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Roughness Ecosystem-based Approach to Estimate the Exposure Area of Tsunami on a Coastal City: A Case Study in Bengkulu City, Indonesia

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***Abstract*— Bengkulu City, as the main activity center in Bengkulu Province, is experiencing significant population growth. However, geographically, the city is vulnerable to tsunami disasters. High population growth outside the line with coastal area management also increases the risk of tsunami disasters in Bengkulu City due to green land conversion into built-up land. This condition is exacerbated by coastal abrasion that threatens the coastline, brings residential settlements closer to the shoreline, and conflicts over spatial utilization of the coastal green belt. Therefore, implementing tsunami mitigation measures, mainly through coastal ecosystem-based strategies, is crucial. This study compares the spatial modeling of tsunami inundation in Bengkulu City with three roughness scenarios of coastal vegetation: coastal forest and mangrove. These scenarios include a scenario without coastal vegetation, a scenario based on existing conditions, and a scenario with optimized coastal vegetation. Spatial modeling was conducted using cost distance analysis modeling to calculate the effectiveness of coastal vegetation in reducing tsunamis. The results showed that coastal forests and mangroves in existing conditions could effectively reduce tsunamis by 3.84% compared to land cover without coastal forests and mangroves. The coastal vegetation optimization scenario has effectively reduced the exposure area by 5.00% compared to that without vegetation. The coastal vegetation optimization scenario also has an effectiveness of 1.20% compared to the existing condition. The findings underscore the critical role of coastal vegetation as a natural barrier against tsunamis and emphasize the potential advantages of optimizing land cover to improve coastal protection.**

***Keywords*—Ecosystem-based; coastal forest; mangrove; roughness; spatial modeling; tsunami inundation.**

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I. INTRODUCTION

Globally, coastal areas face an increasing threat of natural disasters, one of which is the tsunami [1]. Many efforts have been made to protect coastal areas. Initially, coastal protection mainly focused on developing grey infrastructure, such as dikes and concrete walls [2]. However, grey infrastructure tends to have limitations regarding effectiveness, cost, and environmental impact [3], [4]. The 2011 earthquake and tsunami in Tohoku, Japan, demonstrated the ineffectiveness of grey infrastructure [5]. While solid structures can protect coastal areas, they often cause damage to local ecosystems and can even generate new risks where they are not intended [6]. Grey infrastructure seeks to protect communities from disaster impacts, but it cannot address the fundamental causes and factors contributing to hazards, vulnerability, and exposures [4]

On the other hand, green infrastructure has emerged as a promising alternative by leveraging ecosystem services for disaster mitigation, known as Ecosystem-based Disaster Risk Reduction [7], [8]. This concept has been incorporated into several frameworks in sustainable development, including (1) The Ramsar Convention on Wetlands in 1972 and The Convention of Biological Diversity; (2) The Sendai Framework for Disaster Risk Reduction (2015-2030); (3) The Paris Agreement on Climate Change, and (4) the Sustainable Development Goals (SDGs). The number of Nature-based Solutions (NbS) interventions driven by international policy processes such as the United Nations Framework Convention on Climate Change (UNFCCC) Conference of Parties (COP) is increasing exponentially, where large amounts of funding are not only pledged by both public and private entities for NbS but also by government regulations [9]. Ecosystems provide valuable services in reducing the risks of disasters through various pathways, which are increasingly recognized as sustainable strategies for disaster management [10]. Coastal vegetation provides essential ecosystem services to prevent the adverse impacts of tsunamis. Vegetation buffers are valuable methods that reduce wave energy associated with destructiveness and control floating debris accumulation [11]. Coastal vegetation such as mangroves, coastal forests, dense trees, and stemmed plants can help slow down and amplify tsunami waves before they reach land [12], [13]. Mangroves reduce the impact of tsunamis in two ways: water velocity is reduced due to friction with dense mangrove forests, and the volume of water from tsunami waves reaching land is reduced because the water is dispersed into many channels in the mangrove ecosystem [14]. Design and management of planned networks of natural and seminatural areas are equipped with environmental features to deliver a wide range of ecosystem services [2].

This is in line with a study conducted on the structure of mangrove vegetation in Kirinda, Kalametiya, and Rekawa in Sri Lanka that withstood tsunami waves of different extents in 2004, and which was studied in detail to determine the wave-damping function of mangrove vegetation. The study found that tsunami run-up height and tsunami inundation distance were negatively correlated with tree volume, forest width, and tree height while positively correlated with mangrove vegetation porosity [15]. Apart from mangroves, the simulation results of tsunami wave forces on the length function of the Coastal Pine Forest model indicate that as the Coastal Pine model becomes longer, the optimal decrease in tsunami forces occurs when the waves hit the canopy [16].

Coastal vegetation also plays a role in maintaining soil stability and fortifying the shoreline [17]. This can help prevent coastal erosion and ensure the land remains stable during and after a tsunami. Coastal vegetation also plays a vital role in preventing adverse impacts from tsunamis and helps maintain the stability of coastal ecosystems [18], [19]. Coastal vegetation provides a physical barrier that helps reduce the speed and intensity of waves, thereby reducing the risk of damage to buildings and loss of life [20], [21]. This was evident in the 2006 Pangandaran tsunami, where areas lacking coastal vegetation were devastated, whereas vegetated areas experienced only minor damage from the 4-5 meter tsunami [22].

Research was also conducted in the coastal forest of Pananjung Nature Reserve with a vegetation density of > 2000 individuals/ha, an average tree diameter of 15.94 cm, and a width of coastal forest between 120 and 325 m. The height of the coastal forest of Pananjung Nature Reserve is undulating between 0-59 m above sea level. Pananjung Nature Reserve coastal forest elevation is 0 and 59 m above sea level. The modeling results show that the effectiveness of the Pananjung Nature Reserve coastal forest as a buffer in reducing tsunami energy has a reduction value of 41.18%, so it belongs to the effective category [23]. Similarly, a subsequent study conducted spatial modeling that considered existing land cover conditions showed an affected area of 3,231 hectares, which represents approximately 4.64% of the total area of Padang city. However, modifying the land cover based on ecological land suitability, including converting shrubs and bare land, reduced the affected coastal area to 2,839 hectares. This represents a reduction of 0.56% and corresponds to 4.08% of the total area of Padang City [24]. A related study also explored how Pacitan Bay, Indonesia's coastal vegetation, can help mitigate tsunamis. The study used simulations and field data to evaluate how coastal vegetation reduces tsunami wave energy and improves coastal resilience. The findings emphasize the role of coastal vegetation in reducing tsunami impacts, as larger areas of forest and denser vegetation result in more effective wave reduction [25].

Referring to these previous studies, applying ecosystem-based disaster risk reduction is essential to optimize NbS's effectiveness in dealing with tsunamis. Natural-based solutions are actions to protect, sustainably manage, and restore natural or modified ecosystems to address societal challenges such as tsunami disaster risk effectively and adaptively while simultaneously benefiting human well-being and biodiversity [1]. The need to implement ecosystem-based disaster risk reduction is increasingly urgent as ecosystems are increasingly subjected to multiple interests, such as population and economic pressures that reduce the capacity of ecosystems to deliver their services. At the same time, the potential tsunami hazard does not decrease [26]. This is suspected to be the case in Bengkulu City, which is geographically and geologically vulnerable to tsunami hazards [27], [28]. However, the green land of coastal vegetation, the first shield for tsunamis, is experiencing a downward trend [29].

Bengkulu City is one of the areas that has a high potential for earthquakes and tsunamis because its location is right above the subduction zone of the Indo-Australian plate with the Eurasian plate [30]. The city has the potential to be struck by earthquakes and tsunamis that can have a significant impact on population and infrastructure [31], [32]. Earthquakes have been identified as the central issue in Bengkulu City for the last two decades [33]. The earthquake’s damage can be defined as a scale of VIII to X. The prediction of damage intensity level is generally consistent with field evidence found during the earthquake [28]. The potential for such disasters is higher in Bengkulu Province than in West Sumatra Province [31]. Then, the high population growth that is not in line with coastal area management can result in land conversion from green to built-up, increasing the risk of disaster [18], [29]. This condition is exacerbated by coastal abrasion, which threatens the coastline and brings residential settlements closer to the shoreline, particularly in the coastal area of Bengkulu, where deeper waters and larger currents and waves from the Indonesian Ocean make it more prone to abrasion, and conflicts over spatial utilization in the coastal green belt hinder sustainable management [28], [34], [35]. Given these conditions, an ecosystem-based tsunami risk reduction study in Bengkulu City is necessary for the tsunami mitigation effort.

This research compares the spatial modeling of tsunami inundation in Bengkulu City with three scenarios of coastal vegetation in coastal forests and mangroves. These scenarios include a scenario without coastal vegetation, based on existing conditions, and with coastal vegetation optimization. The scenario without coastal vegetation is modifying coastal forest and mangrove land cover into open land. The scenario based on existing conditions uses the land cover of Bengkulu City in 2023 without being modified. The scenario with coastal vegetation optimization involves modifying existing land covers, such as shrubs and open land, into coastal forests and mangroves based on the suitability of coastal forests and mangroves in the coastal area of Bengkulu City [24]. This study compares these three models to assess how land cover changes, such as coastal forests and mangroves, can effectively reduce tsunami inundation.

II. Materials and Methods

A. Description of the Study Sites

This research was conducted in Bengkulu City, based on the high potential for tsunamis based on historical tsunami data and previous research. In addition, Bengkulu City is also the center of activity with the largest population in Bengkulu Province. This means that the potential number of people exposed in Bengkulu City is more significant than in other districts. Bengkulu City is astronomically located at 3° 43' 37" Latitude South to 3° 56' 41" Latitude South and 102° 14' 49" Longitude East to 102° 24' 21" Longitude East. Administratively, Bengkulu City consists of 9 sub-districts, of which six sub-districts are coastal areas, as shown in Figure 1. Bengkulu City is directly adjacent to the Indian Ocean, so most of the area of Bengkulu City is a coastal area with low elevation. This is in line with the slope of Bengkulu City, which is dominated by the low slope class that is evenly distributed in all sub-districts in Bengkulu City.

B. Data Collection and Analysis

The research began with the study and deepening of the theory conducted through literature studies (books, journals, proceedings, modules, and other scientific works) and institutional studies (reports, databases, and websites). First, the slope variable was obtained from the processing of DEM NAS 0912-11, DEM NAS 0912-12, DEM NAS 0912-13, and DEM NAS 0912-14 collected from the Geospatial Information Agency. DEM NAS is built from several data sources, including IFSAR (5m resolution), TERRASAR-X (5m resampling resolution from the original 5-10m resolution), and ALOS PALSAR (11.25m resolution) data, by adding mass point data used in the creation of the Indonesian Rupa Bumi Indonesia map (RBI). The spatial resolution of DEMNAS is 0.27-arcsecond, using the EGM2008 vertical datum. These DEM NAS were then processed into slope data with degree units.

Secondly, land cover data processing involves two main stages, namely pre-processing and further processing, including analysis. Pre-processing aims to make corrections to the image, both in terms of geometry and radiometry, so that the image has an accurate geographical position by the WGS 1984 global geographical coordinate system. The result of this stage is image data ready to be analyzed and overlaid with other digital vector maps. The advanced processing stage uses the Sentinel 2A Year 2023 dataset. A cloud masking algorithm was performed to remove clouds from the image, and the pixels without clouds were integrated with the same year satellite image using a median aggregation filter. The median aggregation filter was chosen because the method is effective in avoiding cloud pixels and provides accurate results in representing the current land use/cover conditions, better than other methods such as Function of mask, Automated Cloud Cover Assessment (ACCA), linear regression, and kernel regression.

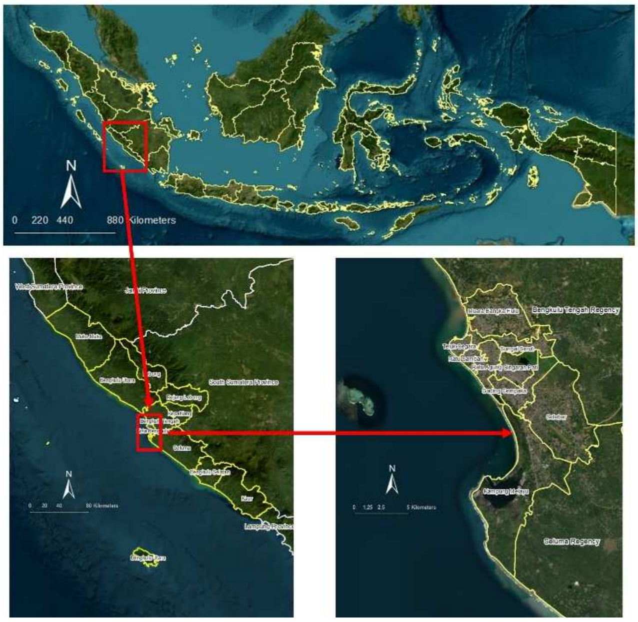


Fig. 1 Map of research location, Bengkulu City

Furthermore, the corrected raster images were interpreted using the supervised classification method using Google Earth Engine to identify 11 land cover classes, including natural forest, coastal forest, agricultural land, built-up land, open land, mangrove, sand, plantation, shrubs and ponds (Table 1). The result was checked in the field, and the image-to-image method using Google Earth was used to prove the interpretation results. This validation was carried out by random sampling of 30 points on each land cover so that, in total, there were 330 points per year of land cover. Validation data was entered to obtain an accuracy assessment. Accuracy assessment includes Confusion Matrix, User's Accuracy (UA), Producer's Accuracy (PA), Overall Accuracy (PA), and Kappa Coefficient. [36], [37], [38]. After obtaining sufficient accuracy, the land cover classes were translated into a surface roughness index (Table 1). The surface roughness index determines the amount of resistance each land cover has. The higher the index value, the higher the level of surface roughness in a land cover classification.

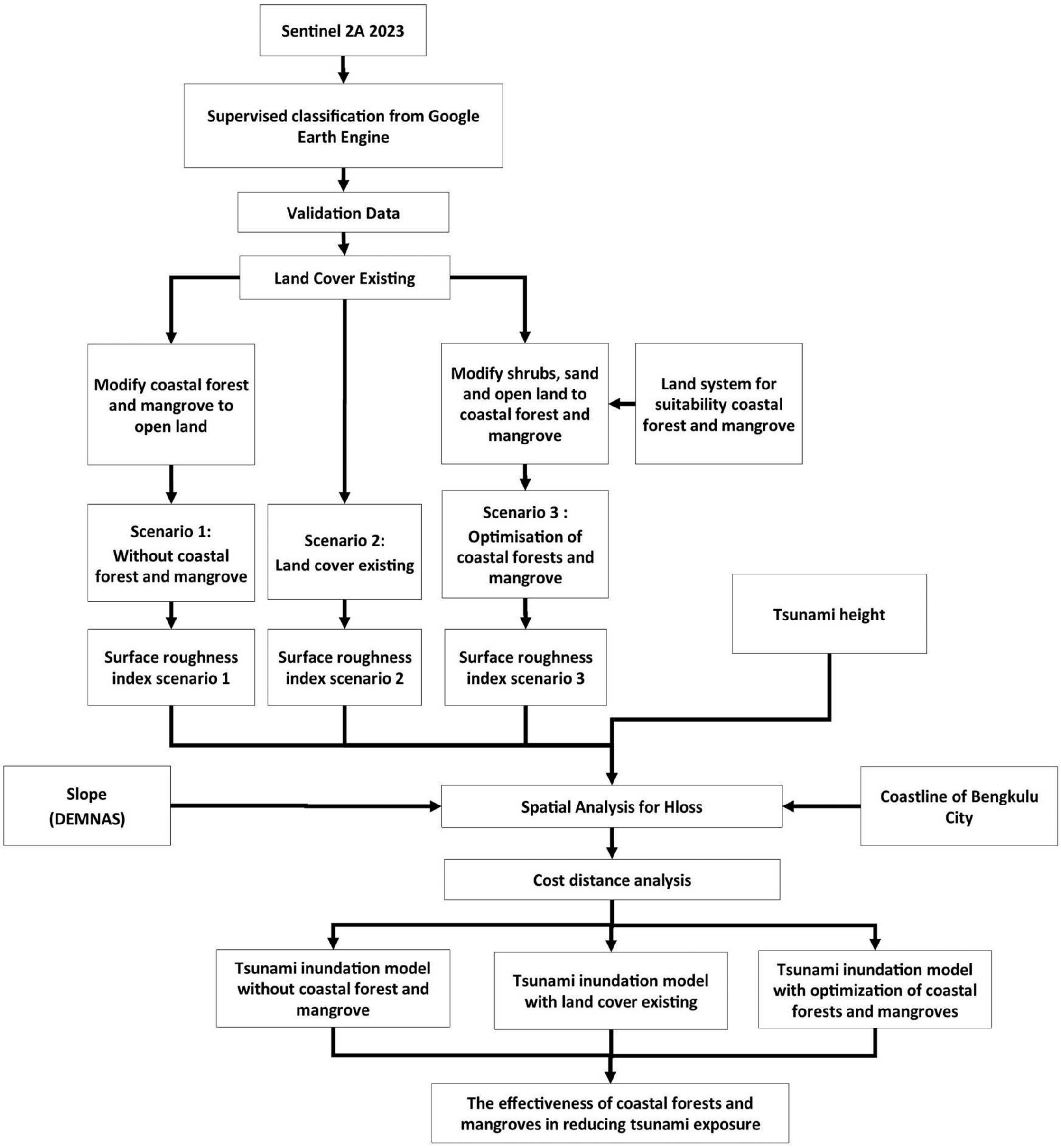


Fig. 2 Research Flowchart

Third, the tsunami height input from the coastline refers to the publication "A National Tsunami Hazard Assessment for Indonesia" by Horspool et al. [39], which used the Probabilistic Tsunami Hazard Assessment (PTHA) for all regions in Indonesia. This research took the worst-case tsunami height in Bengkulu City with the maximum tsunami height at the coast for a 2500-year return period of 21.6 meters. Fourth, the coastline is obtained by converting the Geospatial Information Agency Indonesia in 2022 boundary polygon issued into a polyline.

TABLE I
LAND COVER AND SURFACE ROUGHNESS INDEX
(NATIONAL DISASTER MANAGEMENT AUTHORITY INDONESIA, 2018)

Land Cover	Surface Roughness Index
Water Body	0.007
Natural Forest	0.070
Coastal Forest	0.070
Agricultural Land	0.025
Built-up Land	0.050
Open Land	0.015
Mangrove	0.060
Sand	0.018
Plantation	0.035
Shrubs	0.040
Pond	0.010

After preparing all the inputted data, the distribution of tsunami exposure areas was analyzed concerning tsunami modeling in the Technical Module for the Preparation of Tsunami Risk Assessments issued by the National Disaster Management Agency in 2018. The model calculates the reduction in tsunami height per meter of inundation distance, using distance to slope and surface roughness with the following equation [40], [41]:

$$\text{Hloss} = \left(\frac{167\, n^2}{{H_0}^{1/3}}\right) + 5\ Sin\ S \quad (1)$$

where Hloss = tsunami height loss per 1 m inundation height distance.

N = surface roughness index

H_0 = tsunami wave height at the shoreline (m)

S = magnitude of surface slope (degree)

In this equation, the sin value of the slope (SinS) is needed so that the degree value of the slope can be converted into radians. The conversion is done with the slope data with degree units multiplied by 0.01745 (the result of π/180). N shows the surface roughness index based on the land cover classification by converting the type of land cover data from vector to raster with the exact spatial resolution in the satellite image processing of 30 meters. The modeling uses three scenarios. Scenario 1, without coastal vegetation, involves changing land cover, where coastal forests and mangroves are converted to open land. Scenario 2, based on existing conditions, uses 2023 Bengkulu City land cover data without modification. Scenario 3 with coastal vegetation optimization involves modifying the existing land cover, such as converting shrubs, sand, and open land to coastal forests and mangroves. Scenario three is adjusted to the land system, which consists of geomorphological and geological information suitable for developing coastal forests and mangroves.

The three scenarios selected for analysis, without coastal vegetation, existing conditions, and optimized coastal vegetation—provide vital insights into coastal management strategies, especially concerning mitigating damage and loss during a tsunami. The "without coastal vegetation" scenario serves as a critical baseline to understand the natural dynamics of the coastal area without any vegetative protection. This scenario allows us to quantify the full impact of a tsunami when there is no natural barrier to mitigate its force, often resulting in extensive damage to infrastructure, significant loss of life, and severe economic impacts due to the unchecked energy of the waves crashing onto the shore. The "existing conditions" scenario represents the current state of coastal vegetation, offering a realistic assessment of its effectiveness in reducing tsunami damage. In this scenario, the existing vegetation provides some level of protection, helping to reduce wave energy and the extent of inundation. Consequently, the damage and loss in this scenario are less severe than in the first scenario but still significant, as the existing vegetation might not be optimally placed or dense enough to provide complete protection.

The "optimized coastal vegetation" scenario explores the potential benefits of enhancing the coastal greenbelt. This scenario demonstrates the maximum potential of nature-based solutions in tsunami protection. An optimized greenbelt, with increased density and strategic vegetation placement, can significantly reduce the force of incoming tsunami waves by acting as a natural barrier that absorbs and deflects wave energy, thereby minimizing structural damage and loss of life. In this scenario, the damage and loss are substantially reduced compared to the other two scenarios, showcasing the effectiveness of a well-designed vegetative barrier in protecting coastal communities. By examining these three scenarios, we can understand the critical role of coastal vegetation, particularly greenbelts, in tsunami mitigation.

Furthermore, H_0 represents the maximum tsunami wave potential based on the worst-case scenario of a tsunami height of 21.6 meters. The Hloss value is required to calculate the Cost Distance for the exposure area limited by the maximum run-up point. Shoreline data were inputted as the initial boundary of the Cost Distance measurement. The Cost Distance value is the coverage value of tsunami waves reaching the run-up point based on the Hloss result. The exposure area is obtained from the maximum tsunami wave potential value in Bengkulu City minus the Cost Distance result. The value of the exposure area decreases further away from the coast following the three land cover scenarios developed. The effectiveness of coastal forests and mangroves was then calculated using the following equation (modified from [42]).

$$Effectiveness\ (\%) = 100\% - \frac{h_1}{h_0} \times 100\% \quad (2)$$

Where h_1 = tsunami inundation area with a larger area of coastal forest and mangroves. h_0 = tsunami inundation area with less coastal forest and mangrove area

III. Results and Discussion

Before entering the land cover scenario, the accuracy test of the existing land cover classification in 2023 was carried out by random sampling of 30 points for each land cover class. This means that there were 330 points for data validation through field observations and Google Earth. The accuracy and kappa values obtained were 88.63% and 0.86, respectively. The overall accuracy value of 88,63% indicated that 11.37% was a classification error. Errors in the image classification results occur if the area is classified in the wrong class (commission error) and if an area is not classified in the correct class (omission error) in the field. This can be due to the limited resolution of Landsat satellite imagery, which is only 30 meters. An interpretation result can be used for analysis purposes if the level of accuracy reaches at least 80-85%. The validation test of the category of Sentinel 2A image interpretation results 2023 shows that all land cover categories have met the standard, namely the interpretation results above 85%.

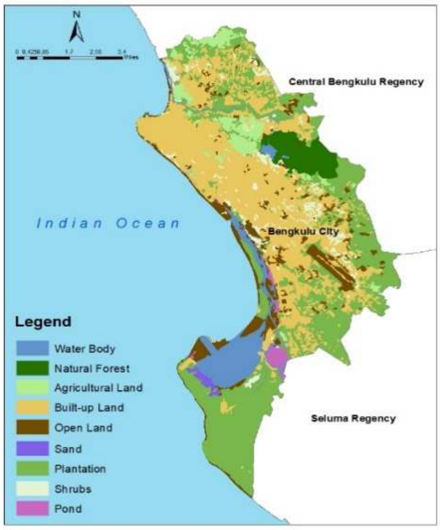
Based on the existing land cover condition in 2023, it is known that the area of coastal forest is 365.77 ha and mangrove is 170.44 ha. These coastal forests and mangroves are scattered along the coast of Bengkulu City, with most of the area spread in the Panjang Beach and Baai Island Natural Tourism Park areas. Based on The Inventory of the Potential of the Nature Park Pantai Panjang and Pulau Baai Areas of Bengkulu City published by the Bengkulu Natural Resources Conservation Centre (BKSDA) in 2021, Bengkulu City consists of several types of coastal plants, such as *Casuarina equisetifolia, Calophyllum inophyllum, Barringtonia asiatica, Hibiscus tiliaceus, Cerbera manghas, Morinda citrifolia,* and *Terminalia catappa*. In addition, exotic plants such as Acacia sp are found [43]. Meanwhile, mangrove forests consist of several mangrove species, including *Acanthus ilicifolius, Acanthaceae jeruju, Avicennia alba, Avicennia marina, Bruguiera gymnorhiza, Rhizophoraceae putut, Excoecaria agallocha, Nypha frutican, Rhizophora mucronata, Rhizophora stylosa, Rhizophora apiculata, Sonneratia alba,* and *Sonneratia caseolaris* [35], [43]. This existing land cover condition is scenario 2 in the surface roughness index input for tsunami modeling.

TABLE II
LAND COVER OF BENGKULU CITY IN EACH SCENARIO

Land Cover	Scenario 1	Scenario 2	Scenario 3
Water Body	1089.52	1089.52	1089.52
Natural Forest	636.67	636.67	636.67
Coastal Forest	0.00	365.77	525.80
Agricultural Land	700.76	700.76	701.12
Built-up Land	5952.32	5952.32	5952.32
Open Land	1244.90	708.69	646.36
Mangrove	0.00	170.44	347,32
Sand	82.49	82.49	0.00
Plantation	5339.11	5339.11	5339.11
Shrubs	577.63	577.63	385.55
Pond	170.77	170.77	170.77
Total	15794.18	15794.18	15794.18

Scenario 1, the land cover without mangroves and coastal forests, was modified from the existing land cover in 2023, where coastal forests and mangroves were converted to open land. Under this scenario, the existing open land cover of 708.69 ha was changed to 1244.90 ha (Table 2). Scenario 3 involves changes to the existing land cover to increase coastal vegetation, such as converting open land, shrubs, and sand into coastal forests and mangroves. This scenario is based on adjustments to the land system that consider information on geomorphology and geology that support the growth of coastal forests and mangroves. In this scenario, land modification aims to enhance natural coastal protection and cushion the potential impacts of events such as tsunamis. In this scenario, coastal forest land cover increased by 160.03 ha from existing conditions to 525.80 ha. At the same time, mangrove land cover increased by 176,88 ha from existing conditions to 347,32 ha (Table 2). Most of this coastal forest and mangrove optimization can be carried out in the central to southern parts of Bengkulu City. In contrast, the northern part of Bengkulu City is already very densely developed, so little land cover can be optimized into coastal forests and mangroves (Figure 3).

In the face of tsunami threats, coastal vegetation, especially coastal forests and mangroves, is one of the critical strategies to reduce the risk and impact of natural disasters. Analysis of data from three different scenarios - tsunami inundation without coastal forests and mangroves (Scenario 1), tsunami inundation under existing conditions (Scenario 2), and tsunami inundation with optimized coastal forests and mangroves (Scenario 3) - provides an overview of the effectiveness of coastal forests and mangroves in each scenario in reducing the area of tsunami exposure. In each scenario, 7 out of 9 sub-districts in Bengkulu City were affected by tsunami exposure. The sub-districts affected by tsunami exposure include Gading Cempaka sub-district, Kampung Melayu sub-district, Muara Bangka Hulu sub-district, Ratu Agung sub-district, Ratu Samban sub-district, Sungai Serutsub-district, and Teluk Segara sub-district. In contrast, the two sub-districts unaffected by tsunami exposure in the three scenario models are the Singaran Pati sub-district and the Selebar sub-district.

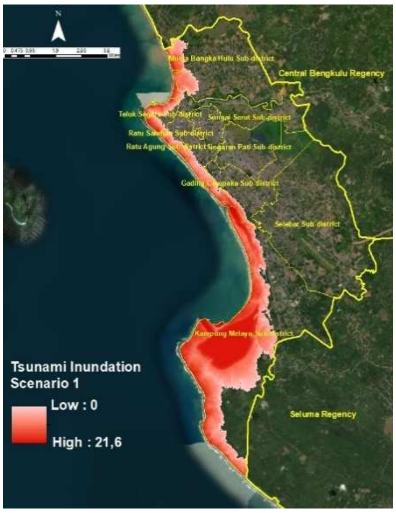


Scenario 1: Land cover without coastal forest and mangrove

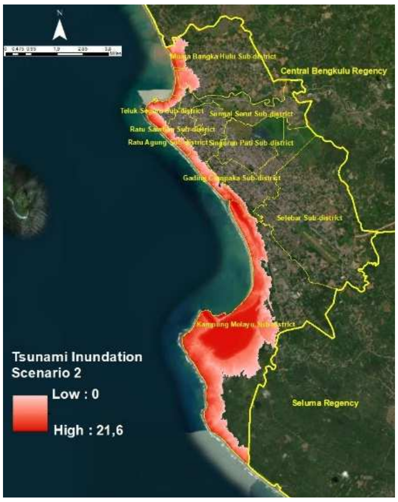
Scenario 2: Land cover existing (2023)

Scenario 3: Land cover with optimized coastal forest and mangrove

Fig. 3 Land Cover of Bengkulu City in Each Scenario



Scenario 1: Land cover without coastal forest and mangrove



Scenario 2: Land cover existing (2023)

Scenario 3: Land cover with optimized of coastal forest and mangrove

Fig. 4 Tsunami Inundation Each Scenario

In Scenario 1, where there is no tsunami buffering vegetation in the form of coastal forests and mangroves, the total tsunami area reaches 3,982.55 km² or 25.22% of the total area of Bengkulu City. Bengkulu City faces considerable consequences without this natural protection, and tsunami exposure is evenly distributed throughout its coastal areas. In this scenario, the Kampung Melayu sub-district is the most significantly affected, followed by the Muara Bangka Hulu sub-district. The Kampung Melayu sub-district mostly has land cover from water bodies with a low surface roughness index.

Scenario 2 represents the existing conditions; Table 3 shows that the total tsunami exposure area in the scenario is 3829.51 ha or 24.24% of the total area of Bengkulu City. The most significant change in the reduced area can be seen in Kampung Melayu Sub-district, which initially had a tsunami exposure area of 2993.99 ha, reduced by 97.39 ha to 2896.60 ha. Compared to scenario 1, without coastal forest and mangrove vegetation, scenario 2 can reduce the tsunami by 153.04 ha. The effectiveness of coastal forest and mangroves in scenario 2 can reduce the tsunami by 3.84% compared to scenario 1, with land cover without coastal forest and mangroves.

TABLE III
DISTRIBUTION OF TSUNAMI EXPOSURE AREA IN EACH AFFECTED SUB-DISTRICT UNDER EACH SCENARIO

Sub-district	Scenario 1:	Scenario 2:	Scenario 3:
Gading Cempaka	82.06	75.50	74.62
Kampung Melayu	2993.99	2896.60	2861.65
Muara Bangka Hulu	305.96	284.18	276.99
Ratu Agung	223.09	211.68	210.76
Ratu Samban	112.62	106.08	104.22
Sungai Serut	67.28	64.74	64.59
Teluk Segara	197.55	190.73	190.65
Total	3982.55	3829.51	3783.49

Remarks:
Scenario 1: Tsunami inundation without coastal forest and mangroves (ha).
Scenario 2: Tsunami inundation with existing conditions (ha).
Scenario 3: Tsunami inundation with optimized coastal forest and mangroves (ha)

Scenario 3, which involves optimizing coastal forests and mangroves, has a tsunami exposure area of 3783.49 ha, or 23.95% of Bengkulu City. Scenario 3 was then compared with the results of scenarios 1 and 2 to see how effectively optimizing coastal forests and mangroves reduced the tsunami exposure area. Compared to scenario 1 (without coastal forest and mangroves), this optimization can reduce the area of tsunami exposure by 199.06 ha. Scenario 3 effectively reduces the exposure area by 5.00% compared to scenario 1.

Similar to scenario 2, in scenario 3, the highest area change was in the Kampung Melayu sub-district, from the original tsunami exposure area of 2993.99 ha in scenario 1, reduced by 132.34 ha to 2861.65 ha. Scenario 3 of coastal forest and mangrove optimization was then compared with scenario 2, the existing condition, and it was found that scenario 3 could reduce the tsunami exposure area by 46.02 ha. Scenario 3 has an effectiveness of 1.20% compared to scenario 2.

The presence and condition of coastal forests and mangroves significantly influence the roughness of coastal landscapes, thereby impacting their ability to mitigate the impact of tsunamis. In Scenario 1, where coastal forests and mangroves are absent, the landscape lacks natural barriers to dissipate wave energy, resulting in a smoother coastline with lower roughness. This absence of roughness elements exacerbates Bengkulu City's vulnerability to tsunamis, as there are no features to impede the flow of incoming waves and reduce their force.

Conversely, in Scenario 2, where existing coastal forests and mangroves are maintained, the roughness of the coastal landscape is increased due to the presence of vegetation. Coastal forests and mangroves act as roughness elements that obstruct the flow of tsunami waves, reducing their velocity and height as they move inland. This increased roughness enhances coastal resilience by dissipating wave energy and stabilizing coastal sediments, thereby reducing the extent of tsunami inundation and associated damage.

In Scenario 3, where coastal forests and mangroves are optimized through restoration and land-use planning, the roughness of the coastal landscape is further enhanced. The roughness elements are optimized by strategically planting and restoring coastal vegetation to maximize their protective functions against tsunamis. This optimized roughness effectively reduces the tsunami exposure area beyond what is achieved in Scenario 2, highlighting the importance of actively managing and enhancing coastal forests and mangroves to minimize the impact of tsunamis. Both mangroves and coastal forests effectively mitigate tsunami impacts, each thriving in different substrates. Mangroves generally develop well in muddy substrates, where their complex root systems can effectively absorb and dissipate wave energy. On the other hand, coastal forests thrive in sandy substrates, where species like Casuarina and Pandanus can thrive and provide significant protection against waves and erosion.

The research conducted in Bengkulu City serves as an initial study, demonstrating the crucial role of coastal vegetation, including coastal forests and mangroves, in mitigating the impact of tsunami waves. These findings are highly relevant for application in other coastal areas across Indonesia that encounter similar geomorphological and environmental conditions and face significant tsunami risks.

Establishing and maintaining coastal vegetation belts, including mangroves and coastal forests, should be considered an essential component of disaster risk reduction strategies. Policymakers are encouraged to integrate coastal vegetation management into local and regional planning frameworks, ensuring these natural barriers are preserved and restored where necessary. Promoting reforestation and afforestation efforts is crucial to further enhancing coastal vegetation, as local communities are involved in planting and maintaining these ecosystems.

Moreover, the benefits of eco-DRR (ecosystem-based disaster risk reduction) extend beyond the immediate reduction of tsunami energy. When tsunamis are not occurring, coastal ecosystems provide a wide range of valuable ecosystem services that benefit the environment and human communities. These services include habitat provision for various terrestrial and aquatic species, erosion control, pollutant trapping, carbon storage, and the provision of different food resources (provisioning services). By maintaining healthy coastal ecosystems, local communities enhance their resilience to tsunamis and secure multiple environmental and economic benefits.

The results of this study can be a starting point for further research. The limitation of this research is that it relies on the existing data and has yet to incorporate temporal analysis. For effective long-term planning, examining the trends in coastal vegetation changes with time series data is essential to identify patterns and potential threats. Future studies need to include a comprehensive analysis of ecological aspects of coastal vegetation, such as forest width, tree diameter, tree density, tree height, species composition, and habitat quality, to provide a more detailed understanding of the factors affecting coastal vegetation.

It is also necessary to analyze economic sustainability in the context of coastal forest and mangrove management. It is also essential to analyze economic sustainability in the context of coastal forest and mangrove management. Assessing the economic impacts of investments in coastal vegetation can be crucial in building the case for sustainable policies and practices. Questions such as how to engage local communities in the sustainable use of natural resources and how to support local economies through these practices are essential aspects to be further explored.

In developing ecosystem-based disaster mitigation strategies, it is also necessary to consider adaptation to climate change that may affect coastal vegetation dynamics. Increased storm intensity or sea level changes may require mitigation planning and implementation adjustments. Therefore, further research can investigate how coastal vegetation can be integrated into adaptation strategies to climate change in coastal areas. Equally important, the active involvement of communities and local policymakers in decision-making related to coastal vegetation management should be considered in future research. Understanding the dynamics of community participation can provide valuable insights for designing more effective and sustainable policies. Understanding local perceptions, values, and knowledge can shape community attitudes and actions toward coastal forest and mangrove conservation and restoration. It is also important to consider policies and institutions in coastal management.

Furthermore, this research can be developed into a sustainable blue financing model. Funds previously allocated for disaster recovery can be diverted to other interests that support regional sustainable development. Sustainable Impact Bond provides incentives to reduce disaster risk and encourages sustainable development that considers social and environmental values while creating sustainable financial opportunities for the regions involved. The Blue Insurance model combines disaster risk mitigation with environmental conservation through economic incentives such as tax deductions. The model proposes an insurance premium formula and determining benefits through reduced tax deductions and carbon investments for investors based on the amount of coastal vegetation planted and maintained. Considering these elements, further research can provide holistic guidance in developing sustainable and ecosystem-based disaster mitigation strategies. Thus, involving these aspects can result in more significant positive impacts in maintaining environmental sustainability and minimizing disaster risks in coastal areas.

IV. Conclusion

This study highlights the critical role of coastal forests and mangroves in mitigating the impact of tsunamis in Bengkulu City. The three scenarios' analysis showed that coastal vegetation and optimization significantly reduce tsunami exposure compared to scenarios without coastal forests, mangroves, and existing conditions. Scenario 3, which involves the strategic optimization of coastal forests and mangroves, demonstrates the highest effectiveness in reducing tsunami exposure, underscoring the importance of proactive management and enhancement of coastal vegetation for disaster risk reduction. The results emphasize the need for maintaining and restoring coastal forests and mangroves as natural protective barriers against tsunamis.

Furthermore, the study suggests avenues for further research, including exploring ecological parameters of coastal vegetation, analyzing economic sustainability, integrating coastal vegetation into climate change adaptation strategies, engaging local communities in decision-making, and conducting comparative analyses with similar coastal areas. Incorporating these aspects into future research efforts can provide comprehensive guidance for developing sustainable and ecosystem-based disaster mitigation strategies, ultimately contributing to maintaining environmental sustainability and minimizing disaster risks in coastal regions.

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