Coastal ecology-based management for tsunami mitigation in Padang city, West Sumatera, Indonesia

[1,2]Hendry Frananda, [2]Fredinan Yulianda, [2]Mennofatria Boer,
[3]I. Wayan Nurjaya

[1] Geography Department, Faculty of Social Science, Universitas Negeri Padang, Padang, West Sumatera, 25173, Indonesia; [2] Department of Aquatic Resources Management, Faculty of Fisheries and Marine Sciences, IPB University, Darmaga Bogor, West Java, 16680, Indonesia; [3] Department of Marine Science and Technology, Faculty of Fisheries and Marine Sciences, IPB University, Darmaga Bogor, West Java, 16680, Indonesia.
Corresponding author: H. Frananda, hendryfrananda@fis.unp.ac.id

Abstract. The western coast of Sumatra Island is highly susceptible to earthquakes, which have the potential to trigger tsunami hazards. Padang, the largest city along this coast, is particularly vulnerable to these seismic events. Therefore, it is crucial to implement tsunami mitigation measures, specifically coastal ecology-based strategies. This research aimed to compare the extent of tsunami runoff in Padang city using two different models. The first model simulated tsunami runoff based on the existing land cover conditions, while the second model optimized land cover conditions in line with coastal ecological suitability. The simulation results indicated that the model based on the current land cover conditions, predicted a tsunami inundation area spanning 3,231 hectares. However, by optimizing land cover conditions based on coastal ecology, the inundation area was reduced to 2,839 hectares. This shows the adoption of the coastal ecology-based modeling approach led to a reduction of 391 hectares in a tsunami inundation area.

Key Words: hazards, land cover, modelling, tsunami inundation.

Introduction. The coastal zone plays a crucial role in supporting coastal ecosystems, offering a wide array of direct and indirect services to humans, accompanied by significant environmental benefits (Sondak & Kaligis 2022; Yudhistira et al 2023). In tsunami-prone areas, such as the western region of Sumatra, the strategic design of the coastal belt can serve as a mitigation measure, amplifying these benefits (KKP 2012).

The western region of Sumatra is characterized by dynamic tectonic processes involving the convergence or collision of two tectonic plates comprising the Indian-Australian oceanic plate and the Eurasian continental plate (Sieh 2005). This collision leads to the subduction of the Indian-Australian plate beneath the Eurasian plate. As a consequence of these geographical conditions, the western region of Sumatra Island exhibits a significantly high potential for earthquakes and tsunami hazards (McCaughey et al 2012).

Padang, located in a geographically vulnerable position, is susceptible to earthquakes originating from the Megathrust Fault (Natawidjaja et al 2006). Historical records document two significant tsunami hazards in Padang city, occurring in 1797 and 1833 (McCaughey et al 2012). As of 2022, the city had a population of 939,112 people (BPS 2022), with an estimated 273,755 people at risk of tsunami (BNPB 2012).

Extensive research by the international scientific community consistently indicated the high risk and vulnerability of Padang city to tsunami hazards. This vulnerability stemmed primarily from its geographical location and associated conditions (Borrero et al 2006; McCloskey et al 2008; Taubenböck et al 2009). Other research predicted a series of earthquakes in the coming decades following the 8.4 magnitude earthquake in 2007 (Sieh et al 2008).

Ecosystem-based mitigation measures offer a distinct advantage in tropical and subtropical regions (Takagi 2019). Among these solutions, mangrove ecosystems and coastal vegetation play a vital role, showcasing multifaceted physical, chemical, biological, and economic functions (Chandra & Frananda 2018). Extensive research indicated the effectiveness of mangrove forests and coastal vegetation in reducing the impact of tsunami hazards, with the size and density of mangrove forests playing a significant role (Hiraishi & Harada 2003; Harada & Kawata 2005; Iimura & Tanaka 2012; Li et al 2012). Furthermore, the density of vegetation influences its ability to absorb tsunami hazards (Ohira et al 2012). Coastal vegetation and mangrove ecosystems contribute to reducing the height of tsunami waves and attenuating the energy as the waves pass through these forests and vegetation (MSSRF 2005). The presence of trees decreases the speed of tsunami waves, leading to a reduction in their volume and splitting, resulting in a significant decrease in wave magnitude upon landfall.

Further research is needed to explore the technical aspects of coastal ecosystems and their role in protecting coastal areas in Indonesia. Particularly in tropical regions, mangrove ecosystems, and coastal vegetation offer a potential alternative approach to tsunami mitigation. This research aims to compare the impacts of a tsunami event in Padang city between the current land use conditions and a coastal ecological-based system. The ecological-based method involves modifying the existing land cover, such as shrubs and vacant land, to incorporate mangrove forests or coastal vegetation based on the ecological suitability of the coastal areas. By comparing these two models, this research aims to assess how land use changes driven by coastal ecology can effectively reduce the impact of tsunami hazards.

Material and Method

Description of the research sites. This research was conducted from July to December 2022 within the administrative area of Padang city, located in West Sumatra Province. Padang city is situated on the western coast of Sumatra Island, facing the Indian Ocean. The selection of this location was based on scientific research that emphasized its high susceptibility to tsunami hazards (Muhammad et al 2017). Padang city consisted of 11 subdistricts, with 6 subdistricts directly bordering the coastline, as shown in Figure 1.

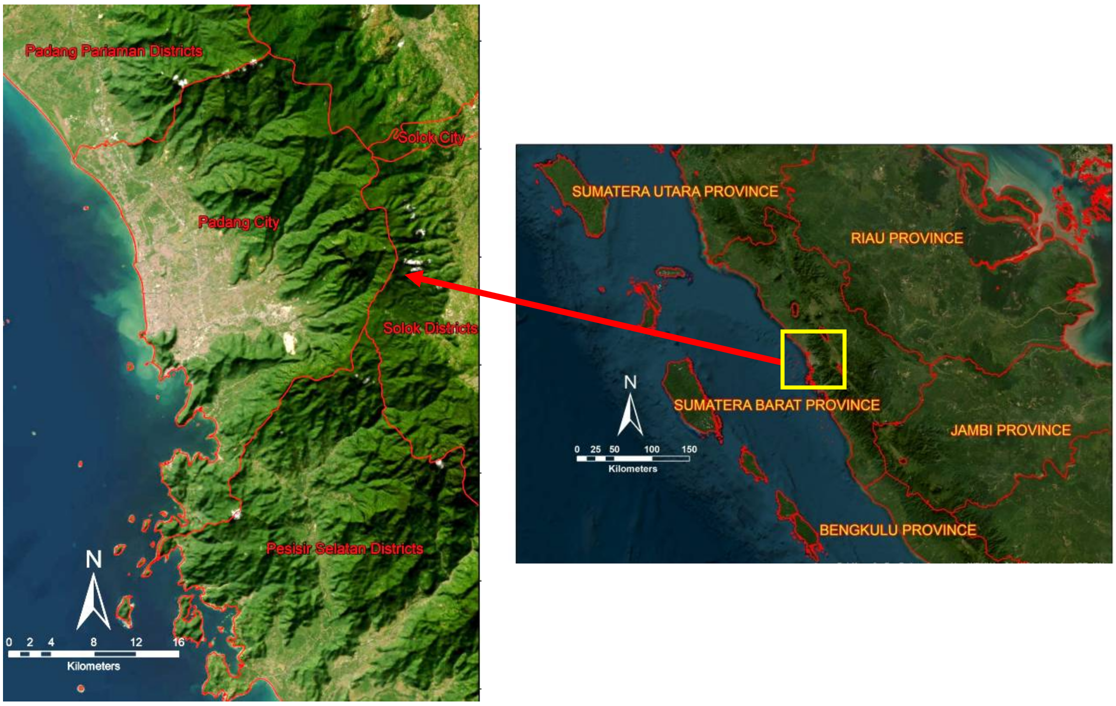

Figure 1. Map of Padang.

The geographical terrain of the city was relatively flat in coastal area and the central area, while the coastal areas attracted numerous community activities. The city center, located along the coast, accommodated essential infrastructure, public facilities, and social amenities (Ashar et al 2014).

Data collection and analysis*.* In this research, the assessment of areas affected by tsunami hazards was conducted using Digital Elevation Model (DEM) data obtained from DEMNAS, which were sourced from the Geospatial Information Agency (BIG). The data could be accessed through the website (https://tanahair.indonesia.go.id/portal-web). Land cover data used in the analysis were also sourced from BIG. These datasets were integrated with the interpretation of high-resolution satellite imagery (Pleiades), aerial photographs, and field surveys to generate a comprehensive map of the existing land use conditions.

To model land cover scenarios based on coastal ecology, a physical land suitability analysis was employed. This analysis aimed to map ecologically suitable areas for establishing mangrove ecosystems or coastal vegetation. Several physical variables were considered, including current land cover, soil type or base substrate, slope, and distance from the river (Kusmana 2003; Yulianda et al 2010). By assessing these factors, this research aimed to identify areas that exhibited favorable conditions for the growth and development of mangroves or coastal vegetation.

In this research, the modeling of tsunami inundation areas employed the Hloss method (Berryman 2006), which focused on reducing the height of the tsunami wave as it reached the coastline. This approach was specifically selected because it incorporated surface roughness variables, such as land cover, in addition to slope and elevation. By considering these additional factors, the Hloss method enabled more accurate mapping of tsunami inundation areas. The equation employed in the Hloss method to model the decrease in tsunami wave height was as follows:

$$\mathrm{H}loss = \left(\frac{167\ \mathrm{n}^2}{\mathrm{H_0}^{1/3}}\right) + 5\ \mathrm{Sin\ S}$$

where: Hloss = value of water drop when entering the land (loss of height per 1 meter of inundation distance);

n = surface roughness coefficient;

H_0 = tsunami wave height on the shoreline (in meters);

S = slope (in degrees).

The Hloss method was a modeling approach that predicted the extent of tsunami inundation by considering wave height, slope, and the surface roughness coefficient. The surface roughness coefficient represented the capacity of different land cover types to impede the flow of seawater toward the land during a tsunami. Table 1 presents the corresponding roughness values for various land use categories.

Table 1

Surface roughness coefficient value (Berryman 2006)

Types of land use and cover	*Roughness coefficient value*
Body of water	0.007
Shrubs	0.040
Forest/coastal vegetation	0.070
Plantation	0.035
Agricultural land	0.025
Vacant land	0.015
Settlements	0.045
Mangroves	0.025
Ponds	0.010

The potential height of a tsunami along the coastline in the Padang city area is estimated to range from 5 to 11 meters, as reported by various sources and the precalculated tsunami database for all of Indonesia (Latief 2012). In this research, the tsunami arrival height at the coastline (H_0) was based on the National Guidebook for National Tsunami Disaster Risk Assessment issued by the National Disaster Management Agency (BNPB 2011). The guidebook specified a maximum height of 11 meters, representing the worst-case scenario based on previous reviews.

This research employed two tsunami inundation models. The first scenario used the existing land cover conditions, while the second involved modifying the land cover in the coastal area. Specifically, vacant land or shrubland areas were transformed into mangrove ecosystems or coastal vegetation based on the ecological suitability of the coastal land.

Results and Discussion. The first modeling scenario focused on analyzing tsunami inundation using the current land cover conditions. However, the second scenario involved an initial analysis of land suitability based on coastal ecology, followed by a tsunami runoff analysis.

The results of the land suitability analysis considering coastal ecology indicated that the west coast of Padang city is primarily characterized by dense urban development. Specifically, high levels of urbanization were observed in areas such as the North Padang, West Padang, and East Padang subdistricts. The presence of bare land or shrubs in these areas was relatively limited. Therefore, when considering the land cover change scenario based on coastal ecological suitability, minimal changes were observed in the land cover conditions.

a b

c d

Figure 2. Current land cover conditions.

In the northern part of Koto Tangah subdistrict, a significant portion of the land cover consisted of vacant land (Figure 2a) and shrubs (Figures 2b and 2c). An ecological suitability analysis determined the most suitable land cover type for this area, whether it was mangroves or coastal vegetation. Padang city was divided by three canalized rivers (Figure 2d), potentially resulting in a wider tsunami inundation area due to the rapid entry of tsunami hazards through these rivers.

The results of the first tsunami inundation modeling (Figure 3a) indicated that the land cover within the tsunami inundation area comprised 504.7 hectares of vacant land

and shrubs. Within the same area, the mangrove ecosystem covered an area of 185.5 hectares, while coastal vegetation covered 247.3 hectares. After conducting an ecological-based land suitability analysis, the mangrove ecosystem area expanded by 167.6 hectares, reaching a total of 353 hectares. Similarly, the coastal vegetation area expanded by 337.1 hectares, resulting in a total of 584.4 hectares. A second modeling analysis could be conducted based on these changes in area and spatial distribution (Figure 3c).

Figure 3a

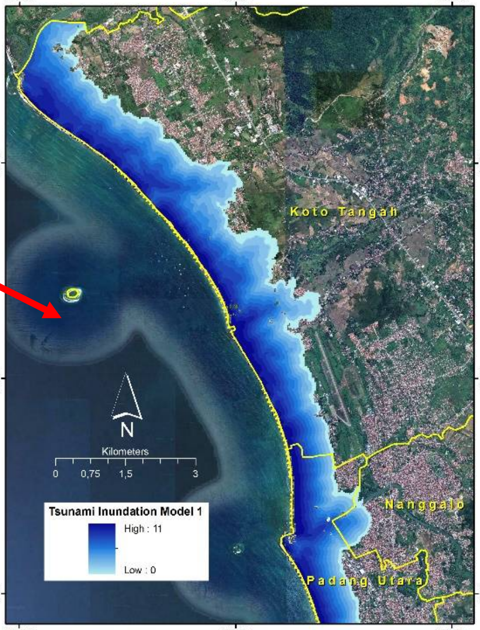

Figure 3b

Figure 3c

Figure 3d

Figure 3 showed the results of tsunami inundation modelings. Figure 3a displayed the outcomes of the first modeling, which represented the current land cover conditions. Figure 3b showed the partially affected areas based on the results of the first modeling. Figure 3c presented the results of the second modeling, where the ecological suitability of the coastal area was maximized. Finally, Figure 3d showed the partially affected areas with a significant reduction in inundation.

The results of the first modeling (current land cover conditions) and the second modeling (land cover conditions based on coastal ecological suitability) showed that eight subdistricts in Padang city experienced tsunami inundation. However, 3 subdistricts, including Kuranji, Pauh, and Lubuk Kilangan, remained unaffected by tsunami inundation due to factors involving their considerable distance from the coast, the presence of obstructing land cover types, and their relatively high elevation.

Regarding the analysis of tsunami inundation in the first modeling scenario, it utilized current land use data from various sources, including the BIG, high-resolution imagery interpretation, aerial photography, and field surveys (Table 2). The affected area of Padang city was found to be 3,231 hectares, representing approximately 4.64 % of the total area of the city, which was 69,496 hectares (BPS 2022). The impact of tsunami inundation was observed in 8 subdistricts within the city. Among these subdistricts, Koto Tangah subdistrict exhibited the highest potential for broad impact, with an affected area of 1,393 hectares. However, East Padang subdistrict had the smallest affected area, covering only 8.3 hectares.

Based on the analysis of the second model (Table 2), tsunami inundation areas cover 2,839 hectares, which accounts for approximately 4.08 % of the total area of Padang city. This inundation affects 8 subdistricts within the city, with Koto Tangah experiencing the most extensive impact, covering an area of 1,116 hectares, representing around 5% of the total area. However, East Padang has the smallest affected area, spanning only 6.3 hectares.

Table 2

Inundation area for each subdistrict from each model

No	*Subdistrict*	*Model 1 affected area (ha)*	*Model 2 affected area (ha)*
1	Koto Tangah	1,393	1,116
2	North Padang	392	368
3	West Padang	407	400
4	East Padang	8	6
5	South Padang	102	93
6	Nanggalo	52	17
7	Lubuk Begalung	55	55
8	Bungus Teluk Kabung	822	784
	Total area	3,231	2,839

When comparing the two models, the subdistrict that exhibits the most significant change in tsunami slope subsidence is Koto Tangah, with an area of 277 hectares. Bungus Teluk Kabung follows closely with a change in slope area of 38 hectares, while East Padang displays the least change in slope area, with only 2 hectares. This minimal change can be attributed to the predominance of buildings in the existing land cover of this subdistrict, rendering it unsuitable for land suitability simulations based on coastal ecology.

Furthermore, it is necessary to assess the social, economic, and environmental impacts of the changes in coastal ecological land suitability. While the second modeling scenario indicates a decrease in the extent of tsunami inundation areas, it is crucial to consider the potential consequences for existing human activities and coastal ecosystems. Therefore, a comprehensive evaluation is needed, considering social, economic, and ecological aspects and involving stakeholder participation. This approach will facilitate the design of effective and widely accepted mitigation strategies to reduce tsunami risks and protect the coastal areas of Padang city.

The lack of effective supervision by relevant authorities can significantly contribute to or exacerbate the situation by permitting encroachments on coastal areas, wetlands, and the destruction of coastal vegetation and mangrove forests (Mulyani et al 2015). These practices can further exacerbate the impacts of natural hazards and, in turn, lead to increased disaster losses.

To develop effective tsunami risk mitigation strategies, active engagement of stakeholders is crucial, including local governments, communities, research institutions, and non-governmental organizations. Involving these stakeholders in the decision-making process allows for a more comprehensive understanding of the needs, preferences, and challenges faced by the local community. Additionally, engaging stakeholders enhances the acceptance and implementation of proposed mitigation strategies.

In addition to tsunami inundation analysis, it is important to consider other factors that can influence tsunami risks, such as elevation levels, ocean currents, and coastal dynamics. Integrating tsunami inundation modeling with these factors provides a more holistic understanding of tsunami risks in Padang city. Therefore, continuous monitoring of coastal conditions and changes is necessary. Factors such as climate change, coastal dynamics, land cover changes in coastal areas, and others can alter coastal characteristics and affect potential tsunami risks in the future. Through continuous monitoring, appropriate actions can be taken to reduce risks and ensure the sustainable protection of the coastal areas in Padang city.

Conclusions. The implementation of mitigation measures was crucial to address the precise and unpredictable nature of tsunami hazards, particularly in light of projected events and the intensity of earthquakes and tsunamis. Coastal ecology-based tsunami mitigation emerged as a practical approach to mitigating the hazard in Padang city. This approach was supported by the ability of coastal ecosystems to reduce the impact of tsunami hazards, as observed in the analysis of tsunami inundation modeling scenarios.

The analysis of the first modeling scenario, which considered the current land cover conditions, indicated an affected area of 3,231 hectares, accounting for approximately 4.64 % of the total area of Padang city. However, modifying the land cover based on ecological-based land suitability, including the conversion of shrubs and vacant land, reduced the total affected coastal area to 2,839 hectares. This reduction represented a 0.56 % decrease and corresponded to 4.08% of the total area of Padang city. These results indicated the effectiveness of coastal ecology-based mitigation measures in reducing the extent of tsunami impact, emphasizing the importance of their implementation to enhance resilience against tsunami hazards in Padang City.

Analyzing tsunami inundation based on both current land cover conditions and ecological-based coastal land suitability modeling provided a more comprehensive understanding of potential tsunami risks in Padang city. However, it is essential to carefully consider the social, economic, and environmental impacts of these changes. Stakeholder participation and continuous monitoring play pivotal roles in developing effective and sustainable tsunami risk mitigation strategies for the coastal areas of Padang city.

Furthermore, ongoing evaluations of implemented mitigation strategies are crucial to ensure their effectiveness in addressing tsunami risks. These evaluations have to include measuring public awareness and preparedness, evaluating the performance of early warning systems, emergency response infrastructure, and the implementation of evacuation plans. Regular assessments enable the identification of weaknesses and improvements needed to enhance response capabilities and mitigate tsunami risks in Padang city.

In the long term, it is imperative to integrate tsunami risk mitigation efforts with sustainable development planning in coastal management. This integration entailed implementing proper spatial planning, controlling development in tsunami-prone areas, and safeguarding coastal ecosystems. These steps are vital in reducing risk and fostering the resilience of communities against disasters. Collaborative efforts among the government, academia, and the private sector play a vital role in generating holistic and sustainable policies and actions that addressed tsunami risks.

Tsunami risk mitigation needs to remain a continual priority and an evolving agenda for coastal management in Padang city. By adopting a comprehensive approach that involves all stakeholders and integrated mitigation strategies into sustainable development planning, Padang city could effectively minimize the impacts and losses caused by tsunami threats. Such efforts would ensure the protection of communities and valuable resources in the coastal region.

Acknowledgements. The authors are grateful to Lembaga Pengelola Dana Pendidikan (LPDP) for the funding provided through a research grant. The authors are also grateful to all individuals who have contributed to data collection and manuscript writing.

Conflict of interest. The authors declare that there is no conflicts of interest.

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Received: 06 July 2023. Accepted: 27 July 2023. Published online: 10 August 2023.

Authors:
Hendry Frananda, Universitas Negeri Padang, Faculty of Social Science, Geography Department, Prof. Dr. Hamka Street, Air Tawar, 25173, Padang, West Sumatera, Indonesia, e-mail: hendryfrananda@fis.unp.ac.id
Fredinan Yulianda, IPB University, Faculty of Fisheries and Marine Sciences, Department of Aquatic Resources Management, Lingkar Akademik Street, 16680, Bogor, West Java, Indonesia, e-mail: fredinan@apps.ipb.ac.id
Mennofatria Boer, IPB University, Faculty of Fisheries and Marine Sciences, Department of Aquatic Resources Management, Lingkar Akademik Street, 16680, Bogor, West Java, Indonesia, e-mail: mboer@apps.ipb.ac.id
I. Wayan Nurjaya, IPB University, Faculty of Fisheries and Marine Science, Department of Marine Science and Technology, Lingkar Akademik Street, 16680, Bogor, West Java, Indonesia, e-mail: i.wayan.nurjaya@apps.ipb.ac.id

How to cite this article:
Frananda H., Yulianda F., Boer M., Nurjaya I. W., 2023 Coastal ecology-based management for tsunami mitigation in Padang city, West Sumatera, Indonesia. AACL Bioflux 16(4):2072-2080.