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Modelling the Effect of Vegetation on Tsunami Reduction in Parts of the Gunungkidul Coast

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ABSTRACT

The coastal area of Gunungkidul Regency, which directly borders the Indian Ocean, possesses substantial coastal tourism potential, complemented by underground rivers emerging from its karst formations. Its natural attractions have contributed to tourism development and increased visitor numbers. However, the coastline is also exposed to a high level of tsunami hazard. This study aimed to model the effectiveness of coastal vegetation in attenuating tsunami energy as a nature-based disaster mitigation strategy. Aerial imagery acquired using an unmanned aerial vehicle (UAV) was processed to generate orthophotos and a digital elevation model (DEM). The orthophotos were used to classify land use and assign surface roughness parameters, while the DEM was used to characterize coastal topography. A vegetation greenbelt scenario was subsequently incorporated into the TUNAMI numerical tsunami model by modifying surface roughness parameters. The simulation results indicated that the proposed greenbelt reduced tsunami energy by 4.6% under the modeled conditions. These findings suggest that integrated coastal spatial planning incorporating three functional zones—a beach zone for coastal tourism, a vegetation greenbelt serving as a protective buffer, and a developed zone supporting tourism activities—could contribute to tsunami risk mitigation along the Gunungkidul coastline.

INTRODUCTION

Gunungkidul Regency, located in the Special Region of Yogyakarta, Indonesia, directly borders the Indian Ocean and possesses substantial potential for coastal tourism development. Its predominantly karst landscape also provides distinctive geological attractions, including caves and underground rivers, which contribute to the region's tourism appeal. Despite these natural advantages, Gunungkidul is exposed to various geological hazards, particularly earthquakes and tsunamis, because of its proximity to the active Sunda subduction zone, where the Indo-Australian Plate converges with and subducts beneath the Sunda Plate. Continued tectonic convergence generates seismic activity along the southern coast of Java. Under certain

conditions, large submarine earthquakes that produce significant vertical seafloor displacement can generate tsunamis, posing considerable risks to coastal communities, tourism infrastructure, and economic activities.

Historically, human settlements have frequently developed near rivers and other natural resources, despite their exposure to flooding and related hazards (Dandapat & Panda, 2018). Access to essential resources and livelihood opportunities has consistently influenced settlement patterns, often resulting in human activities becoming concentrated in disaster-prone areas. Consequently, societies have developed various approaches to managing natural hazards while maintaining access to resources necessary for economic and social well-being. Katanha and Simatele (2019) highlighted historical developments in disaster risk mitigation, including responses to the 1755 Lisbon earthquake and flood management initiatives in the mid-twentieth century. Identifying and assessing potential hazards is therefore essential for developing effective disaster mitigation strategies that enable communities to utilize natural resources while minimizing exposure and vulnerability. In this context, the present study examined tsunami hazards in a coastal tourism area where natural attractions support local livelihoods and economic development.

Tectonic earthquakes frequently occur along the Sunda subduction zone south of Java Island, creating the potential for tsunamigenic events. Figure 1 illustrates the spatial distribution of historical earthquake and tsunami events along the southern coast of Java. These records indicate that the coastal areas of Gunungkidul Regency are exposed to potential tsunami hazards associated with submarine earthquakes and the resulting vertical displacement of the seafloor. This geological setting underscores the importance of evaluating coastal tsunami hazards and identifying appropriate mitigation measures to reduce potential impacts on coastal communities and tourism infrastructure.

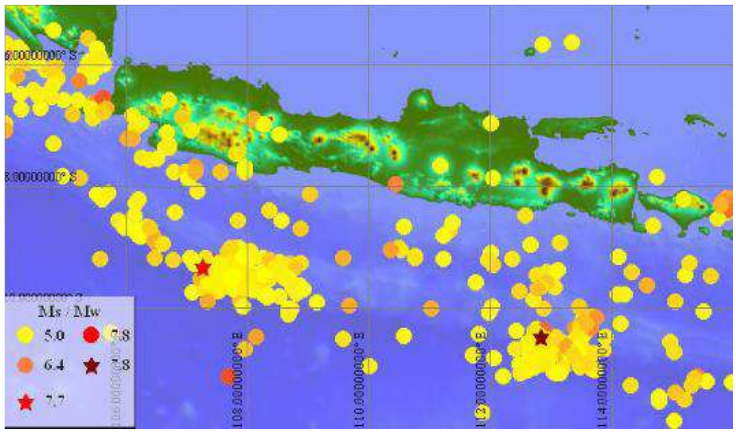


Figure 1. Seismicity Map of Java Island and Its Surroundings
Source: (Kongko, 2011)

Figure 1 illustrates that several major tectonic earthquakes have occurred along the southern coast of Java. Notable tsunamigenic earthquakes include the 1994 Banyuwangi earthquake, with a moment magnitude (Mw) of 7.8 and a reported maximum tsunami run-up height of 19.1 meters, and the 2006 Pangandaran earthquake, with a moment magnitude of 7.7 (Chaeroni et al., 2013; Kongko, 2011; Setiyono et al., 2018; Zaitunah et al., 2018).

The term tsunami originates from Japanese and literally means "harbor wave." A tsunami is a series of long-period waves generated by the sudden displacement of a substantial

volume of water, commonly resulting from submarine tectonic activity (Nugroho et al., 2018). Triatmadja (2010) described tsunamis as long waves that can originate from seafloor displacement associated with tectonic deformation. Such displacement may involve vertical, horizontal, or combined movements of the Earth's crust, although significant vertical displacement is generally the principal mechanism responsible for generating earthquake-induced tsunamis. Basith et al. (2015) explained that sudden seafloor deformation can disturb the equilibrium of the overlying water column, generating waves that propagate across the ocean toward coastal areas. Other potential tsunami-generating mechanisms include submarine landslides, volcanic eruptions, and meteorite impacts.

Submarine tectonic deformation is commonly associated with earthquakes, whose sizes are quantified using magnitude scales. Prakoso (2016) reported a positive relationship between earthquake magnitude and tsunami characteristics, including wave height, maximum inland penetration, and the spatial extent of wave propagation. However, tsunami severity also depends on earthquake rupture characteristics, water depth, coastal bathymetry, and nearshore topography. Tsunami run-up refers to the maximum vertical elevation reached by tsunami water above a specified reference sea level. Sorensen (1997), as cited in Jufri (2016), described run-up as the maximum vertical height attained by tsunami water along the coast. Low-lying coastal areas exposed to tsunami inundation are particularly vulnerable to associated hazards. Although tsunami research has advanced considerably since the late 1980s, uncertainties remain regarding wave transformation, nearshore propagation, and inundation dynamics (Samaras et al., 2015).

Variations in coastal geomorphology and topography can influence tsunami propagation, inundation characteristics, and the severity of coastal impacts, including differences in wave velocity and height (Wibowo, 2019). High-resolution aerial imagery acquired using unmanned aerial vehicles (UAVs) can support tsunami hazard modeling through the generation of orthophotos and digital elevation datasets, including digital surface models (DSMs) and digital terrain models (DTMs) (Wibowo et al., 2019). Although tsunami early warning systems can detect potentially tsunamigenic earthquakes and provide forecasts following an event, the precise timing and location of future tsunamis cannot currently be predicted. Apotsos et al. (2012) similarly emphasized that tsunamis are relatively infrequent and difficult-to-predict events that can nevertheless cause substantial human casualties and economic losses.

The continued development of coastal tourism and increasing visitor numbers in Gunungkidul Regency have created significant economic opportunities. However, these developments also increase potential exposure to tsunami hazards, with tsunami heights exceeding 3 meters under certain scenarios. Consequently, comprehensive tsunami disaster risk assessments are essential for coastal areas of Gunungkidul, incorporating hazard characterization, vulnerability assessment, response capacity, and mitigation planning. Regulation of the Head of the National Disaster Management Agency (Peraturan Kepala Badan Nasional Penanggulangan Bencana, PERKA BNPB) No. 2 of 2012 establishes a framework for disaster risk assessment that considers the interaction of hazards, vulnerability, and capacity (Badan Nasional Penanggulangan Bencana [BNPB], 2012). Within this framework, disaster vulnerability refers to the conditions that increase the susceptibility of communities, infrastructure, and other exposed elements to adverse impacts, whereas hazard refers to the

potential occurrence of a damaging event. Nugroho et al. (2018), in the Technical Module for Tsunami Disaster Risk Assessment, further emphasized the importance of distinguishing tsunami hazard characteristics from the vulnerability of exposed populations and assets.

Tsunami hazard maps provide spatial information on the potential extent and intensity of tsunami impacts, including inundation depth, inundation extent, and run-up elevation, depending on the assessment methodology (BNPB, 2012). Where sufficient data are available, hazard assessments may also incorporate event probabilities or recurrence intervals. In contrast, tsunami susceptibility maps primarily identify areas potentially affected by tsunami inundation based on physical and geographical characteristics, without necessarily quantifying event frequency or probability. Importantly, hazard mapping is distinct from disaster risk mapping, which additionally considers the exposure and vulnerability of affected elements and the capacity to manage potential impacts.

Nugroho et al. (2018) identified several spatial datasets required for tsunami hazard mapping and assessment, as summarized in Table 1.

Table 1. Types of Data for Modelling Tsunami Hazard

No.	Data Type	Data Format
1.	Administrative Boundary	GIS Vector (Polygon)
2.	Land Cover	GIS Vector (Polygon)
3.	Coastline	GIS Vector (Polygon)
4.	DEM (*Digital Elevation Model*)	GIS Raster (Grid)
5.	Maximum Tsunami Wave Height	Tabular/GIS Raster (Grid)

Source: (Nugroho et al., 2018)

The spatial datasets presented in Table 1 can be obtained from the Geospatial Information Agency (Badan Informasi Geospasial, BIG) through the Indonesian Geospatial Information Portal (https://tanahair.indonesia.go.id/).

Land use and coastal topography are important factors influencing tsunami propagation and inundation characteristics. Land use and land cover determine surface roughness, which affects frictional resistance and tsunami flow velocity, while coastal topography influences flow direction, inundation extent, and water depth. Surface roughness is commonly represented by friction coefficients assigned to different land cover categories, whereas terrain elevation is represented using digital elevation model (DEM) data. These parameters are essential for numerical tsunami modeling because they influence the interaction between tsunami waves and coastal environments.

Regional characteristics, including geographical boundaries and functional relationships, influence spatial planning and development priorities (Rustiadi et al., 2009). Regions comprise interconnected terrestrial and aquatic environments with distinct physical and ecological characteristics (Supriyatin et al., 2020). According to Law No. 1 of 2014 (Government of Indonesia, 2014), coastal areas constitute transitional zones between terrestrial and marine ecosystems, where environmental processes and human activities interact. These characteristics are particularly relevant to tsunami hazard assessment because coastal geomorphology, land use, and ecosystem conditions influence tsunami inundation and potential impacts.

Digital elevation models (DEMs) provide elevation information required to characterize coastal terrain for tsunami simulations. Two commonly used elevation data products are digital surface models (DSMs) and digital terrain models (DTMs). A DSM represents the elevation of the Earth's surface, including above-ground features such as buildings and vegetation, whereas a DTM represents bare-earth terrain elevations with these features removed. For tsunami inundation modeling, DTMs are generally preferred for representing ground elevation, while the effects of buildings, vegetation, and other surface features can be incorporated through appropriate surface roughness parameters.

In addition to coastal topography, land use and land cover significantly influence tsunami flow characteristics through their effects on surface friction. Different land cover categories are assigned specific roughness coefficients to represent their resistance to overland flow (Prakoso, 2016). These coefficients are commonly expressed using Manning's roughness coefficient (n) in numerical tsunami inundation models, depending on the model's friction formulation. Table 2 presents the reference surface roughness coefficients used in tsunami modeling, based on the Technical Module for Tsunami Disaster Risk Assessment issued by the National Disaster Management Agency (Badan Nasional Penanggulangan Bencana, BNPB) (Nugroho et al., 2018).

Table 2. Surface Roughness Coefficients for Each Land Cover/Land Use Type

Land Cover/Land Use Type	Coefficient Value
Water Body	0.007
Swamp	0.015
Pond	0.007
Aquaculture Pond	0.010
Sand/Sand Dune	0.018
Shrub/Bush	0.040
Grassland	0.020
Forest	0.070
Garden/Plantation	0.035
Dry Field	0.030
Paddy Field	0.020
Agricultural Land	0.025
Settlement/Built-up Land	0.050
Mangrove	0.060

Source: (Nugroho et al., 2018)

Five coastal management strategies can be applied to reduce coastal hazards and mitigate potential tsunami impacts. Based on Persson (2008), these strategies are described as follows:

1. Do nothing: This strategy involves maintaining existing coastal conditions without implementing additional interventions when natural coastal processes are considered acceptable and no immediate management measures are required.
2. Managed realignment: This approach involves relocating vulnerable buildings and infrastructure away from high-risk coastal areas to reduce exposure to tsunami inundation and other coastal hazards.

3. Hold the line: This strategy involves constructing or maintaining coastal defense structures, such as seawalls and revetments, to protect existing coastal developments. However, these measures generally require substantial engineering investment and ongoing maintenance.
4. Move seaward: This approach involves extending coastal defenses or creating additional land toward the sea, potentially incorporating engineered or nature-based barriers, such as artificial dunes, to reduce exposure to coastal hazards.
5. Limited intervention: This strategy involves implementing targeted management measures while preserving natural coastal processes and ecosystems. Such measures may include restricting development in environmentally sensitive areas and conserving coastal vegetation, including mangrove forests, that can contribute to wave attenuation.

This study builds on two previous investigations conducted along the same coastline. Wibowo (2019) modeled tsunami responses to variations in coastal geomorphology and identified substantial differences in inundation characteristics across Gunungkidul's coastal landscape, which ranges from gently sloping beaches to steep coastal cliffs. Similarly, Wibowo et al. (2019) demonstrated the applicability of unmanned aerial vehicle (UAV)-derived digital elevation models (DEMs) and orthophotos for numerical tsunami modeling in the Baron–Sepanjang coastal area. However, neither study quantitatively assessed the potential attenuation of tsunami energy through coastal vegetation. A related numerical modeling study by Chusnayah (2019) reported a 3.2–4.1% reduction in tsunami energy associated with a Casuarina equisetifolia greenbelt, although the investigation was conducted along a different coastline and focused on a single vegetation species. These findings highlight a research gap concerning the effectiveness of spatially explicit coastal greenbelt scenarios integrated with functional coastal zoning and high-resolution, locally derived terrain data in the Baron–Sepanjang coastal area. To address this gap, the present study simulated tsunami propagation and inundation under existing coastal conditions and a proposed vegetation greenbelt scenario. The study aimed to quantify the potential contribution of coastal vegetation to tsunami attenuation and translate the modeling results into a three-zone coastal management strategy comprising a beach tourism zone, a vegetated protection zone, and a supporting development zone. The proposed approach was intended to inform nature-based tsunami mitigation planning while supporting sustainable coastal tourism and reducing the exposure of inland infrastructure and other assets to tsunami hazards.

METHOD

Research Flowchart

The research flowchart of this study, “Modelling the Effect of Vegetation on Tsunami Reduction in Parts of the Gunungkidul Coast”, is presented in Figure 2.

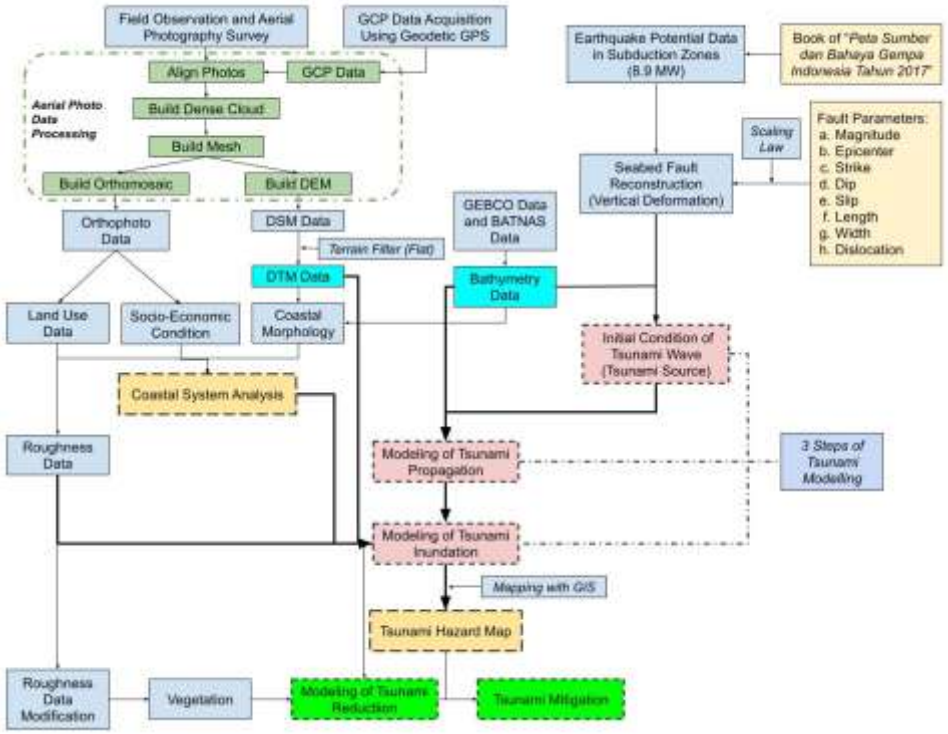


Figure 2. Research Flowchart
Source: Researchers, 2025

Tools and Materials

The tools used in this study include an *Unmanned Aerial Vehicle* (UAV), namely a DJI Phantom 4, as the platform for collecting aerial photo data, and a camera for recording field conditions. The software used includes aerial photo processing software, namely Agisoft PhotoScan; spatial data processing software, namely Global Mapper and ArcMap; and tsunami modelling software, namely TUNAMI.

Research Procedure

The first step of the study was collecting primary data in the form of aerial photographs using a UAV in the study area. The aerial photography was planned by considering the desired level of output detail and the characteristics of the study area. The aerial photography output was expected to have a high level of detail and high vertical and horizontal geometric accuracy. The activities carried out before the aerial photography were flight path planning and the installation of *pre-marks* for *ground control point* measurement.

The aerial images obtained from the unmanned aerial vehicle (UAV) were processed using photogrammetric software known as Agisoft PhotoScan. This software can convert aerial images into a mosaic in the form of an *orthophoto*, as well as height data in the form of a *Digital Surface Model* (DSM). The processing approach relies on the *structure from motion* (SfM) principle, which produces point cloud data from the reconstruction of image matching from various viewing angles. The point cloud data store three-dimensional coordinates (x, y, and z).

The results of the aerial photography were georeferenced photographs, which were then processed into *orthophoto* and DEM data representing morphology. All aerial photo data, namely the *orthophoto* and DEM (DSM and DTM), can be used for tsunami modelling

(Wibowo et al., 2019). A field survey of the area's characteristics was also conducted with a camera to observe conditions in the study area for analysis based on land use and morphology. These data were then used as input for roughness values after being classified according to the reference mentioned above. Both the morphological data (DEM) and the land use data (*roughness*) were then processed to model the effect of vegetation as a reducer of tsunami wave energy.

After the data preparation was completed, the data were ready to be modelled. Tsunami propagation was modelled using the TUNAMI program (*Tohoku University's Numerical Analysis Model for Investigation of Near-field Tsunami*). TUNAMI uses a *leap-frog* numerical scheme to calculate wave propagation. TUNAMI simulates tsunami propagation and *run-up* using linear wave theory for deep water and shallow water wave theory for shallow water. Tsunami modelling with this method was carried out to determine the wave height on land and the tsunami arrival time. Dias et al. (2014) describe the need to understand tsunami generation and the subsequent inundation, in addition to tsunami propagation, which can already be modelled with such numerical models.

One effort that can be made to reduce tsunami disaster risk is coastline management. One way to reduce tsunami energy is by applying a *greenbelt* along the coastline. The *greenbelt* can be defined in the DEM data through *Manning roughness* values, which can be entered into the modelling *software*.

RESULTS AND DISCUSSION

Figure 3 shows that the *greenbelt* is placed behind the beach. This placement allows the 50-metre-wide beach to remain usable as a tourist site for water play and enjoying the coastal scenery. A dense *greenbelt* is placed behind the beach while still providing sufficient pathways for access and evacuation. Buildings and other tourism activities can be located behind the *greenbelt*. Zaitunah et al. (2018) state that coastal vegetation forming a *greenbelt* can reduce tsunami energy, thereby reducing its destructive power. This condition benefits building assets, which remain safe, so that the recovery of economic activities after a tsunami does not take long.

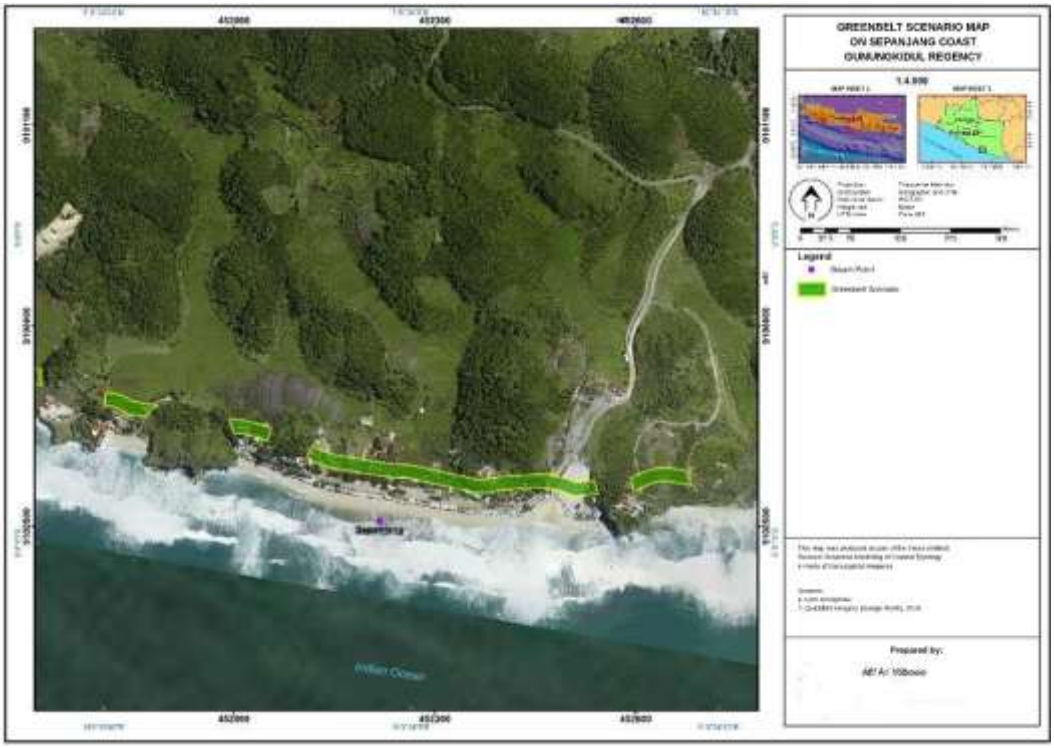


Figure 3. Map of the *Greenbelt* Scenario Application on Sepanjang Coast
Source: Researchers, 2025

The modelling results of applying the *greenbelt* as an effort to reduce tsunami energy are shown in Figure 4.

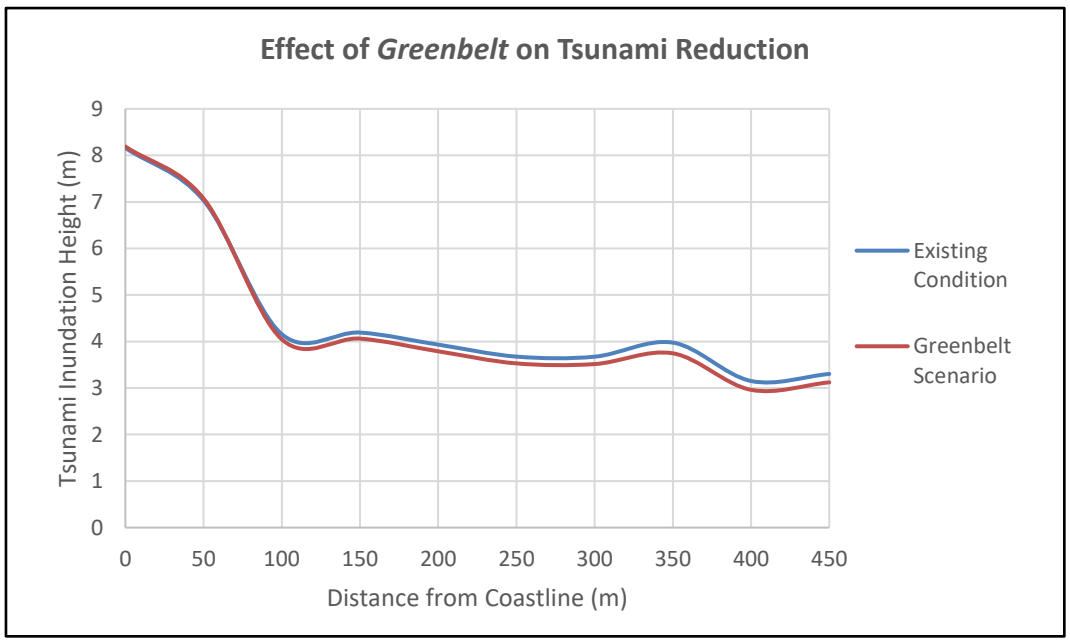


Figure 4. Graph of the Effect of the *Greenbelt* on Tsunami Reduction
Source: Researchers, 2025

There are two graph lines, namely red and blue. The blue line is the tsunami modelling result without the *greenbelt*, or under existing conditions, whereas the red line is the tsunami modelling result with the *greenbelt*. The figure shows that at distances of 0 to approximately 75 metres from the coastline (the beach area), the two lines still coincide. Beyond 75 metres

from the coastline, the lines begin to diverge, with the red line lower than the blue line. This shows that the model confirms that applying a *greenbelt* can reduce tsunami energy. Based on the modelling on three coasts, applying a *greenbelt* reduces the tsunami by approximately 4.6%. This result is consistent with the study by Chusnayah (2019) on the effectiveness of coastal vegetation in reducing tsunamis, which found values of 3.2–4.1%. The vegetation used by Chusnayah (2019) was *Casuarina equisetifolia*, or coastal she-oak (*cemara udang*).

The effectiveness of vegetation in reducing tsunami energy is still relatively low, as the value is less than 5%. Other efforts are needed to increase the effectiveness of tsunami energy reduction that can be applied around the Baron to Sepanjang coast. Modifying the method by applying several types of vegetation in the *greenbelt* is considered a feasible effort. The vegetation is arranged in two or three *layers*, each with its own function. The first *layer* can consist of beach pandanus (*pandan pantai*), the second *layer* of coastal she-oak (*cemara udang*), and the third *layer* of woody trees such as coconut or pule trees.

CONCLUSION

The coastal management strategy was developed using a three-zone approach comprising a beach zone designated for coastal tourism activities, a vegetated greenbelt serving as a protective buffer, and a developed zone supporting tourism infrastructure and related activities. The numerical simulation results indicated that incorporating the proposed greenbelt could reduce tsunami wave energy by up to 4.6% under the modeled conditions.

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CONFLICT OF INTEREST

The authors declare that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

AUTHOR CONTRIBUTIONS

Afif Ari Wibowo[1]: conceptualisation, UAV aerial photo data acquisition, tsunami modelling, analysis, and writing of the original draft. Amalia Nurwijayanti[2]: methodology, validation of the modelling results, and manuscript review and editing. All authors have read and approved the final manuscript.

GENERATIVE AI STATEMENT

The authors declare that generative AI was used to a limited extent to assist in translating the manuscript into English, formatting it according to the journal template, and tidying the citations and reference list. All content, data, analyses, and interpretations are the authors' own work, and the authors take full responsibility for the content of this manuscript.

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