya (Aceh Besar Regency), 30 meters in Lhoknga (Aceh Besar), 10 meters in Lhokruet (Aceh Jaya), and 4.5 meters in Panteraja (Pidie Jaya) (BMKG, 2019).

After the 2004 Aceh tsunami, the estimation of tsunami damage on buildings and settlements has improved, leading to better mapping of tsunami inundation (Imamura, 2009; Paulik et al., 2021). In response, the Indonesian government has begun to examine one of the critical aspects of disaster prevention: planning and organizing areas, including residential and built-up areas. A key focus of post-tsunami reconstruction was developing safer and more sustainable urban and residential planning, following the mandate of Spatial Planning Law No. 26 of 2007 to enhance disaster mitigation and safety. At the provincial level, Qanun Aceh No.

19 of 2013 was also implemented to minimize disaster risks.

In the two decades following the 2004 Aceh Tsunami, it is essential to assess the extent of building development and the implementation of spatial planning to achieve the objectives of habitability and safety in Aceh. Analysis of building distribution is one method to evaluate whether current settlements have been constructed according to spatial planning principles that support disaster mitigation and the critical role of the community in prevention and mitigation Hart et al. (2024). In this context, spatial planning includes the location of buildings within safe zones and examines the structural systems that support the buildings themselves. Thus, this research aims to assess the distribution of buildings in tsunami-affected areas of Aceh and how spatial planning implemented over the past two decades has impacted the feasibility of current residential areas. It also considers the flexibility of future developments as the population grows and demands increase according to land suitability.

However, two decades since the tsunami, no study has been conducted to assess the building growth and its suitability from the perspective of disaster risk reduction in the context of a small island. Sabang is an administrative name of Weh Island. The island is small, covering 122.2 km^2 area, and consisting of only two subdistricts. It has a population of about 43 thousand people. As a small island, Sabang faces difficulties in managing its spatial planning and natural resources to cope with the demands of development growth. On the other hand, this island is characterized by steep topography contours and an active volcano. Previous studies on small island's spatial planning related to tsunami mitigation have focused on tsunami evacuation and building exposures (Fernandes and Pinho, 2017; Paulik et al., 2021; Shultz et al., 2016). This research is aimed at identifying and classifying buildings in Sabang City to assess their suitability for tsunami-prone areas and potential for residential development. Geographically, this is the first study conducted in Indonesia by combining Probabilistic Tsunami Hazard Analysis, Fragility Curves, and Spatial Analysis in the context of a small island.

2 METHODS

Sabang is located at the northern tip of Sumatra Island, on Weh Island, facing the Andaman Sea to the north, the Malacca Strait to the east, and the Indian Ocean to the west and south. It is part of a district in Aceh Province that was affected by the 2004 Aceh tsunami. Administratively, Sabang is divided into 2 sub-districts. Sabang is one of the two districts representing the small island context in Aceh Province. Another one is the Simeulue District, located off the western coast of Sumatra. From a geographical and demographic perspective, Sabang has a population of over 43,000. The island is located about 200 km to the eastern part of the 2004 Aceh tsunami source (The Aceh-Andaman megathrust segment). The term "megathrust segmentation zone" refers to the earthquake source located in the subduction zone. The subduction plate boundary is typically very long and shallow, encompassing the contact area between the plates. The earthquake that occurred in 2004 revealed at least 6 fault subsegments with lengths ranging between 1,200 and 1,300 km (Koshimura et al., 2009). However, another study found that the fault rupture on the seabed extends across 11 segments (Piatanesi et al., 2007). This condition certainly makes Sabang one of the first areas to be impacted by the tsunami waves within less than 25 minutes after the fault rupture (Benazir et al., 2022). Geographically, Sabang is dominated by mountainous terrain, covering 48.17% of the total area, with 14.10% consisting of hills and 37.72% flat land suitable for residential development (Achmad et al., 2020; Jihad et al., 2021; Rani et al., 2017).

This research was conducted in three main steps. First, we conducted a series of field surveys to identify and classify buildings in Sabang. Second, we conducted a Probabilistic Tsunami Hazard Analysis (PTHA) by employing tsunami hazard curves for Sabang. Third, we employed a spatial analysis to assess the suitability of the houses/buildings from the perspectives of future tsunamis (in this case, a 500-year return period tsunami was used).

2.1 Building Data Collection

For building surveys, this study adopted the Rapid Visual Screening (RVS) method. The RVS was originally developed by the Federal Emergency Management Agency (FEMA) to assess and identify buildings at high risk of earthquake damage (Harirchian et al., 2020). Further development, FEMA P-154, involved visually collecting building data, which can be implemented relatively quickly to capture typical building forms for seismic and tsunami hazards. Data collection involved observing the buildings and identifying their physical structures, typically taking 15-20 minutes for each building, making it a rapid assessment (Gentile et al., 2019).

Recently, the RVS has been adapted for tsunami hazards in FEMA 178 (FEMA, 2017). Estimating damage from disaster risks requires data on building models, including their characteristics and the potential impacts on infrastructure and populations in tsunami-prone areas. The National Institute of Building Sciences (NIBS) developed the HAZUS (Hazard United States) system to analyze disaster risk. The U.S. categorizes buildings into 36 building types, with reinforced concrete structures (C1-L) further subdivided into C1-La for single-story buildings and C1-Lb for 2-3-story buildings (Syamsidik et al., 2023). In Sabang, there were only six categories of buildings, as can be seen in Table 1.

Table 1. Building Classification in Aceh

Code	Structural Components and Description	Image
C3-L	Concrete frame with unreinforced masonry	
C1-La	Reinforced concrete with 1 storey	
C1-Lb	Reinforced concrete with 2 storeys	
C1-M	Reinforced concrete with 3 or more storeys	
W1-L	Wood frame with 1 storey	
S1-M	Steel frame	

2.2 Tsunami Probabilistic

The Probabilistic Tsunami Hazard Assessment (PTHA) is an adaptation of the Probabilistic Seismic Hazard Assessment introduced by Cornell (1968), allowing for the estimation of tsunami event probabilities over a given period (Kotani et al., 2020). The primary outcome of the PTHA analysis can be depicted as a hazard curve, indicating the rate of exceedance of a hazard metric relative to probability, with probability expressed as the annual exceedance rate. The most common metric is the maximum wave amplitude, but for subduction zone inundation, land uplift and subsidence are integral to the flooding process (Grezio et al., 2017). PTHA is used to estimate maximum inundation height, as formulated in Equation (1):

$$\lambda(H \geq h) = \sum_{i=1}^{n_s} v_i \sum_{j=1}^{n_m} P\left(H \geq h | m_j\right) P(M_i = m_j) \tag{1}$$

Where H defines a specific magnitude's maximum tsunami height (m). Estimations for maximum tsunami height are expressed as h, with n_s representing the number of earthquake sources i and n_m as the earthquake magnitude m within interval j (Mw). The variable v_i represents the occurrence rate of earthquakes (M) equal to or greater than m_{min}, calculated using the Gutenberg-Richter frequency distribution (Ishimoto, 1939; Gutenberg and Richter, 1994; Mulia et al., 2020). The Equation is shown in Equation (2):

$$v_i = 10^{a - b m_{\text{min}}} \tag{2}$$

The variable v_i represents the number of earthquakes equal to a given magnitude at frequency m. The values of a and b are constants based on observed megathrust seismicity. The value of a represents seismic activity rates in a region, while the b value reflects the relationship between earthquake magnitudes and frequencies. A higher b value indicates frequent smaller quakes, while a lower b value correlates with less frequent, larger quakes due to accumulated energy (Syamsidik et al., 2024). Based on Equation (1), the probability $P(M_i = m_j)$ is defined in Equation (3).

$$P(M_i = m_j) = F_m\left(m_j + 0.5\Delta m\right) - F_m\left(m_j - 0.5\Delta m\right) \tag{3}$$

where Fm is expressed in Equation (4) as follows:

$$F_m = \frac{1 - 10^{-b(m - m_{\text{min}})}}{1 - 10^{-b(m_{\text{max}} - m_{\text{min}})}} \tag{4}$$

where m is the earthquake magnitude (Mw) and Δm is the magnitude interval (Mw). Based on Equation (1), the value $P\left(H \geq h | m_j\right)$ is defined in Equation (5) as follows:

$$P\left(H \geq h|m_j\right) = 1 - \Phi\left\{\frac{\ln\left(h\right) - \ln\left(H\right)}{\beta}\right\} \quad (5)$$

where Φ is the cumulative normal distribution, and β accounts for tsunami uncertainty ($\beta = \ln\left(\kappa\right)$). Uncertainty is assessed based on numerical simulations and validated against field measurement data. Validation data were obtained from NOAA, including tsunami height data across Aceh after the 2004 tsunami (Tursina et al., 2021).

2.3 Land Development Capability

The analysis of land capability concerning disaster aspects aims to understand the condition and feasibility of development in relation to the level of disaster risk in the area. This analysis serves as an evaluation tool for development and helps avoid utilizing land in areas prone to natural disasters (Awaluddin, 2022). Creating the land capability map involves weighting and spatial analysis (Buchori et al., 2013). The stages of the analysis are shown in Figure 1.

This method involved one main variable and two limiting variables. The variables and their weighting are shown in Table 2.

The results from the main variable scores were processed using ArcGIS with the weighted sum and overlay analysis method. The map is then classified based on the land development feasibility classification range, details of which can be found in Table 3.

Table 2. Classification Values, Weights, and Scores for the Main Variable

Variable	Classification	Classification Value	Weight	Score
Slope	$0-2\%$	5	25	50
	$2-8\%$	4		40
	$8-15\%$	3		30
	$15-40\%$	2		20
	$>40\%$	1		10
Soil Type	Very Hard	5	25	50
	Hard	4		40
	Medium	3		30
	Soft	3		30
	Very Soft	2		20
Tsunami Inundation	$0-0.5$ m	5	50	125
	$0.5-1$ m	4		100
	$1-2$ m	3		75
	$2-5$ m	2		50
	>5 m	1		25

The classification of development flexibility into low, medium, and high categories was based on a modified version of the framework developed by Buchori et al. (2013). The low category designates areas as protected zones, where development is highly restricted due to legal and environmental considerations. The medium category represents areas where development is possible but requires physical engineering measures to mitigate hazards, especially tsunami risks. The high category refers to areas with intensive development potential, where construction can proceed without significant engineering interventions and with minimal tsunami threat.

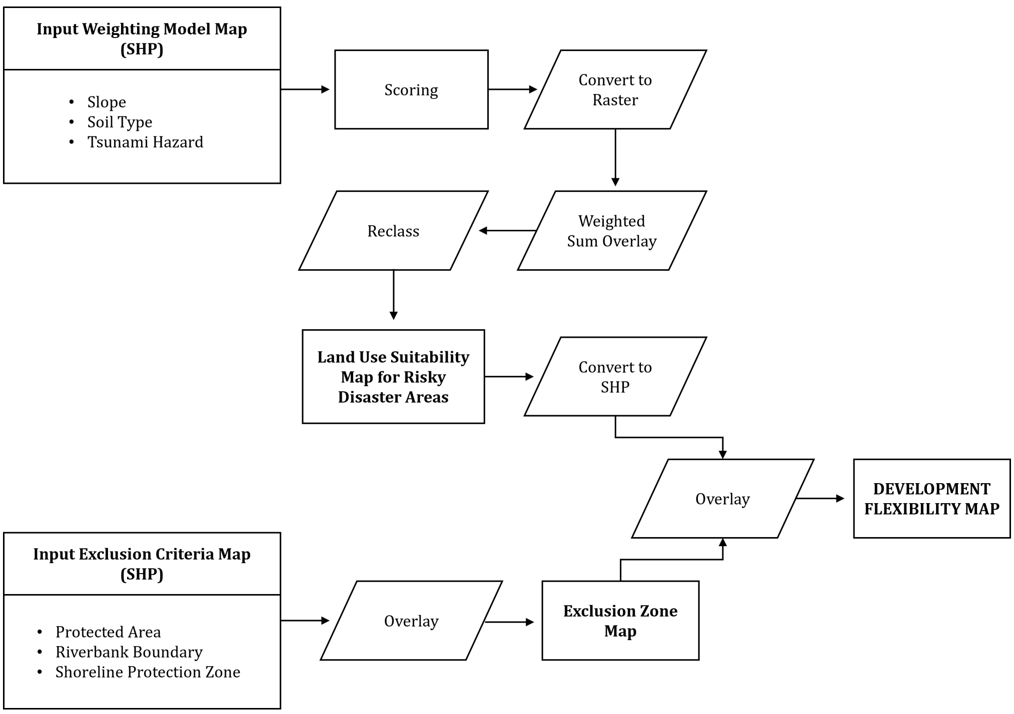

Figure 1 Flowchart illustrating the Spatial Analysis of Land Development Capability.

Table 3. Development Flexibility Score Classification

Total Score	Development Flexibility	Description	Land Use Recommendation
90 – 210	Low	Area with relatively steep slopes, prone to soil erosion and natural disasters.	Reserved as a protected area, not suitable for development.
210–330	Medium	Area that has potential for disasters and is recommended for limited-scale development.	Development in this area should consider certain aspects to avoid hazards.
330–450	High	Area with intensive development.	It does not require physical engineering and offers great flexibility for land use development.

The limiting variables act as constraints. The classification map from the main variable will be combined with the limiting variables. Areas affected by the limiting zones are automatically considered to have low development feasibility. Limiting variables consist of protected areas, coastal setback zones, and river setback zones. Table 4 provides full details.

Table 4. Exclusion Variable

Exclusion Variable	Description	Class
Protected/ Conservation Area	Includes protected forests, nature reserves, cultural reserves, and a 25-meter buffer zone on both sides of the river	Restricted
River and Coastal Buffer	Includes a 100-meter buffer inland from the highest tide water inundation line	Restricted

2.4 Land Suitability for Settlements

Land suitability for settlements must be well-planned and regulated. Planning documents can serve as references in addressing urban settlement issues. Understanding a city's physical characteristics is necessary to solve settlement problems and improve settlement resilience, particularly in disaster-prone areas (Nurfikasari and Yuliani, 2022). Land suitability analysis for settlements can be conducted using spatial analysis methods with overlay tools. The overlay method is a spatial analysis technique that combines multiple spatial elements into a new spatial element (Larasati et al., 2017). This technique aims to assess how existing settlements align with disaster-prone zones. The analysis flowchart is shown in Figure 2.

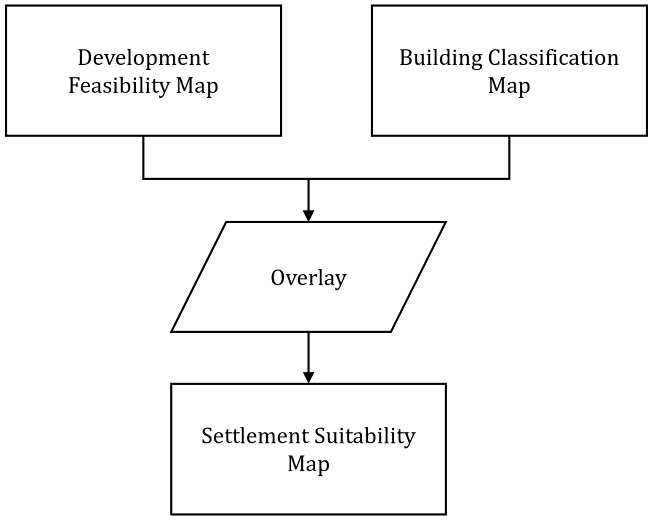

Figure 2 Flowchart Showing the Spatial Analysis of Settlement Suitability.

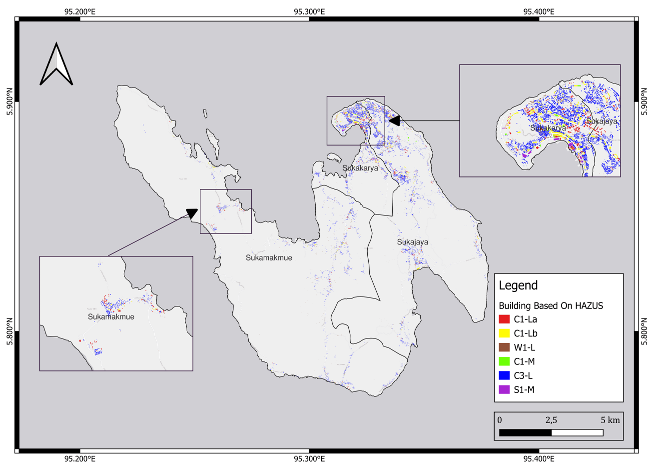

Figure 3 Building Classification in Sabang City Based on HAZUS.

3 RESULTS

3.1 Building Distribution

Based on the building survey and classification conducted in the second half of 2023, in collaboration with Aceh Development and Planning Agency (Bappeda), the Tsunami Disaster Mitigation Research Center (TMDRC) conducted a typical building survey on Sabang Island. Building footprints were digitized using Quantum GIS (QGIS) software to calculate building areas from satellite imagery. Each digitized building was classified based on typical building types from HAZUS (FEMA, 2015). Six typical types—C1-La, C1-Lb, C3-L, C1-M, S1-M, and W1-L—were adapted and modified based on the building types found in Sabang. The building distribution in Sabang City in 2023 is shown in Figure 3.

The total number of buildings identified in Sabang City was 14,104 units, with varied classifications. Buildings of type C3-L dominated over 80% of the total data, amounting to 11,369 units. One-story reinforced concrete buildings (C1-La) and two-story reinforced concrete buildings (C1-Lb) were 825 and 841 units, respectively. Reinforced concrete buildings with three or more storeys (C1-M) accounted for 40 units. Steel frame buildings (S1-M) had the fewest units at 19. Finally, wooden frame buildings (W1-L) accounted for 1,010 units. A summary of typical building data for Sabang City is shown in Figure 4

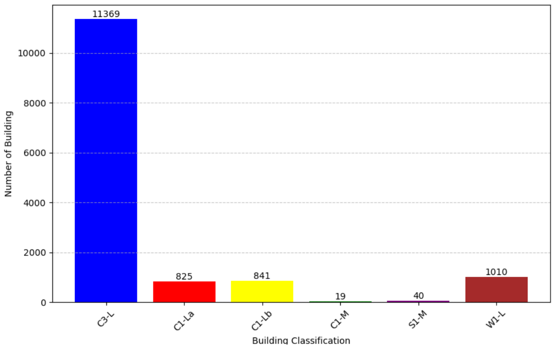

Figure 4 Number of Buildings in Sabang as in the 2023 survey based on HAZUS classification.

3.2 Probabilistic Tsunami Inundation

The 2004 Aceh tsunami originated from the Aceh-Andaman Megathrust segment and was analyzed with a recurrence interval using the PTHA formula. Based on the analysis of Probabilistic Tsunami Hazard Assessment (PTHA), the probabilistic tsunami inundation height for 250, 500, and 1000-year recurrence periods was simulated by the TDMRC USK team (Syamsidik et al., 2023). The tsunami inundation for the 500-year recurrence period, which reached a run-up of 14.5 meters along the Banda Aceh coast and parts of Aceh Besar, was used as the main input variable for land development capability weighting in Sabang. The 500-year recurrence tsunami inundation map is shown in Figure 5.

3.3 Land Development Capability

Land capability refers to an area's capacity or potential to support various uses or activities (Laiko, 2010). The land development capability map shows the land suitability and limiting zones consisting of protected areas and setback zones. The levels of land development capability are divided into three categories: low, medium, and high. The spatial analysis results for Sabang are shown in Table 5.

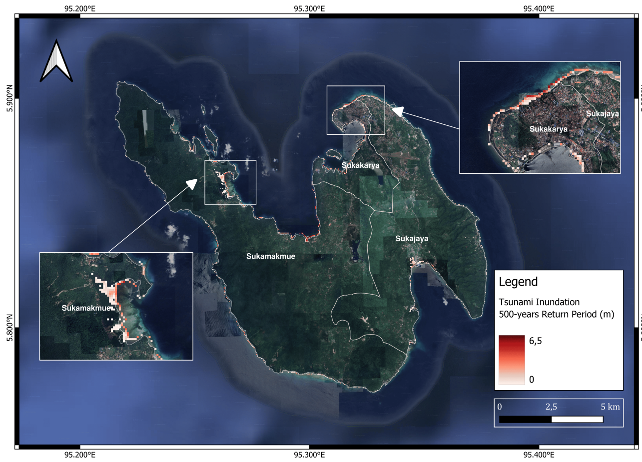

Figure 5 Tsunami inundation map for a 500-year return period in Aceh Province.

Sabang had 9,851.03 hectares of land with low development capability, 9.62 hectares with medium capability, and 2,599.25 hectares with high capability. Protected areas and coastal and river setback zones dominated the development feasibility. As a small island, Sabang faced development constraints due to the dominance of protected forest areas and coastal setback lines. Additionally, the predominantly mountainous and hilly topography, characterized by steep slopes, further limited land development for settlements to 2,599.25 hectares. However, based on tsunami inundation modeling for a 500-year return period, the maximum inundation distance was approximately 200 meters from the coastline, indicating that the designated settlement areas were outside the tsunami hazard zone and were considered safe for development.

3.4 Settlement Suitability and Spatial Planning

Settlement suitability with spatial planning indicates the extent to which existing settlements align with land capability levels. Land capability is determined by examining physical environmental conditions and disaster vulnerability. This analysis aims to determine the suitability of existing settlement buildings with respect land capability. The distribution of building data based on land suitability can be seen in Table 6.

Table 5. Area Size by Capability Level, Limiting Factors, and Development Feasibility

District/City	Land Suitability (ha)			Exclusion Zone (ha)		Development Flexibility (ha)		
	High	Medium	Low	Separator	Non-Separator	High	Medium	Low
Sabang	11,605.71	53.34	1.48	9,849.86	2,651.47	2,599.25	9.62	9,851.03

Table 6. Building distribution by land suitability level

District/City	Class	C1-La	C1-Lb	C1-M	C3-L	S1-M	W1-L	Total
Sabang	Low	378	384	2	5,248	23	701	6,726
	Medium	0	4	0	30	1	4	39
	High	447	453	17	6,091	16	305	7,329
	Total	825	841	19	11,369	40	1,010	14,104

According to the analysis results, settlement suitability in Sabang City varied due to its topographical characteristics. While a significant portion of buildings (6,726 units or 47.7% of the total units) were in areas with low development capability, the majority (7,329 units or 51.96% of the total units) were situated in high development capability zones. This finding suggested that despite the presence of buildings in less suitable areas, most settlements were still concentrated in regions with better development potential. This result is possibly influenced by several factors, including limitations in DEM data that could have depicted Sabang City's topography better. The building distribution, overlaid with land capability levels, is shown in Figure 6.

The map below shows the distribution of residential areas and building types according to land development feasibility in Sabang City, the study area for this research. The results indicated that many residential areas were in low land development capability zones. Areas with low development capability showed limited capacity to support settlement activities. Furthermore, the comparison of building types at each level of development feasibility was also provided for the study location. The existing buildings were generally located in areas with high development feasibility. However, in Sabang City, many buildings were found in areas with low development feasibility, as much of the land in Sabang was designated as protected forest and coastal setback zones. Due to the limited availability of land, many buildings have been constructed in these zones.

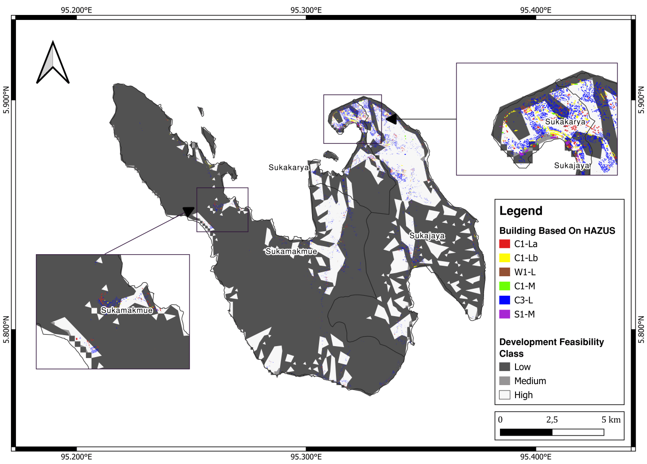

Figure 6 Building Distribution Map in Sabang City Based on Development Feasibility.

4 DISCUSSION

This study revealed critical insights into land development challenges and settlement suitability in Sabang, a small island with limited land availability. Its development model must be aligned with the spatial analysis approach supported by the scientific framework informed by expert judgment, and its spatial phenomena. This study also showed that almost half (47.7%) of the total surveyed buildings were in zones with a low capacity for development. This is possibly due to the island's rugged, mountainous topography, the predominance of protected forest areas, and the coastal setback zones. Geographical and environmental restraints greatly constrain land availability for sustainable development. As a result, houses, for example, have been built in inappropriate places, making them more prone to be affected by hazards such as tsunamis. Again, it raises concerns about the compliance of the development with spatial planning rules and whether the existing urban planning framework can allow population growth without endangering the environment and human life.

This study also found that 18.4% of buildings were classified into high-capability zones. Most of the land considered to be highly suitable was undeveloped, which can be attributable to competing land uses or regulatory constraints. C3-L building types dominated high and low capability zones, suggesting a pattern of need-driven construction across existing land use that lacks alignment with land development feasibility. The limited medium-capability zones of only 9.62 hectares signaled the island's persistent struggle between urbanism and nature (Ahmeti and Üstündağ, 2022). The resolution of the Digital Elevation Model (DEM) data used in the analysis, among other factors, might affect the accuracy of the suitability classifications, indicating possible improvements in data quality for future studies. In the case of a 500-year tsunami return period, the maximum tsunami inundation could reach about 200 m from the coastline. This will affect 124 buildings around the coast. Compared to the other 13,980 buildings that will be exempted from the impacts; therefore, the area will be relatively safe for inland ward development.

Based on these results, it is important to consider strategic interventions for sustainable development in Sabang, where tsunami mitigation is one of the essential issues. Policymakers should focus on moving settlements away from the low-capability landscape and the Highly Protected Zone. This can also include incentivizing sustainable land use, updating spatial planning guidelines, and integrating disaster risk assessments into urban planning processes. The resilience of the settlements in the vulnerable areas must also be improved, especially through better infrastructure and community-based disaster preparedness projects. Longer-term solutions for development on the island should consider balancing the development of the island with the protection of naturally preserved areas. This would ensure that growth will not come at the expense of the region's ecological preservation. These reinforce an imminent need for data-driven planning and policymaking to address the competing pressures of urban development in small islands such as Sabang. No generic solution is available for small island contexts (Dominey-Howes and Goff, 2013). This implies that specific and further studies are needed to explore concrete measures to mitigate the impact of future tsunamis for Sabang.

5 CONCLUSION

Based on the data analysis presented, it can be concluded that residential areas in Sabang show a mismatch in the development of settlements on land classified as having low and medium capability. This is due to several factors, including the dominance of mountainous and hilly areas, which influence the limiting variables in the analysis. Efforts to preserve biodiversity, such as protected forests and traditional natural resources, often hinder the potential for more extensive economic development. As a result, the region struggles with environmental conservation and efforts to improve living standards through economic development. One potential solution to address tsunami mitigation in coastal areas, especially in Sabang, is implementing the co-benefits structure approach, which involves modifying existing buildings to serve as tsunami evacuation sites. This approach aligns with Qanun Aceh No. 19 of 2013, which outlines the Aceh government's efforts to minimize disaster risk and improve disaster mitigation strategies.

DISCLAIMER

The authors declare no conflict of interest.

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