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Research Article

Procedural Planning System for Appropriate Land Use Configuration: Anticipating Tsunami in Glagah Village, Yogyakarta

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ABSTRACT
The establishment of Kulon Progo as a strategic zone must consider the threat of coastal disasters besides aspiring economic growth and development. By employing Unmanned Aerial Vehicles for data acquisition, this research modeled flood inundation and developed theoretical contributions on tsunami hazard, vulnerability, capacity, and risk, as well as a procedural planning system for reconfiguring land use that emphasized the mitigation aspects. This study found that the tsunami hazard index in Glagah Village was in a low category, dominated by vacant land and sandy land, accounting for up to 25.38% of the total area. Besides, vulnerability and risk in Glagah Village were mostly in a moderate index, while its capacity was categorized as high since the village already had an evacuation route, a notable tsunami early warning system, and was equipped with safety gear. By combining the index values for hazard, vulnerability, and capacity, the tsunami disaster risk in Glagah Village was categorized as moderate. Spatial planning in Glagah Village recommended that the main facilities related to community activities, such as transportation and housing, be located in areas not exposed to the tsunami. This plan allows everyone to evacuate themselves while being reinforced by a security warning system that stays on alert. Furthermore, detailed spatial maps are expected to be useful as instruments for tsunami disaster mitigation at the pre-disaster stage by recommending better land use configurations.

Keywords: Glagah Village; hazard index; Kulon Progo; tsunami

INTRODUCTION

The South Coastal Region of Java, seen from the conception of development, is categorized as a functional area as it has certain functional coherence and interdependence with other parts that are functionally corresponding (Muta'ali, 2011). Therefore, infrastructure development on Java's south coast must conform to its surroundings' prerequisites and requirements because it has links between regions (connectivity) and sectors (integration). The tsunami is an unexpected disaster and one of the most prominent threats to Indonesians (Chen et al., 2016), and in the last decade, it has damaged the coastal structure (Nandasena et al., 2012). Although tsunamis on a large scale are relatively rare compared to most hydrometeorological disasters, their impact is destructive and causes many fatalities when they occur. Technically, tsunamis are waves that are far superior in terms of speed, height, and strength compared to storm surges.

On 26 December 2004, a tsunami was triggered by an earthquake with a magnitude of 9.1 on the Richter Scale (RS) in the Indian Ocean. The tsunami wave reaching 30 m in height had killed more than 200,000 people in more than 10 countries directly adjacent to the Indian Ocean (Grilli et al., 2007; Wright et al., 2013), destroying billions of dollars in property values (Iverson & Prasad, 2007), and changing the shape of beaches in India (Roshan et al., 2016). Six years later, on 27 February 2010, another tsunami was triggered by an 8.8 RS off the coast of Chile. The tsunami waves reached a local run-up as high as 29 meters on the coastal cliffs (Geist & Parsons, 2006). The following year, on 11 March 2011, an earthquake with a magnitude of 9.0 occurred near Japan's northeastern coast, causing a tsunami to wash over the coast and inland waters with a wave height of 40 meters (Yeh et al., 2013). Still, due to seismic processes, an earthquake with a magnitude of 8.3 on 16 September 2015 off the central coast of Chile triggered a tsunami with a wave reaching 13 meters (Contreras-López et al., 2017).

One tsunami considerably changed the structure of the port in Thailand, where the pier slab at the Khao Lak port and the fishing port deck of Ban Nam Kem were badly uplifted by the 2004 Indian Ocean Tsunami (Ghobarah et al., 2006). The same damage also occurred in Japan in 2011 against the port of Sendai in the Tohoku region, as its severely damaged infrastructure can be seen through satellite images (Suppasri et al., 2012). The Indonesian archipelago is geographically located on the perimeter of three large plates: the Eurasian, the Indo-Australian, and the Pacific. Besides the deformation of plate boundaries, tectonic movements of the earth's plates will cause the formation of many active faults on land and the seabed. Therefore, plate boundaries and active faults are the sources of tectonic earthquakes to anticipate (Putranto & Supartoyo, 2004).

The coast of the Special Region of Yogyakarta sits at the boundary of convergent tectonic plates where subduction zones can produce underwater earthquakes with vertical shifts of the seafloor. Therefore, this area is tsunami-prone. Moreover, earthquakes often arise due to plate movement and are usually followed by other subsequent disasters, such as tsunamis, landslides, and liquefaction (Rijanta et al., 2018). The tsunami is threatening the Kulon Progo Regency, a coastal area with much infrastructure, potentially making the area grow physically and becoming a center for new activities and growth, especially with the presence of New Yogyakarta International Airport. With the establishment of Kulon Progo as a strategic area, it is hoped that regional development will reconsider the primary problem threatening coastal areas, especially tsunamis that can cause considerable damage.

The tsunami tragedy has prompted in-depth studies that intersect the level of vulnerability, inundation, and severity of tsunami against land use (Meilianda et al., 2019), human settlements (Herrmann-Lunecke & Villagra, 2020; Scheele et al., 2020), building structures (Batzakis et al., 2020; Sathiparan, 2020), property (Sanderson et al., 2021), and quality of life (Gim & Shin, 2022; Joseph & Jaswal, 2021). Globally, studies on tsunamis and their conjunction with human activities are widely studied using remote sensing data for mitigation measures. The consequence of one catastrophe is closely associated with the community's quality of life, especially in the health and economic aspects. Considering that economic recovery requires enormous effort, various methods are taken to provide prevention guidance so that the effects of disasters can be diminished to as little as possible. United Nations Platform for Space-based Information for Disaster Management and Emergency Response (2024) recommends using optical imagery and radar at different spatial and temporal resolutions for disaster assessment and mitigation measures. As a result, various studies are increasingly producing multi-hazard maps used to facilitate disaster response and mitigation utilizing optical imagery and radar in various countries (Aksha et al., 2020; De Angeli et al., 2022; Khan et al., 2020; Pourghasemi et al., 2020; Uddin & Matin, 2021).

Optical remotely sensed imagery, consisting of optical and infrared wavebands across the electromagnetic spectrum collected by sensors, is the most popular spatial analysis in disaster (Anusha & Bharathi, 2020; Ge et al., 2020; Hakdaoui & Emran, 2020; Hébert et al., 2020; Koshimura et al., 2020; Wang et al., 2023). The Landsat system and ESA's Sentinel series of satellites have made optical imagery the most familiar data source due to its accessibility. Optical sensed imagery in several studies has produced successful flood maps (Quirós & Gagnon, 2020; Theilen-Willige & Mansouri, 2022; Woessner & Farahani, 2020; Yokoya et al., 2022). Lillesand et al. (2015) stated that the availability of many sensors and ease of interpretation are the two biggest reasons why optical imagery is massively used to produce disaster maps. Furthermore, its method can overcome measurement gaps due to weather conditions, can process dynamic and static changes, and allows users to perform dense time-series analysis. However, Mohammadi et al. (2021) stated that optical data is highly dependent on bright daylight situations and is strongly influenced by topographic effects and sun-glint. Furthermore, it does not penetrate vegetation/soil and is not responsive to dielectric properties (Sabins Jr & Ellis, 2020).

The weakness of optical imagery relying on daylight and clear weather leads to synthetic aperture radar (SAR) as an alternative. According to Wieland et al. (2016), this method can obtain data in cloudy conditions and does not depend on daylight. A single wavelength per sensor in the SAR method can provide information about vegetation and soil that can be optimally used for flood mapping. The sensitivity of this method to land cover structure and dielectric properties allows users to determine the area of open water. As a result, various studies have produced high-resolution flood information maps over large areas, increasing the effectiveness of relief measures and mapping flood boundaries (Clement et al., 2018; Mason et al., 2014; Shen et al., 2019). However, Joyce et al. (2014) stated that SAR is often limited to segmenting submerged and not submerged flood classes. Besides requiring high energy for satellite observations, the SAR method is also limited to identifying water features in urban areas because of the angular reflection principle. Furthermore, its information is also relatively complex to interpret (Passah et al., 2023; Rambour et al., 2020).

Although optical imagery and SAR methods are suitable for rapid disaster mapping, their data acquisition is costly, and weather conditions limit their temporal resolution. These shortcomings make remote sensing methods based on unmanned aerial vehicles (UAV) in disaster mitigation an alternative, especially in reducing costs. According to Karamuz et al. (2020), UAVs can provide accurate, up-to-date georeference information about the location of river coastlines, channel geometry, and detailed vegetation information. The use of UAV technology for environmental monitoring has proven effective in providing accurate and precise environmental spatial information. Anderson and Gaston (2013) confirmed that the UAV method produces relatively low-cost environmental data with high spatial resolution. Because the user completely controls the observation scheme, monitoring with the UAV method can be carried out with high frequency in various atmospheric conditions.

The popularity and application of UAV technology in disaster-related research have been successful (Chen et al., 2023; Khan et al., 2022; Morgan et al., 2022; Rezaldi et al., 2021; Yang et al., 2022). Feng et al. (2015) employed mini-UAV to monitor the severe urban waterlogging in China and found that UAV is an ideal platform for urban flood monitoring due to its extraordinary ability to extract flooded areas accurately. Since observations in difficult-to-reach environments require practical solutions, Tauro et al. (2016) conducted a comparative analysis between drone-based large-scale particle image velocimetry (LSPIV) and traditional LSPIV implementations. Their experiments on measurement accuracy, tracker sensitivity, and platform mobility on the two methods found that drone-based observations produced superior data, especially in outdoor environments.

The popularity, practicability, and accuracy offered by UAV technology have also been successful in updating flood hazard assessment (Karamuz et al., 2020), validating a hydraulic model for flood calculation in Ñuble River (Clasing et al., 2023), delineating near-real-time inundation for storm events using an actual flooding-event; 2020 Atlantic hurricane season-Hurricane Zeta (Wienhold et al., 2023), and for emergency management of natural hazards by simplifying the large UAV image datasets. Furthermore, this method is the most widely adopted solution and has been developed to solve various problems, especially in complex landscapes with limited infrastructure (La Salandra et al., 2024).

The adoption of UAV technology has been proven to produce accurate data, costs relatively less, and enables rapid assessment. However, automatic monitoring with UAVs is expensive because manual measurements would take time and much effort. According to Tauro et al. (2016), obtaining and installing the necessary equipment at each station when monitoring UAVs requires quite a lot of money. Regarding the use and operation of tools, the UAV method requires users to have special abilities in accessing, measuring, and ensuring the safety of humans and equipment during observations. Specific regulations in various countries also regulate this capability.

Although the UAV method allows users to operate independently, the use of UAVs is restricted by the limited flight duration due to battery life (Elmeseiry et al., 2021; Mohsan et al., 2022). Therefore, the choice of time and flight path must be considered carefully. Other challenges are also influenced by the equipment specifications and loads this technology carries. Large fixed-wing UAVs are challenging to operate in relatively narrow and closed areas. On the other hand, UAVs with small quadcopters are powerless to windy conditions, rain, and dense clouds. During data acquisition, too high flying reduces the spatial resolution of the image, and water vapor can weaken the signal (Gómez-Candón et al., 2014).

According to Kedzierski et al. (2019), changes in solar radiation significantly affect the quality of UAV images. Therefore, the large amounts of image acquisition to avoid poor data quality cause a heavy computational workload during the processing stage (Adão et al., 2017). Considering that the UAV method requires the user to have special abilities, careless use will trigger safety problems related to the spatial interference of civil aircraft (Hardin & Jensen, 2011), the privacy of specific areas, and particular policies adopted by certain regions (Klemas, 2015). Therefore, future innovations and opportunities for UAV platforms (Chávez et al., 2020) must be complemented by solid aviation policies and regulations for optimal use.

Spatial planning is one of the mitigation steps used to reduce disaster risk through zoning arrangements and spatial schemes that refer to vulnerability, capacity, and danger levels. Globally, the threat posed by extreme events invites innovative and collaborative approaches to mitigation (Durán-Romero et al., 2020; Mavroulis et al., 2022; Moallemi et al., 2020; Oetjen et al., 2022). According to Anfuso et al. (2021), coastal management requires a strategic adaptation strategy through various scenarios. Furthermore, varied disaster scenarios equipped with in-depth analysis of risk, capacity, adaptability, and vulnerability enable powerful actions to be taken before the anticipated disaster occurs (Lei et al., 2014). Active resilience management can be carried out through restoration, maintenance, adjustment, and allocation of various elements related to human activities. Therefore, actively managing, reorganizing, and designing land use requires a procedural planning system that can reduce risks and benefit the socio-ecological system. Procedural planning is carried out to support and regulate land use for security control (BNPB, 2012).

The process of reevaluating land configuration must be simplified by giving greater confidence to scientists in optimizing disaster risk reduction. Risk reduction through handling green and gray infrastructure needs to receive regulatory support. Therefore, the respectable land configuration in locations with complex gray infrastructure will be effective if it can utilize environmental services (nature), considering that socio-ecological benefits cannot be separated from human needs (Bayraktarov et al., 2016). Therefore, disaster resilience planning requires a procedural planning system, especially when faced with decision-making in critical conditions. Procedural planning for land configuration must consider environmental dynamics, including geomorphological and oceanographic factors. Antunes do Carmo (2017) stated that morphodynamic characteristics influence how a region responds to disasters. Empirical field studies and aerial photography adopting remote sensing techniques provide opportunities to monitor the dynamic properties of land cost-effectively.

According to several studies (Ferreira et al., 2021; Guptha et al., 2021; Rezvani et al., 2023), remote sensing techniques combined with numerical models are valuable in assessing threats, designing regional resilience, and developing land use arrangements. The general methodology for assessing risk and vulnerability to disasters is regulated by the Intergovernmental Panel on Climate Change-Coastal Zone Management (Intergovernmental Panel on Climate Change-Coastal Zone Management, 2018). As research on coastal disasters developed, assessing risk and vulnerability has increasingly focused on specific national coastal management programs in various countries (Baills et al., 2020; Bera et al., 2022; Gallina et al., 2020; Kay et al., 1996).

Many researchers present the concept of coastal vulnerability by combining social, economic, and land use analysis to facilitate decision-making. Considering that risk and vulnerability studies are helpful in coastal management, disaster response, and pre-post adaptation, the adoption of guidelines by the Intergovernmental Panel on Climate Change-Coastal Zone Management has been developed carefully and adapted to produce structured planning, especially in land use planning. According to Vázquez-González et al. (2021), the impact of a disaster depends on the level of exposure, vulnerability, adaptive response, resilience, and adaptive capacity. Furthermore, Du et al. (2020) stated that resilience can be significantly improved by adjusting land use to appropriate usage by considering an environment's physical conditions and infrastructure.

Captivating regional planning development must start with a comprehensive assessment and hazard identification. Apart from that, land policies and regional dynamics must go side by side in terms of land use optimization. According to McFadden & Green (2007), coastal area management must consider vulnerability by considering ecosystem, physical, and socio-economic dimensions. An integrated approach from various dimensions must also be linked to coastal dynamics, development intensity, development patterns, tourism areas, and infrastructure supporting community activities. Kay et al. (1996) found that the Mediterranean coastal region consisting of 22 coastal countries has signed and adopted the IPCC-CZM protocol. As one of the references in the procedural planning system, this protocol regulates anthropogenic elements, development pressures, infrastructure intensity, tourism trends, and vulnerability to hazards related to climate change. The formulation and implementation of coastal zone policies have also progressed and significantly impacted various regions (Pal et al., 2023; Van Assche et al., 2020; Wong, 2009). A study by Ye et al. (2014) evaluated the performance of Integrated Coastal Management in Quanzhou found that the methodology used as a reference for assessing integrated coastal management has important implications for evaluating the performance of coastal zone management, facilitating adaptive management in responding to changing conditions in the future.

Strengthening the environment's and society's resilience to disasters can be done by ensuring strong coordination in disaster response. These efforts must be based on science and supported by genuine data, government, and relevant stakeholders. Chou et al. (2021) found that coastal cities that practice integrated coastal zone management are better positioned and prepared to face emerging threats because coastal management initiatives and strategies for dealing with disasters have been organized sustainably (Lin et al., 2021). Socio-economic aspects are essential in assessing coastal vulnerability (Noor & Abdul Maulud, 2022). Therefore, coastal area managers must be able to find ways to provide backup for threatened coastal areas through various restoration strategies. The study by Chen et al. (2019) on enhancing Taiwan's coastal management framework through a new dedicated law beyond sectoral management found that the new law regarding coastal zones on an integrated coastal management framework has improved cross-sectoral coastal management and produced various strategies to protect the coastal environment. Furthermore, measurable coastal management can simplify issues involving coordination and harmonization between various sectors and levels of government.

Integrated coastal zone management, which constructs proper procedural planning, can increase land use integration effectively. Portman et al. (2012) found that research topics related to environmental issues proved to increase the integration of science across sectors in eight countries (Belgium, India, Israel, Italy, Portugal, Sweden, the UK, and Vietnam). Their findings found that planning and regulation can only encourage public-government integration when adopting coastline management established on scientific evidence becomes a standard reference. This scheme means that the involvement of all sectors is vital so that good studies can be implemented optimally. Ahmed et al. (2018) stated that development in many coastal areas of Bangladesh has followed coastal zone policy protocols by considering potential disasters and possible adverse impacts. Procedural planning in coastal areas in Bangladesh also considers how people living in disaster-prone areas may be affected.

Herrmann-Lunecke and Villagra (2020) stated that the formulation of the coastal development strategy has greatly optimized community resilience to disasters. Coastal land management must consider innovation-intensive risk strategies and prioritize development for economic acceleration. Therefore, analyzing development policies and their implications for land dynamics is sensitive work, especially in coastal areas. The planned spatial zoning based on land use is expected to reduce negative impacts should a disaster occur. In Indonesia, procedural planning of land use to minimize the risks posed by the tsunami disaster can refer to the spatial planning procedures stipulated in the Regulation of the Minister of Public Works and Housing Number 20 of 2011 (2011) and the Regulation of the Minister of Agrarian Affairs and Spatial Planning/Land Agency National Number 16 of 2016 (2016). These regulations are used as a reference for preparing land use plans, determining handling priorities, preparing provisions for space utilization, and maintaining consistency/harmony in regional development.

Several studies have found that variations in initial wave height, run-up, and inundation in areas affected by tsunamis have varying impacts depending on topography, roughness coefficient, sources, and propagation (Esteban et al., 2020; Fukui et al., 2022; Ishii et al., 2021; Kumar et al., 2021; Mabrouk et al., 2023). Besides, vegetation and buildings (green-gray infrastructure) had different impacts on the severity and pattern of tsunami inundation either when one was relied on or both were combined (Ali & Tanaka, 2020; Anjum & Tanaka, 2023; Sadashiva et al., 2022). A study by Woessner & Farahani (2020), which carried out modeling in a location where it is unlikely that a tsunami will occur (Shikoku Beach, Japan), found that the danger and risk of a tsunami is still a threat to occur unexpectedly due to beach characteristics connected to the open seas, for example, coast facing the Pacific ocean. Therefore, detailed tsunami wave modeling must consider the roughness coefficient and regional characteristics.

Tsunamis triggered by large magnitudes generally cause extensive inundations due to complex non-linear relationships that influence wave propagation and direction. Considering that the level of tsunami risk is directly related to the impact felt by humans, preparedness is essential to implement, especially in areas that are likely to be affected by tsunami waves and impending inundation (Chen et al., 2022; Hébert et al., 2020; Rafliana et al., 2022; Srinivasa Kumar & Manneela, 2021). Therefore, an in-depth assessment of the danger and risk of tsunami inundation is critical, especially in high-density areas. The study by Kihara et al. (2021), who modeled inundation and tsunami wave pressure at coastal industrial locations, found that inundation depth varied with the size of the affected area. They also confirmed that the inundation variations were caused by the influence of surrounding structures and blocking. It is crucial to evaluate disasters and highlight the potential for disaster reduction as a robust mitigation measure since coastal areas directly adjacent to the direction of the wave are exceptionally vulnerable to large tsunamis.

Several studies (Fukui et al., 2019; Yamaguchi & Sekiguchi, 2015) employed complex topography variables found that inundation and turbulence from tsunami events varied according to regional characteristics. The type and location of land use determine an area's vulnerability, capacity, and risk. These findings are supported by Park et al. (2013) through experiments on inundation height and flow velocity on a series of coastal structures. Reducing the severity of inundation due to the tsunami disaster can be done through appropriate land use configurations, especially by anticipating distances between the community and shorelines. According to Fukutani et al. (2018), quantitative risk assessment is vital for making effective decisions regarding tsunami risk management through assessments that can be applied to various land use types and scenarios. Indeed, coastal areas will experience the most significant inundation compared to areas far from the coast.

Furthermore, Freire et al. (2013) stated that the coastal area is susceptible to various hazard scenarios. Evaluation of inundation associated with land use type can produce accurate loss avoidance estimates. Remote sensing technology has played an essential role in tsunami disaster risk assessment, monitoring, and management. Fekete et al. (2015) conducted real-time risk assessments to facilitate rapid and coordinated disaster response. Their efforts have proven to have improved mechanisms that contribute to disaster resilience and preparedness. Therefore, paying more attention to areas prone to tsunami inundation is essential. Optimizing land-use configurations must be executed and implemented carefully so that the quality of life of coastal communities can improve.

In Indonesia, Vektori (2014), through observations, interviews, documentation, and triangulation studies, found that risk reduction due to the tsunami disaster in Bantul Regency, Special Region of Yogyakarta, can be done through institutional strengthening, risk assessment, planning, education, training, rehearsals, simulation, prepared early warning services, and robust evacuation facilities. In Kulonprogo Regency, which is still within the Special Region of Yogyakarta, Henny (2016) identified disaster risk factors and determined the level of tsunami disaster risk in Wates District using a geographic information system. Their study modeled tsunami hazards based on inundation variations (wave heights) with the help of Image Worldview-2, hazard modeling with the Berryman equation, and cost distance analysis.

Using a method that was relatively similar to the previous study, Habibi and Khakim (2016) extracted remote sensing data to obtain data on roads, land use, tsunami run-up, and evacuation route planning in Wates District when a tsunami transpired. It is believed that these findings could lead to sustainable coastal development in a better direction through policy integration, changes in government governance, and urban growth projections. Tang et al. (2011) stated that coastal management is beneficial in various activities: estuary and coastal protection; protection of beaches, hills, cliffs, and rocky shores; providing public access to beaches; revitalization of coastal areas, urban areas, and accommodation for port development.

Previous studies that has been carried out on a local and global scale has examined the dangers, vulnerabilities, and risks of tsunamis. However, they did not include a Procedural Planning System to support spatial planning that could reduce the risk of a tsunami disaster. Flood inundation modeling in this study used primary data from data acquisition in the field using Unmanned Aerial Vehicles (UAV). Land use data from the UAV acquisition that had gone through the orthorectification process was used for interpretation. This research also built and developed theoretical contributions related to tsunami hazard, vulnerability, capacity, and risk. Furthermore, the novelty offered by this research is the concept of a procedural planning system to develop spatial use zoning that places greater emphasis on mitigation aspects.

METHODS

Analysis of hazard, vulnerability, capacity, and risk level in Glagah Village can contribute new knowledge to regional development and spatial planning based on disaster mitigation. In addition, it is hoped that the spatial planning concept and land use allocations can be utilized by the Yogyakarta Special Region Government and stakeholders when considering development in Glagah Village, Temon District, Kulon Progo Regency, Yogyakarta Special Region. Analysis of danger, vulnerability, capacity, and risk level due to the tsunami disaster in Glagah Village was carried out using qualitative and quantitative methods. This method can provide a better understanding of tsunami disaster studies. This research consists of several stages: preparation, field survey, data collection, modeling, validation, evaluation, hazard assessment, and spatial planning. In the preparation stage, this research compiled a flight path and recorded the appearance of Glagah Village using Unmanned Aerial Vehicles (UAVs).

The risk of a tsunami disaster was developed by assessing the vulnerability by identifying and calculating the level of vulnerability from land use, the physical condition of the area, social conditions, availability of infrastructure, and economic elements. The next stage was a capacity analysis, which was obtained by assessing regional resilience and community preparedness. In the final stage, a spatial plan was designed to recommend land use that considers the impact of tsunami waves in the 5 m and 11 m scenarios. Detailed spatial maps with scales of 1:5,000 and 1:1,000 are expected to be useful as instruments for tsunami disaster mitigation at the pre-disaster stage by recommending better land use configuration.

Aerial Photography

Aerial photography was done with the Skywalker X-8 carrying a Sony A5000 with a focal length of 16 mm. The vehicle's cruising height was 300-500 meters, with an average flight length of 25-35 minutes/flight. The area coverage was 500 ha/flight with a 27-35 km/flight distance. Considering the research area's weather conditions and anticipating cloud challenges, the recording was done from 8:00 to 11:00 a.m. and 2:00 to 3:30 p.m.

Photo Acquisition

The aerial photo acquisition stage was carried out by describing the flight path in as much detail as possible using the Mission Planner. Figure 1 below shows the flight path results using the Mission Planner software.

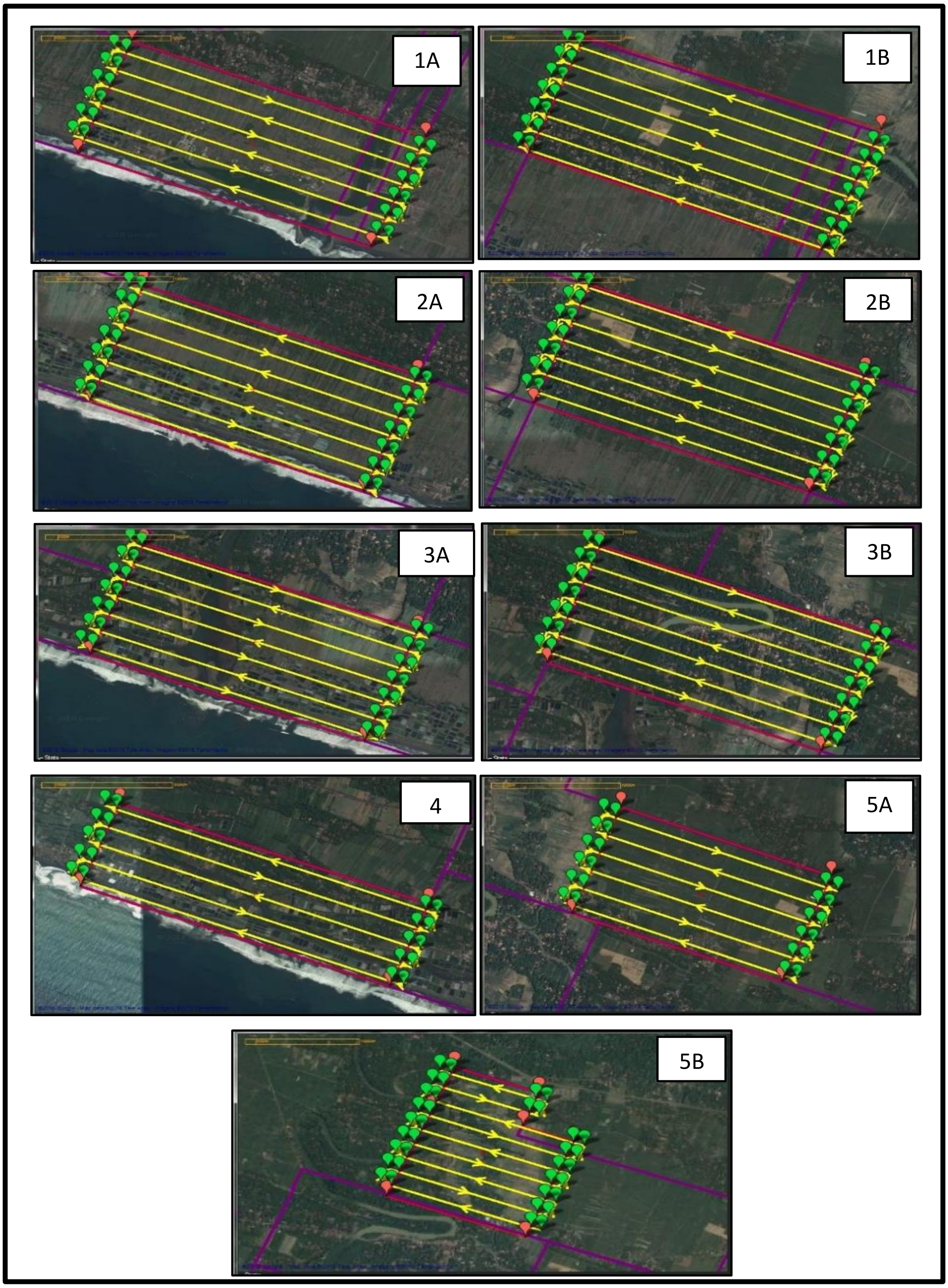


Figure 1. The flight path using the mission planner

The flight path was divided into nine blocks, considering the UAVs' capability in data acquisition, optimum recording conditions, weather conditions, and wind speed. Considering wind speeds are relatively fast in coastal areas, the acquisition process began on 18-21 October 2018. Data acquisition in the Temon District, representing Glagah Village, resulted in 1,524 photos. Since there were some disturbances in the results of the photos, not all photos used in the processing became orthophotos. Table 1 below shows the number of photos in each block.

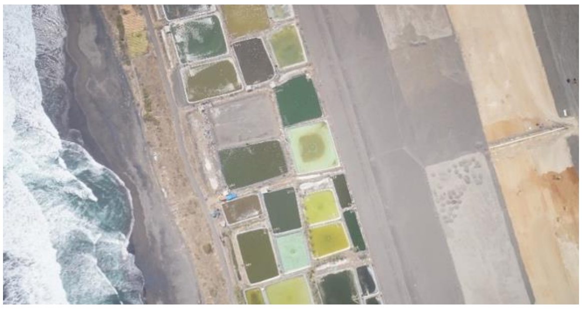
Table 1. Number of Photos on Each Flight's Block

No	Flyway blocks	Total photos
1	Block 1A	145
2	Block 1B	198
3	Block 2A	193
4	Block 2B	187
5	Block 3A	190
6	Block 3B	188
7	Block 4	146
8	Block 5A	131
9	Block 5B	146
Total		1,524

Several aerial photographs using the UAV are shown in Figure 2.

a. Over exposure

b. Normal exposure



c. Underexposure

Figure 2. Aerial photography acquisition results using a UAV in various exposures

There are several differences in brightness levels caused by lighting and camera quality. Figure 2a shows an overexposure result where the photo contains an excessive brightness level, while Figure 2b gives a normal exposure. Besides, Figure 2c shows an underexposed photo due to a low brightness level.

Processing of aerial photographs into digital surface model data, orthophoto mosaics, and digital terrain model.

The subsequent processing stages after a photo acquisition were selecting and uniforming the contrast and brightness of each photo. Contrasting uniformity and sharpening (enhancement) needed to be done so that the point cloud detection in detecting sequence and position could run smoothly. If contrast uniformity were not carried out, the high contrast difference would fail in the identification process. As a result, it will not be easy to process the orthophoto mosaic; therefore, the photos cannot be processed into Digital Surface Modeling (DSM). The results of uniformity of contrast and brightness are presented in Figure 3.

Figure 3. Contrast and brightness enhancement results

The collected photos from the enhancement results were then processed using Agisoft Photoscan. The orientation factor in the camera calibration results was included to minimize errors due to camera lens distortion. The best geometric accuracy test results from these configurations were used as the primary spatial data in this study.

Digital Surface and Digital Terrain Modeling

The essential basic topography and terrain elevation data were used to model the tsunami run-up height, tsunami wave refraction, and slope maps. The earliest function of DSM was the creation of orthophoto mosaics (Ruzgienė et al., 2015), and it was used to eliminate relief errors from aerial photographs so that aerial photographs had orthogonal projections and the same scale in all areas of the photograph. Making DSM with Agisoft Photoscan was made at the point cloud densification stage. The densification was then continued with the interpolation process to become a DSM into a raster file.

As a data product derived from DSM, the Digital Terrain Model (DTM) is a height model of the earth's surface without vegetation objects and manmade features. The stages of deriving DTM data from DSM data started from determining, selecting, and removing the height of objects that were not ground-level heights. The removed area was then interpolated with the surrounding ground-level data (Perko, 2013; Sammartano & Spanò, 2016).

Orthophoto Mosaics

The last stage of aerial photo processing was creating orthophotos for each processed aerial photo and combining them into an orthophoto mosaic. The process used DSM input (in the form of TIN) and aerial photographs. The TIN format was used to correct the relief displacement of objects from aerial photographs so that the photos were projected **orthogonal** and the coordinate positions were accurate. If all the photos in the block had gone through the orthorectification process, the following process was the blending process between the photos so that the joints between the photos, contrast, and brightness were uniform for all areas.

Testing the Geometric Accuracy of The UAV Acquisition Results

Accuracy tests were carried out on orthophoto mosaics for horizontal accuracy, while vertical accuracy tests were carried out on Digital Surface Model (DSM) data. The geometric accuracy test was carried out based by compared the coordinates (x, y, z) at the Independent Check Point (ICP) using the Geodetic GNSS with orthophoto and DSM coordinates (x, y, and z). Accuracy calculations were carried out at 20 distribution points and the number of Ground Control Points (GCP). The design position and total distribution of GCP and ICP in Temon District can be seen in Figure 4.

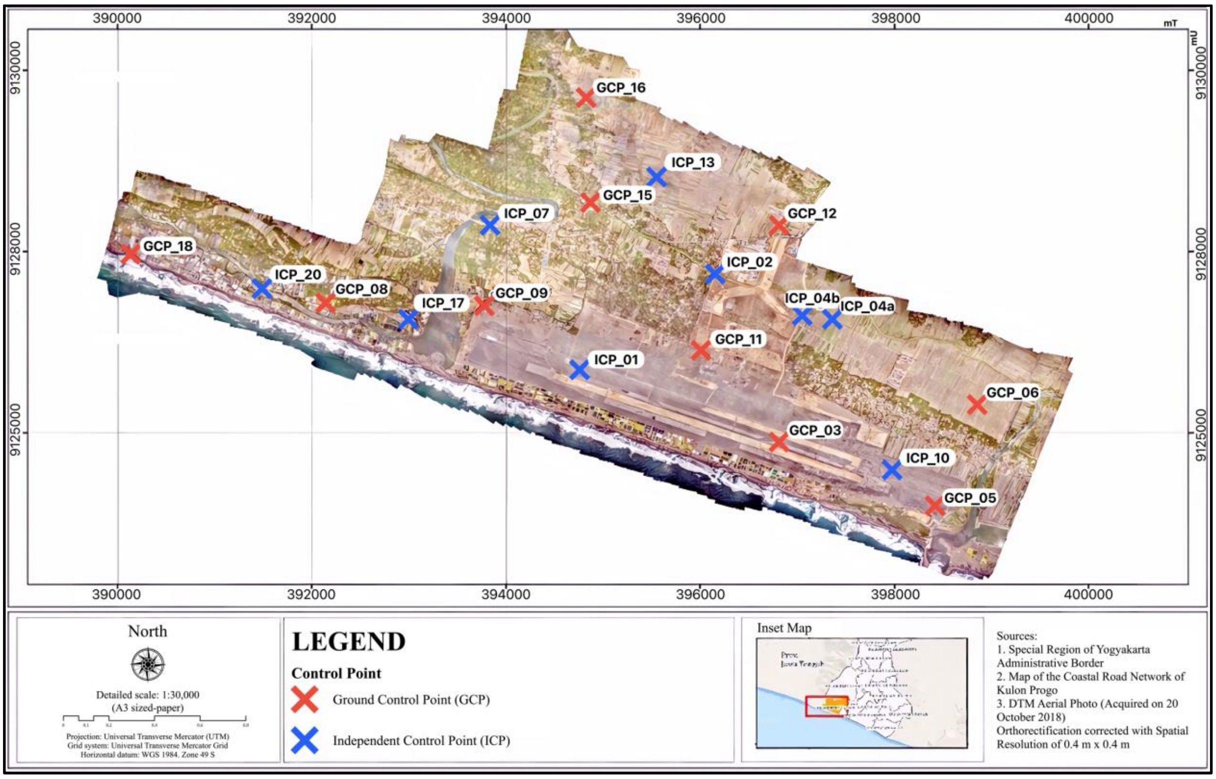


Figure 4. Map of the distribution of Ground Control Points and Independent Checkpoints in Temon District 2019

The results of the geometric accuracy test showed that the orthophoto mosaics in this study had fulfilled the requirements based on PERKA BIG No. 15 of 2014 concerning Basic Map Accuracy Technical Guidelines as primary spatial data on a 1:2,500 scale mapping. RMSE results obtained a value of 0.067, the horizontal accuracy of CE95 was 0.116, and the horizontal accuracy of CE90 was 0.101. Those values met the requirements according to the Basic Map Accuracy Technical Guidelines (PERKA BIG 15, 2014).

Tsunami Hazard

Tsunami hazard analysis was done through the below equations:

$$c = \sqrt{g.h} \quad (1)$$

Where c is speed, g = 9.8 m/s, and h is water depth.

Tsunami scale (Magnitude)

$$m = \text{Log2}\ H_{max} \quad (2)$$

Where m is the magnitude, and H_{max} is the wave height.

$$m = 2.26\ M - 14.18 \quad (3)$$

Where m is tsunami magnitude, and M is earthquake magnitude.

Tsunami numerical modeling

The model used in this study was an inundation model according to mathematical calculations based on Equation 1 with the help of a spatial analyst in the Geographic Information System software. The parameter used was the worst possible tsunami wave height that could occur due to the tsunami propagation according to the Imamura-Iida scale (Diposaptono, 2008; Triatmodjo, 1999). This variable, combined with changes in water flow on land and its influence on natural features such as sandbanks, coastal vegetation, buildings, rivers, and topography, dramatically affects inundation. The variable approach used in this modeling, according to Berryman (2006), is the surface roughness coefficient. In flat coastal areas, the equation used to determine the inundation distance toward land according to the UK Tsunami Initiative is as follows:

$$X_{max} = \frac{0.06\ (H_0)^{4/3}}{n^2} \quad (4)$$

X_{max} is the distance of inundation and shoreline toward land, H_0 is the height of the tsunami waves on the shoreline, and n is the surface roughness coefficient.

Equation 4 by Hawke's Bay and Wellington was modified to include variable surface elevation variations (Berryman, 2006). The magnitude of the slope represents variations in surface elevation. Modification of the equation is shown in Equation 5 below:

$$H_{loss} \left(\frac{167\ n^2}{H_0^{1/3}}\right) + 5 \sin S \quad (5)$$

H_{loss} is the loss of tsunami height per 1 m of inundation distance, n is the surface roughness coefficient, H_0 is the height of the tsunami waves on the shoreline, and S is the magnitude of the surface slope.

Vulnerability

Assessment of the vulnerability level to tsunami hazard was carried out by identifying and calculating the level of vulnerability from land use, the physical condition of the area, social conditions, availability of infrastructure, and economic elements. The village administration was the unit of analysis used to determine the vulnerability level. The steps used to predict the level of vulnerability: (a) carried out the overlay stage of the tsunami hazard map from primary data with administrative maps of villages within the tsunami hazard zone (BNPB, 2012; GIZ-PROTECTS, 2011); (b) identification of the components/elements that are at risk of tsunami hazard in areas consisting of physical, social, economic and environmental elements. The parameters used are based on the regulation of the head of the National Agency for Disaster Countermeasures Number 2 of 2012 (BNPB, 2012).

Capacity Analysis

Regional capacity consists of two main components: regional resilience and community preparedness. Initially, the index and level of regional resilience were assessed using the HFA indicator (UNISDR, 2007). Then, these indicators were updated based on the 2020-24 National Medium Term Development Plan Policy and Strategy Directions: (a) disaster risk reduction within the framework of sustainable development at central and regional levels; (b) reducing the level of vulnerability to disasters; (c) increasing the capacity of the government, regional governments and communities in disaster management. The priority focuses on capacity: (a) strengthening policies and institutions; (b) risk assessment and integrated planning; (c) development of information, training, and logistics systems; (d) thematic handling of disaster-prone areas; (e) increasing the effectiveness of disaster prevention and mitigation; (f) strengthening disaster emergency preparedness and handling; and (g) development of a disaster recovery system. The community preparedness assessment was adapted from the Community Preparedness Study for Tsunami Disaster prepared by the Indonesian Institute of Sciences for the community level and has been implemented since 2013 in District/City level Disaster Risk Assessments in several regions of Indonesia (LIPI-UNESCO/ISDR, 2006).

Risk

Knowing the level of disaster risk in an area can be done by carrying out a disaster risk assessment and connecting several parameters related to disaster risks, such as threat, vulnerability, and local community capacity to face the possibility of a disaster. Tsunami disaster risk assessment was carried out based on the Regulation of the Head of the National Disaster Management Agency Number 2 of 2012 by applying the following risk formulation (BNPB, 2012):

$$R = H \times \frac{V}{C} \tag{6}$$

Where R is disaster risk, H is danger, V is vulnerability, and C is capacity.

Based on Equation 6, it can be seen that the level of disaster risk in an area will be greater if the level of threat and vulnerability is high but the capacity is low. This component was used to obtain a disaster risk level for an area by calculating the potential for exposed lives, property losses, and environmental damage.

Research framework

Inundation modeling was carried out due to the tsunami disaster because Glagah Village is one of the coastal villages experiencing rapid growth due to direct interaction with Yogyakarta International Airport. Pre-inundation modeling began with primary data acquisition in the field using an unmanned aerial vehicle (UAV). Flight path and ground control station to monitor/control aircraft were operated using Mission Planner. Small-format aerial photos from

UAV data were processed with digital photogrammetry using Agisoft Photoscan (Agisoft, 2018). This software uses the Structure from Motion (SfM) method to reconstruct aerial photo blocks into photo mosaics and Digital Surface Models (DSM). Digital Elevation Model (DEM) data was collected in areas with dense infrastructures. Digital Terrain Model (DTM) data was one of the parameters used to produce tsunami hazard maps, and it was obtained by deriving DSM data. Testing the geometric accuracy of the shooting results was carried out by measuring Ground Control Points (GCP) and Independent Control Points (ICP) using a geodetic Global Positioning System. Besides, the distribution and number of GCPs represent the topography and relief configuration (Liu et al., 2022).

GCP is used for the block bundle adjustment process. Thus, the point of cloud coordinates (initially the model coordinates) become actual coordinates in the field. Meanwhile, ICP is a field coordinate for testing the accuracy of orthophoto and digital surface models. GCP and ICP measurements in the field used the geodetic Global Navigation Satellite System with accuracy reaching centimeters or below the pixel size of aerial photographs. The objects selected as GCP and ICP must be apparent, contrast with the surroundings, stationary, remain, and not experience change/shift much over a long period, such as road intersection corners, building corners (not roofs), road markings, and rice field embankment intersections. The design of the number and distribution of GCPs in this study was carried out in 12 configurations. DTM data to produce tsunami hazard maps for rural areas uses Demnas data (TerraSAR-X) from the Geospatial Information Agency of Indonesia (PERKA BIG 15, 2014). Data obtained from UAVs undergoing orthorectification in photo mosaics were used for land use interpretation. Aerial photography planning was started with setting the desired output specifications and assessing the characteristics of the area to be photographed.

The output from aerial photography was expected to have accuracy on a scale of 1:5,000, with horizontal and vertical geometric accuracy as primary data for tsunami disaster mapping. This research was designed to obtain dimensions of spatial resolution with a Ground Sampling Distance <10 cm. Based on the output objectives and assessment of regional characteristics, fly-wing UAVs were suitable for aerial photography vehicles in the study area. The recording time was around 08.00 to 14.00 WIB to avoid strong winds, hotspots/sunglint, and cloud shadows. Tsunami numerical modeling is a mathematical series that explains tsunami waves based on past events and their effects (Mardi et al., 2015). The tsunami inundation modeling in this study is a numerical model, where wave speed and seabed topography, such as propagation models, are not considered. Topographic data obtained from DEM from processing small format UAV aerial photos was derived to obtain slope data. Meanwhile, orthophoto mosaics were interpreted to obtain land use data. Then, land use data was processed to obtain information on the surface roughness of the research area.

Inundation modeling due to tsunamis in this study was carried out with two wave scenarios (5 and 11 m), considering that these two wave heights are tsunami events that often occur on the south coast of central Java (BNPB, 2012). The two derived data (slope and surface roughness) and the tsunami run-up wave height obtained from reference tsunami events in the research area were the inputs in tsunami modeling. The model results appearing in tsunami inundation were then overlaid with land use maps to analyze vulnerability, capacity, and risk in two wave height scenarios. Assessment of the vulnerability level to tsunami hazards was carried out by identifying and calculating the vulnerability of land use, physical conditions of the area, social conditions, availability of infrastructure, and economic elements. The unit of analysis used to determine the level of vulnerability is the village/sub-district administration. Steps used to reduce the level of vulnerability: (a) overlaying tsunami hazard maps from primary data with administrative maps of villages/sub-districts located in the tsunami hazard zone, (b) identifying component elements that are at risk of tsunami hazards consisting of physical, social, economic and environmental elements. The parameters used follow the recommendations of BNPB (BNPB, 2012).

Risk level assessment was carried out by linking several parameters related to disaster risk, such as threats, vulnerabilities, and the capacity of local communities to face the possibility of tsunamis. The tsunami disaster risk assessment follows the Regulation of the Head of the National Disaster Management Agency Number 2 of 2012 (BNPB, 2012). Therefore, the disaster risk level will be greater if the hazard and vulnerability levels are high but the capacity is low. Hazard, vulnerability, and capacity were assessed to obtain disaster risk levels by calculating the potential for exposure to life, property loss, and environmental damage. Disaster risk maps are consist of hazard, vulnerability, and capacity. In the final stage, this research prepared a detailed spatial arrangement with a scale of 1:5,000 and 1:1,000 as a basis for land use configuration and tsunami disaster mitigation instruments at the pre-disaster stage. In addition, land use exposure to tsunamis was configured into four levels: low, medium, high, and unexposed.

RESULTS AND DISCUSSION

The surface roughness coefficient was differentiated based on the type of detailed land use according to Putra (2008), which is the result of a modification and classification of surface roughness based on the type of land cover made by Berryman (2006).

Surface Roughness Coefficient

The primary data needed was processing small format aerial photographs/UAV: DEM and orthophoto mosaics. DEM data was processed to obtain slope data, while orthophoto mosaics were interpreted to obtain land use data. Land use data was derived from information on the surface roughness of the study area. Slope and surface roughness data were used as two inputs in tsunami modeling. The third input was the height of the tsunami run-up wave, obtained from the reference of the tsunami in the study area. The surface roughness data derived from the interpretation of land use is detailed in Table 2.

Table 2. Surface Roughness Coefficient in Glagah Village 2019

No	Land use	Roughness coefficient	Area (ha)	Proportion (%)
1	Sand	0.018	7.04	1.15
2	Main road	0.02	13.02	2.14
3	Field	0.03	49.12	8.05
4	Vacant land	0.02	18.94	3.11
5	Open field	0.02	2.86	0.47
6	Grave	0.03	1.18	0.19
7	Median strip	0.02	0.21	0.03
8	Sports facilities	0.05	0.06	0.01
9	Meadow	0.02	0.03	0.01
10	Beach	0.018	6.51	1.07
11	Tourism and entertainment	0.05	6.57	1.08
12	Dune	0.018	188.53	30.91
13	Breakwater	0.05	0.2	0.03
14	Educational building	0.05	0.34	0.06
15	Worship building	0.05	0.26	0.04
16	Office complex	0.05	0.38	0.06
17	Mixed plantation	0.035	42.81	7.02
18	Other plantations	0.035	1.39	0.23
19	Settlement	0.05	54.78	8.98
20	Streets	0.02	0.01	0.01
21	Runway	0.02	26.8	4.39
22	Rice field	0.02	113.55	18.62
23	Shrubs	0.04	2.77	0.45
24	River	0.007	15.98	2.62
25	Extra High Voltage Overhead Lines	0.05	0.16	0.03
26	Fishponds	0.01	10.44	1.71
27	Transportation	0.05	45.94	7.53

The highest surface roughness coefficient value in Glagah Village is 0.050, consisting of transportation (7.53%), Extra High Voltage Overhead Lines (0.03%), settlements (8.98%), office complex (0.06%), worship building (0.04%), education building (0.06%), breakwater (0.05%), tourism and entertainment (1.08%), sports facilities (0.01%). The second largest surface roughness coefficient value is 0.04 consisting of shrubs (0.45%), followed by a roughness coefficient value of 0.03 consisting of fields (8.05%), graves (0.19%), mixed plantations (7.02%), and other plantations (0.23%). The rest of the roughness coefficient is below 0.03.

Hazard level

The total exposed area in Glagah Village with a 5-m wave scenario was 53.83 ha, primarily affecting areas categorized in low index level (26.04 ha). As expected, the total exposed area with the 11-m wave scenario was higher (168.65 ha), resulting in a difference of 114.82 ha compared to the 5-m wave scenario, as shown in Figure 5.

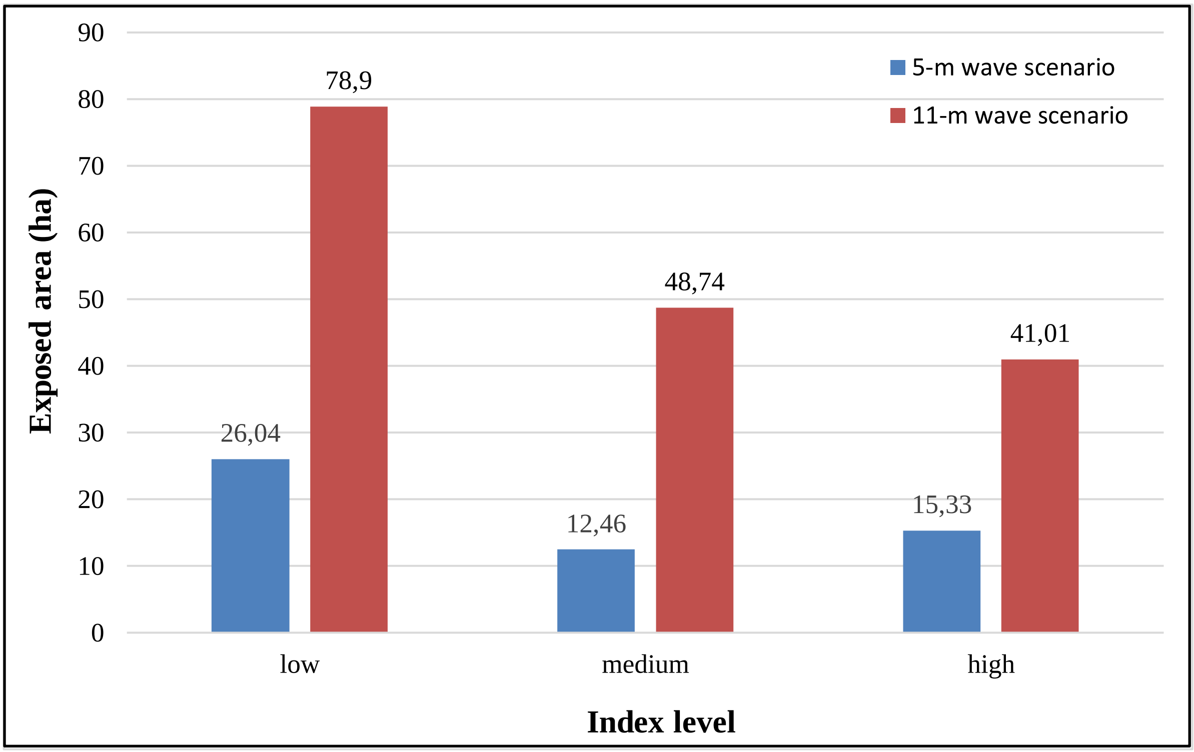


Figure 5. Level of exposed area to tsunami hazard in Glagah Village with 5 and 11 m wave scenarios

Through a 5-m wave scenario, the present study found vacant and sandy land was dominant, accounting for up to 25.38% of the total low-index area (26.04 ha). Vacant land is deemed a low hazard index due to the absence of housing and public infrastructure. This justification is supported by the acquisition of aerial photos showing that the vacant land was undergoing a leveling process for the airport's construction. Various land uses were affected in each index level through an 11-m wave scenario. It is worth noting that the tsunami inundation within medium and high index categories inundated the nearest human settlement to the coastal area, spreading through vacant land, sandy areas, public infrastructures, and rivers. Besides, the UAV acquisition found that the inundation was exacerbated by the presence of the river flow since rivers connected to seas would speed up water flowing into the mainland. It is crucial to reduce exposure to hazards, especially in human settlements falling within the high-vulnerability index, by reconfiguring land use types, increasing capacity, and protection measures using gray and green infrastructure.

Vulnerability

Through a 5-m tsunami wave scenario, the present study found 12.38 ha areas fall into the low vulnerability index, and fishponds were the most affected land use (61.79%). At the same time, rivers represent 30.05% of the 40.60 ha area categorized in a moderate vulnerable index. The present study found a 0.68 ha area categorized in a high-vulnerable index, and 86.78% consisted of housing and human settlement, as shown in Figure 6.

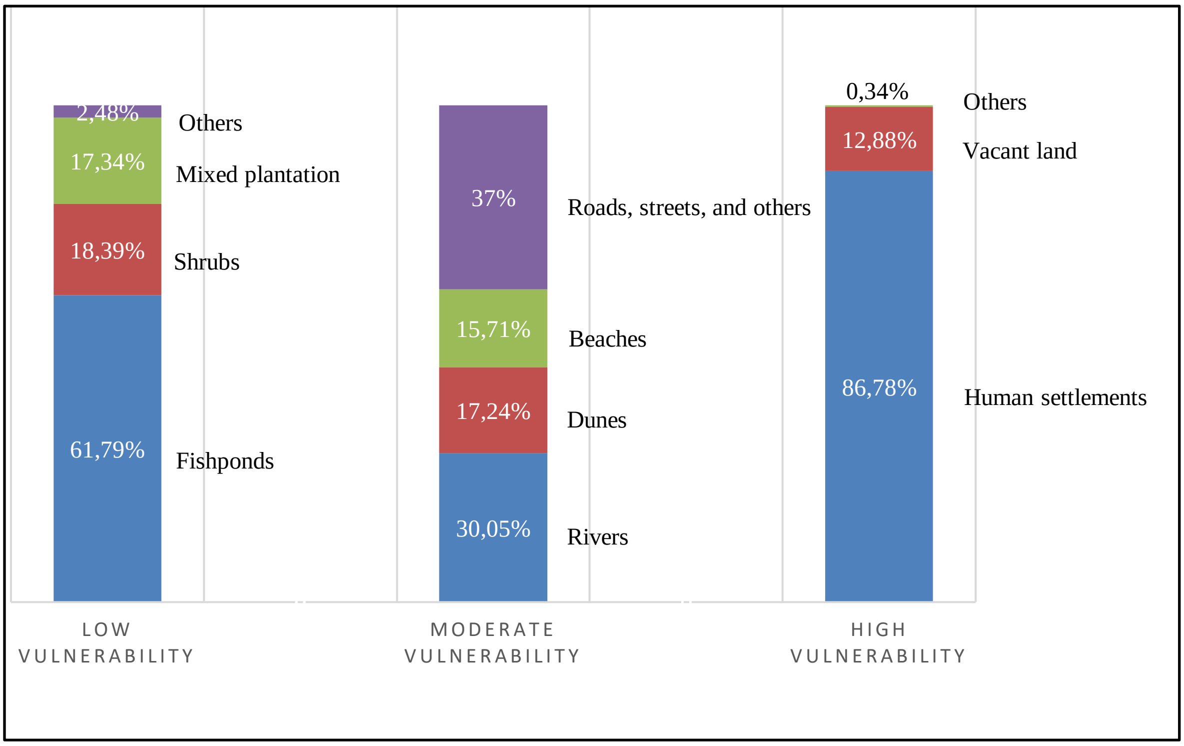


Figure 6. Land use's vulnerability index in Glagah Village with a 5-m wave scenario

When an area is densely populated, mobility, evacuation time, and proximity of settlements to high-risk areas are important indicators in the vulnerability index. According to Chen et al. (2022), evacuation time is affected by access to infrastructure such as bridges, roads, and vertical shelters. Therefore, strategic infrastructure in the evacuation process should be considered while considering the capabilities of the residents living in areas with high risk of tsunami, especially those with high vulnerabilities, such as women, children, the elderly, and people with physical constraints. The vulnerability index map with a 5-m wave scenario is presented in Figure 7.

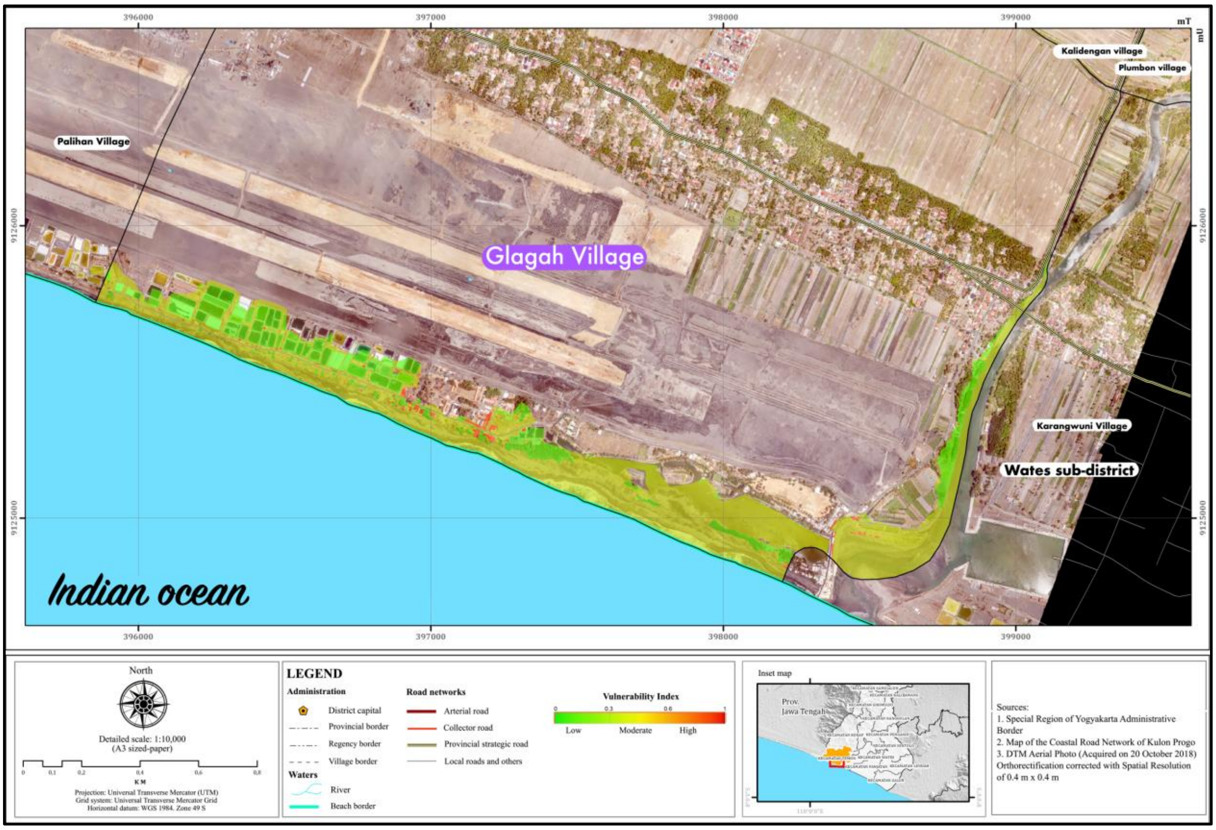


Figure 7. Vulnerability index map in Glagah Village with a 5-m wave scenario

Tsunamis' exposure impacting key land use that the community depends on for living is one of the crucial determinants in vulnerability assessment. In general, the vulnerability index in Glagah Village with a 5-m wave scenario is spread across low, moderate, and high, primarily impacting fishponds, rivers, and beach borders. At a low index (green), the darkest green color can be found in fishponds, considering that this area is not in immediate contact with most human activity. Besides, the eastern region around the river also falls on the low vulnerability index due to mixed plantations and perennials with a relatively high roughness coefficient. Vulnerability in the moderate category can be found mainly at beach borders and rivers because this area has a low roughness coefficient. Besides, rivers and channels enable water to flow into the mainland when a tsunami comes, which may worsen inundation. Some non-permanent settlements fall into the high index category (red color) because these areas are closely related to human activities, both for living and working.

The tsunami inundation model in Glagah Village with an 11-m wave scenario can potentially affect broader land use. In the low vulnerability index, shrubs covering 2.08 ha were destroyed by 95%, while the remaining 5% was found in open land. Land use falling into the moderate category was affected by 162.29 ha, represented by 21 types of land use (28.73% of sandy area, 13.5% of rice fields, and 57.77% of public spaces and other infrastructures). Besides, 4.07 ha areas with a high vulnerability index were spread into 14 types of land use dominated by human settlements as high-risk locations (83.40%), as shown in Figure 8.

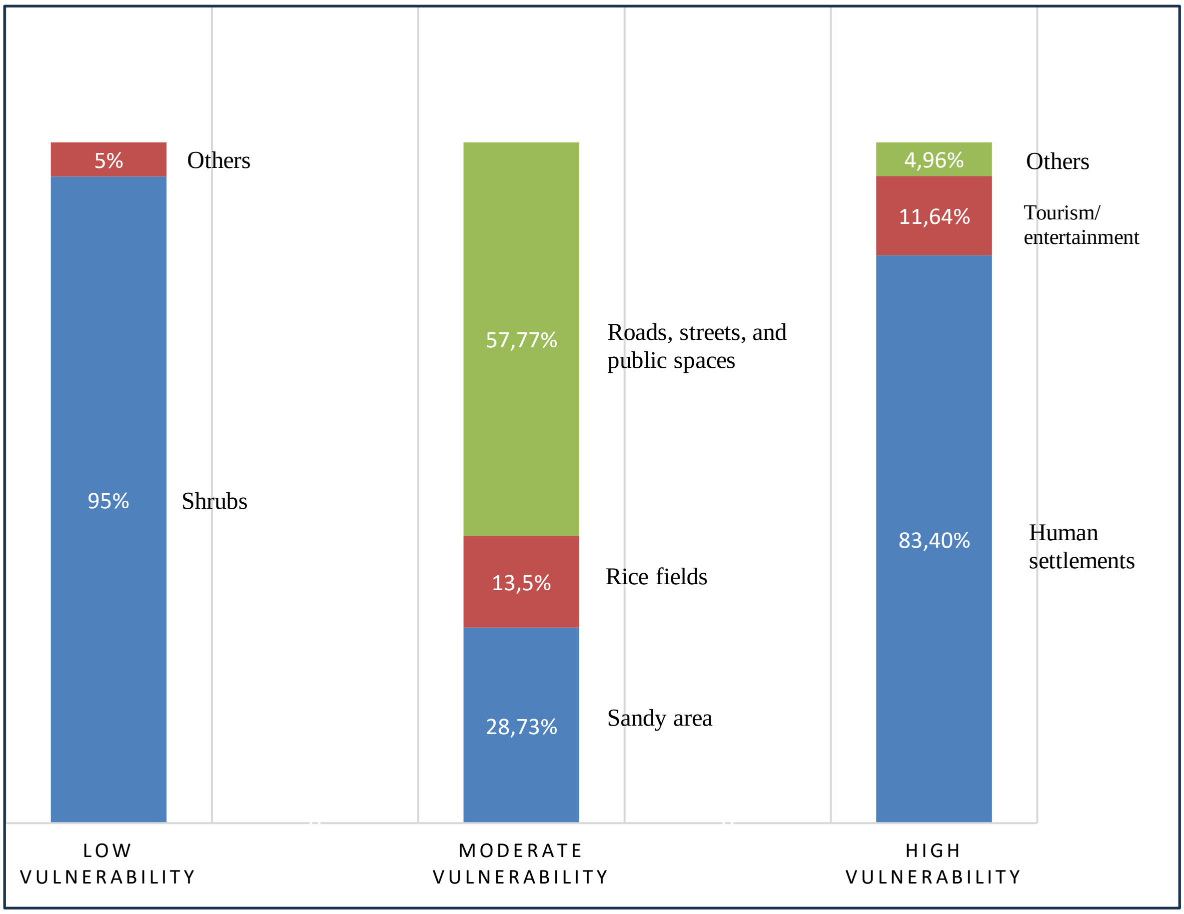


Figure 8. Land use's vulnerability index in Glagah Village with an 11-m wave scenario

Land use as tourism and entertainment ranked second (11.64%), while 12 other land uses were around 4.96%. Vulnerability often refers to the physical vulnerability of the sufferer to a threat measured by potential loss and damage. Besides, vulnerability is also influenced by exposed groups' capacity to respond to an incident. This study found that with a 5-m wave scenario, a high vulnerability index with the highest rate was found in human settlements (Figure 6). A similar result was also found with an 11-m wave scenario, as 83.40% of 4.07 ha consisting of human settlements were at a high-risk zone (Figure 8). The vulnerability index map with an 11-m wave scenario is presented in Figure 9.

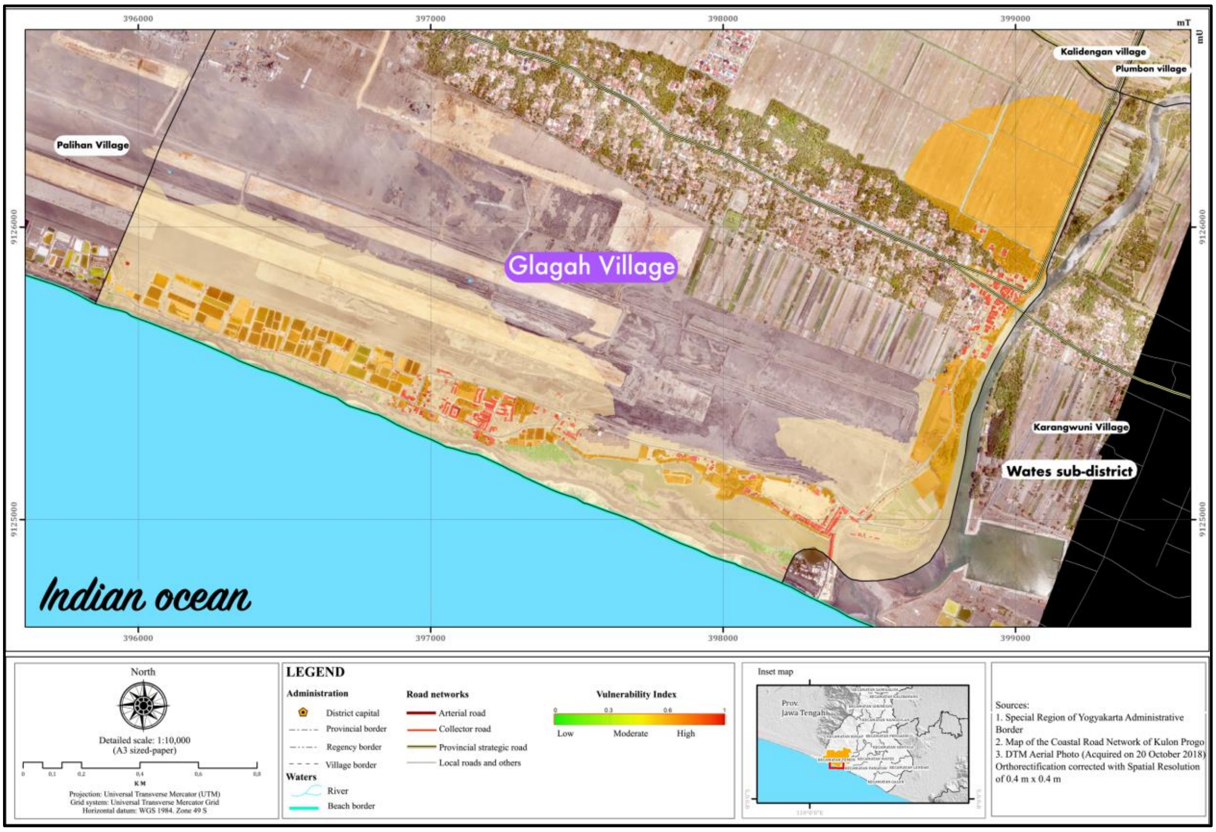


Figure 9. Vulnerability index map in Glagah Village with an 11-m wave scenario

The vulnerability index in Glagah Village with an 11-m wave scenario covers a wider area than the 5-m wave scenario. In general, the vulnerability index in Glagah Village with an 11-m wave scenario is mostly classified in the moderate category (162.29 ha), impacting rice fields, fishponds, public spaces, roads, streets, and other infrastructures. The high wave scenario submerges all non-permanent settlements near the coast related to human activities (high index category marked with red color). Furthermore, in the eastern part, inundations can reach human settlements further, enabled by rivers that have a very low roughness coefficient. The human settlement where a social group lives is an essential element that can define an area's vulnerability since buildings and public facilities cannot be separated from human activity. The location and building density in a specific area are two factors influencing vulnerability to a disaster. Good planning in determining the location and access to safe places influences preparedness, leading to capacity for self and group evacuation.

Capacity

Capacity assessment in this research was carried out through literature studies and direct observation in the field. The capacity of the tsunami is the ability of the region and the community to take action in facing threats and potential losses with structured and integrated prevention schemes. Basic assessment in capacity analysis refers to the Regulation of the National Disaster Management Agency Number 2 of 2012 (BNPB, 2012). The primary variables used appeared to be regional resilience and community preparedness. Evacuation routes, distance to the hospital, easy access to the hospital, and the main street lighting strengthen regional resilience. Meanwhile, community preparedness appeared in safety equipment (rubber boats, tents, and masks), functioning tsunami early warning systems, cellular signals, disaster preparedness groups, and disaster mitigation familiarization.

The capacity description in Glagah Village consists of components such as regional resilience and community preparedness. According to the Regional Disaster Management Agency of Kulon Progo Regency (2024), Glagah Village is one of seven Indonesian representatives facilitated to become part of the UNESCO-IOC Tsunami Ready Community. As a council under UNESCO, the Intergovernmental Oceanographic Commission (IOC) has assessed 12 indicators that can be used as capacity benchmarks (UNESCO-IOC, 2024). This collaboration confirms that Glagah Village has an excellent capacity to deal with tsunami disasters because it has:

1. A tsunami hazard map;
2. Reports estimating the number of people in tsunami hazard areas;
3. A public information board;
4. An inventory of economic, infrastructure, political, and social resources to reduce the risk of tsunami hazards;
5. A tsunami evacuation map;
6. Tsunami education and disaster preparedness materials;
7. Regular tsunami education and disaster preparedness activities;
8. Regular tsunami training;
9. A tsunami emergency operations plan;
10. The capacity to implement emergency operations plans;
11. The ability to receive earthquake information and tsunami early warnings 24/7; and
12. The ability to disseminate earthquake information and tsunami early warnings 24/7;

Regional Disaster Management Agency of Kulon Progo Regency (2024) stated that Glagah Village has become a role model for other coastal areas in Indonesia and recommends that the 12 indicators above be replicated so that an area becomes responsive and resilient to disaster threats. Furthermore, through direct observation, the present study categorized Glagah Village as a "high" capacity index since it has an evacuation route, a working tsunami early warning system, and the availability of safety equipment (rubber boats, tents, mask supplies).

Risk

The 5-m wave scenario put Glagah Village in three risk categories: low, moderate, and high. It was found that the low-risk index (52.99 ha) marked as green was expected to affect 15 types of land use, such as mixed plantations, rivers, fishponds, dunes, and sandy areas. The risk index of Glagah Village with a 5-m wave scenario is shown in Figure 10 below:

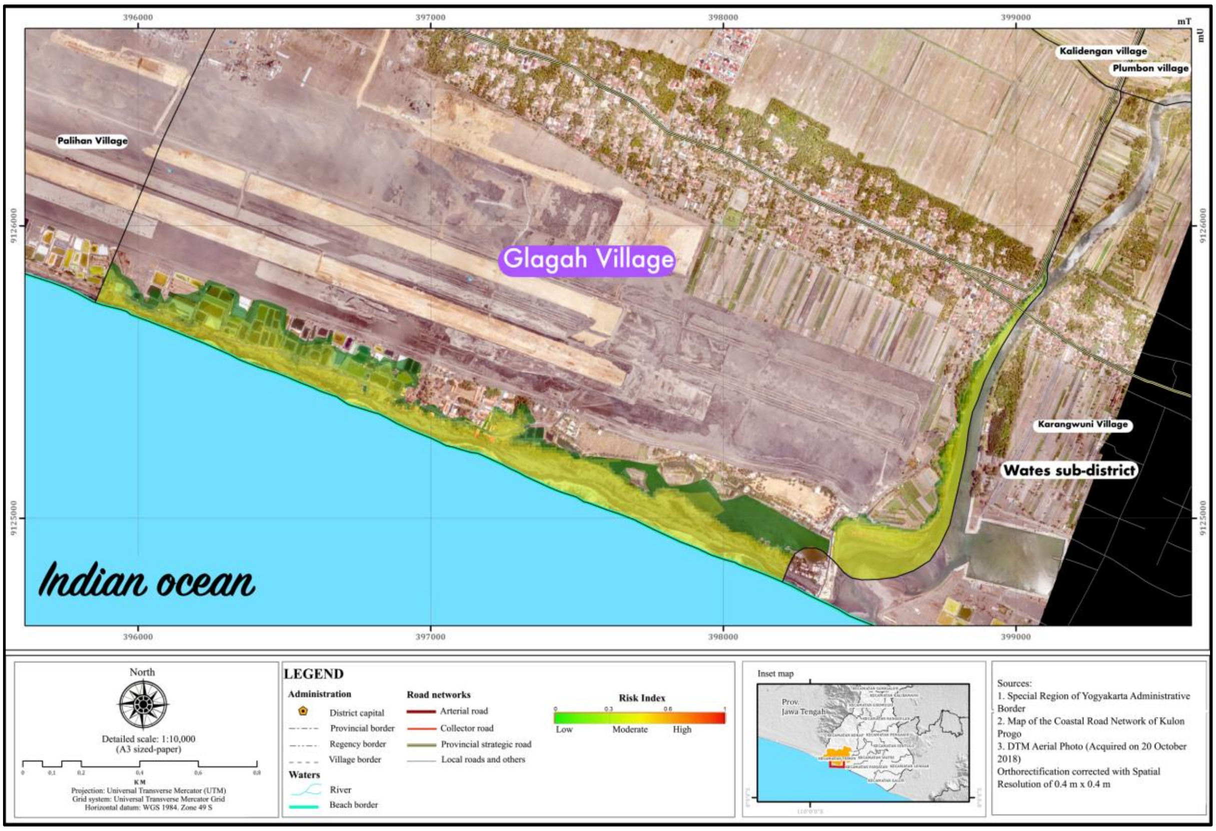


Figure 10. Risk index map of Glagah Village with a 5-m wave scenario

As shown in Figure 10, the moderate-risk category is dominant near the shoreline, beach border, and river since they have a low roughness coefficient (yellow). Besides, areas with high risk consisted of five land uses, dominantly appearing in human settlements, followed by vacant land and dunes. Human settlements fall into the high index category (red color) because this area is where humans harbor their activities. Therefore, protection for human settlements near the coastal area must be prioritized (red color).

Through an 11-m wave scenario, most areas with a low-risk index (36.07 ha) were found in the sandy area (43%), and the remaining were the runway. The medium-risk index was found in 20 types of land use (95.18 ha), dominated by sandy land, which accounted for 31.33 ha, followed by rice fields and other lands of less than 10%. The high-risk index was found in an area of 37.22 ha, spread into 14 types of land use, where rice fields were at high risk (33.21%). Land as tourism and entertainment ranked second with an area of 27.75%. In contrast, 12 other types of land use were less than 1%. The risk index of Glagah Village with an 11-m wave scenario is shown in Figure 11 below:

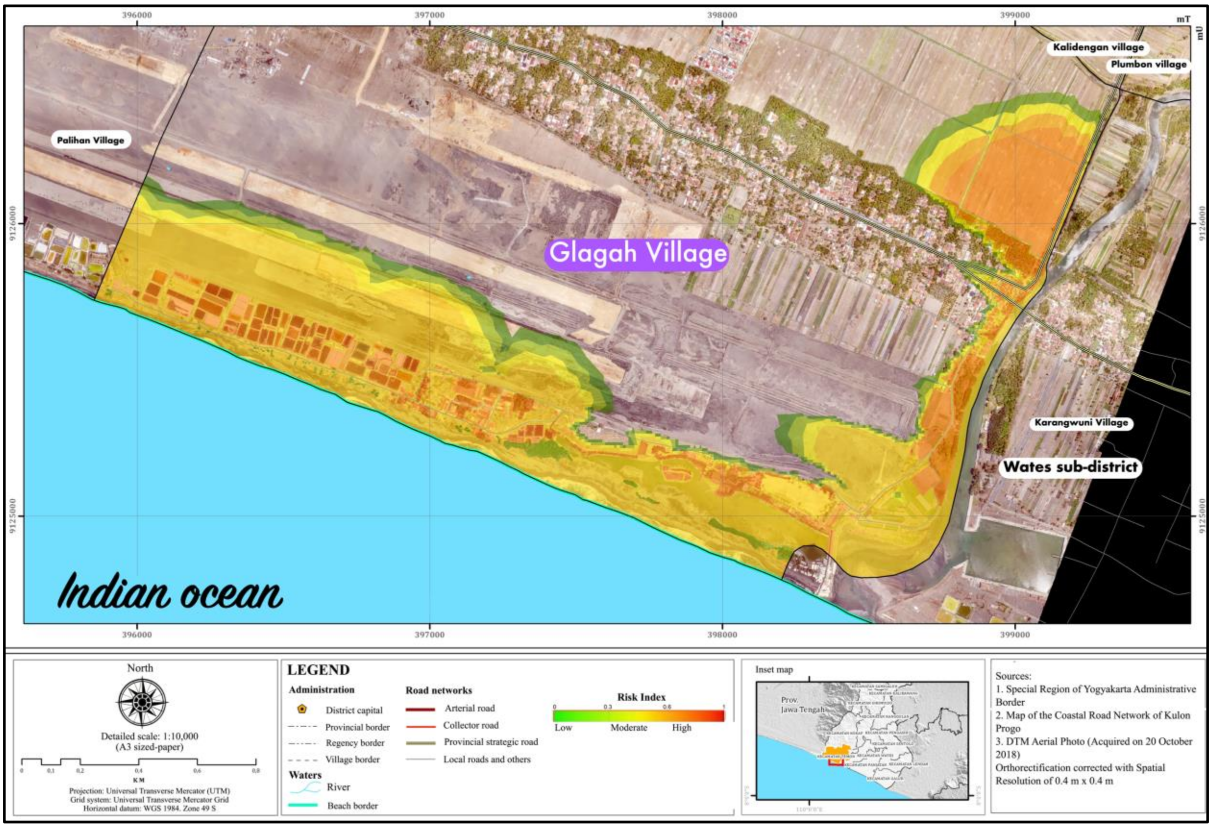


Figure 11. Risk index map of Glagah Village with an 11-m wave scenario

The inundation area with an 11-m wave scenario gives broader exposure, especially in the east, since rivers are enablers allowing water to travel further. All areas close to the coast fall into the moderate and high categories due to the high wave scenario, which results in extensive inundation. There are several areas with low index (green) near the shoreline protected by mixed plantations with relatively high roughness coefficients. Even though the vacant land has a low roughness coefficient, its risk index is categorized as low due to low inundation proportional to the distance from the beach (green color).

Awareness and preparedness to anticipate the risk of the tsunami's impact are determinants of the casualty rate. In addition, tsunami victims can be reduced through increased awareness and better spatial planning by considering disaster risks. The local government has made various efforts to enable risk experts to participate in disaster management through risk area contribution. However, the relationship between vulnerability and the ability to deal with the risks encountered in practice seems challenging to resolve.

According to Løvholt et al. (2014), death and damage rates based on previous disasters can be used to consider essential factors useful in disaster risk management. The expected outcomes from the related assessment will improve the ability of disaster preparedness attributes such as tsunami warning, mass distribution, age population categorization, disaster awareness, building design, and post-disaster budgeting. Given the high tsunami hazard zone threatening human settlements, disaster warning and prevention must be carried out effectively. Communities are expected to understand their position so that knowledge of dynamic population distribution, assembly point maps, tsunami risk maps, shelters, and provision of evacuation pathways becomes evenly distributed, leading to a more mature awareness of tsunami risk. Therefore, familiarizing the community with an awareness of disaster response is expected to reduce disaster risk, considering the potential for a tsunami that affects their homes, which can transpire anytime.

Detailed Spatial Planning: Reducing Exposure to Tsunami Risk

The detailed spatial planning for districts and cities according to the 2011 Regulation of the Minister of Public Works and Housing are areas equipped with zoning regulations consist of (a) structural planning areas, (b) a spatial plan, (c) infrastructure network plans, (d) determination of Sub-Divisions of Planning Areas with priority handling, (e) regulation for spatial utilization, and (f) zoning regulations (Ministry of Public Works and Housing, 2011).

The present study's procedural planning system considers physical, social, economic, and environmental factors, as well as regional and policy factors. Support of planning procedures focuses on capacity development to strengthen the organization and the people involved. Thus, the planning system can better serve a broader population by considering the roles of all stakeholders (Parker & Simpson, 2020). The result of the procedural planning system in the present study is presented in a detailed spatial plan based on tsunami disaster mitigation by considering the risk concept of the Hyogo Framework for Actions, which was adopted and modified by BNPB (2012). By considering that the risk index is correlated with tsunami threats, this research formulated a syntax using ArcGIS 10.5 so that the interpretation of spatial plan based on tsunami disaster risk can be carried out automatically following the hazard and vulnerability index level results. Queries and field syntax for automating space pattern zoning based on a procedural planning system are presented in Table 3.

Table 3. Syntax Queries and Fields for Spatial Pattern Calculation

Queries	Fields
"CLASS_RISK" = 'Low' AND "ZONE_SPATIALPATTERN" = 'Mixed Zone' "CLASS_RISK" = 'Low' AND "ZONE_SPATIALPATTERN" = 'Housing Zone' "CLASS_RISK" = 'Low' AND "ZONE_SPATIALPATTERN" = 'Trade and Services Zone' "CLASS_RISK" = 'Low' AND "ZONE_SPATIALPATTERN" = 'Office Complex Zone' "CLASS_RISK" = 'Low' AND "ZONE_SPATIALPATTERN" = 'Defense and Security Zone' "CLASS_RISK" = 'Low' AND "ZONE_SPATIALPATTERN" = 'Office Complex Zone' "CLASS_RISK" = 'Low' AND "ZONE_SPATIALPATTERN" = 'General Service Zone'	"The floor area ratio of one floor, the green area ratio of 20%, and the building coverage ratio is ≤ 80%."
"CLASS_RISK" = 'Moderate' AND "ZONE_SPATIALPATTERN" = 'Mixed Zone' "CLASS_RISK" = 'Moderate' AND "ZONE_SPATIALPATTERN" = 'Housing Zone' "CLASS_RISK" = 'Moderate' AND "ZONE_SPATIALPATTERN" = 'Trade and Services Zone' "CLASS_RISK" = 'Moderate' AND "ZONE_SPATIALPATTERN" = 'Office Complex Zone' "CLASS_RISK" = 'Moderate' AND "ZONE_SPATIALPATTERN" = 'Defense and Security Zone'	"The floor area ratio of two floors, the green area ratio of 25%, and the building coverage ratio is ≤ 75%."

Queries	Fields
"CLASS_RISK" = 'Moderate' AND "ZONE_SPATIALPATTERN" = 'Office Complex Zone' "CLASS_RISK" = 'Moderate' AND "ZONE_SPATIALPATTERN" = 'General Service Zone'	
"CLASS_RISK" = 'High' AND "ZONE_SPATIALPATTERN" = 'Mixed Zone' "CLASS_RISK" = 'High' AND "ZONE_SPATIALPATTERN" = 'Housing Zone' "CLASS_RISK" = 'High' AND "ZONE_SPATIALPATTERN" = 'Trade and Services Zone' "CLASS_RISK" = 'High' AND "ZONE_SPATIALPATTERN" = 'Office Complex Zone' "CLASS_RISK" = 'High' AND "ZONE_SPATIALPATTERN " = 'Defense and Security Zone' "CLASS_RISK" = 'High' AND "ZONE_SPATIALPATTERN" = 'Office Complex Zone' "CLASS_RISK" = 'High' AND "ZONE_SPATIALPATTERN" = 'General Service Zone'	The floor area ratio is≥ two floors, the green area ratio is 30%, and the building coverage ratio is ≤ 70%.

Syntax findings based on planning support system procedures are used to design detailed spatial planning based on tsunami disaster risk on scales of 1:5,000 and 1:1,000.

Detailed spatial planning on a scale of 1:5,000

According to Kato & Huang (2021), anticipating future disaster risks can be done by reducing hazard, vulnerability, and risk. In contrast, resilience elements can be improved by sustainable environmental management, conservation, training, familiarization, and management of land use. Based on the classification and space utilization matrix following the tsunami disaster risk analysis, the design plan for the tsunami's exposure areas on a scale of 1:5,000 is divided into three categories: low, medium, and high, as shown in Table 4.

Table 4. Detailed Spatial Plan of Glagah Village on a Scale of 1:5,000

No	**Low risk**		**Moderate risk**		**High risk**		**Unexposed**	
	Land use	**Area (ha)**	**Land use**	**Area (ha)**	**Land use**	**Area (ha)**	**Land use**	**Area (ha)**
1	Road	1.1	Road	2.6	Road	0.18	Road	10.43
2	River	0.68	River	19.19	River	1.85	River	2.33
3	Housing and support facilities	0.49	Housing and support facilities	0.23	Housing and support facilities	0.18	Housing and trade/services	10.48

No	Low risk		Moderate risk		High risk		Unexposed	
	Land use	Area (ha)	Land use	Area (ha)	Land use	Area (ha)	Land use	Area (ha)
4	Tourism and recreation facilities	0.51	Natural tourism	3.35	Nature tourism facilities	1.14	Manmade tourism	0.01
5	Housing and support facilities	0.01	Market, supermarket, malls, shops, hotels	0.04	Housing and support facilities	0.01	Trade and services	1.09
6	Rice field and farming	6.27	Medium-density mangroves and fisheries	0.45	Housing and support facilities	0.02	Capture fisheries	0.02
7	Low-density perennials	1.52	Defense and security	0.04	Low-density perennials	12.19	Office	0.25
8	Housing and support facilities	1.02	Plantation land	2.44	Medium density perennials	3.85	Plantation farming	51.68
9	Worship area	0.04	Rice field and farming	3.19	Housing and support facilities	0.08	Food crop farming	107.87
10	Airport	21.9	Housing and support facilities	0.18	Airport	0.15	Low-density housing	41.53
11	Cemetery	0.25	Airport	35.06	Cemetery	0	Medium-density housing	4.38
12	Other beach borders	2.23	Cemetery	0.01	Other beach borders	14.06	Public health service facilities	0.19
13	River border	0.06	High-density mangrove border	6.22	River border	3.5	Education public service facilities	0.58
14			Other beach borders	18.63			Public service facilities of worship	0.11
15			River border	3.57			Socio-cultural public service facilities	0.12
16	-	-	-	-	-	-	Public transportation service facilities	202.81
17	-	-	-	-	-	-	The protected area of local wisdom and spirituality	0.07
18	-	-	-	-	-	-	Village park	0.19
19	-	-	-	-	-	-	Cemetery	1.05
20	-	-	-	-	-	-	District park	3.78
21	-	-	-	-	-	-	Sub-district park	0.23
22	-	-	-	-	-	-	Other beach borders	0.67

No	Low risk		Moderate risk		High risk		Unexposed	
	Land use	Area (ha)	Land use	Area (ha)	Land use	Area (ha)	Land use	Area (ha)
23	-	-	-	-	-	-	River border	1.4

At a low-risk level (36.08 ha), the highest land use types consecutively consist of transportation, agriculture/food crops, roads, and beach borders (33.02 ha). The procedural planning identified land use in the low-risk level as a floor area ratio of one floor, a green area ratio of 20%, and a building coverage ratio of less than 80%. The total area in this category primarily consists of housing, support facilities, markets, supermarkets, malls, shops, and hotels (1.56 ha). At a moderate risk level (95.2 ha), the highest types of land use in sequence consist of transportation, river, beach borders, high-density mangroves, and river borders (82.66 ha).

The procedural planning identified land use in the moderate risk category as the floor area ratio of two floors, a green area ratio of 25%, and a building coverage ratio of less than 75%. The total area in this category primarily consists of housing, support facilities, defense and security areas, and markets (0.48 ha). The most common land use types at a high-risk level (37.21 ha) are beach borders, low-density perennials/mangroves, medium-density perennials/mangroves, rivers, and river borders (35.45 ha). The procedural planning identified land use falling in the high-risk category as the floor area ratio of more than two floors, a green area ratio of 30%, and a building coverage ratio of less than 70%. The area in this category primarily consists of housing and support facilities, with a total area of 0.65 ha. Land use configuration using a scale of 1:5,000 is presented in Figure 12.

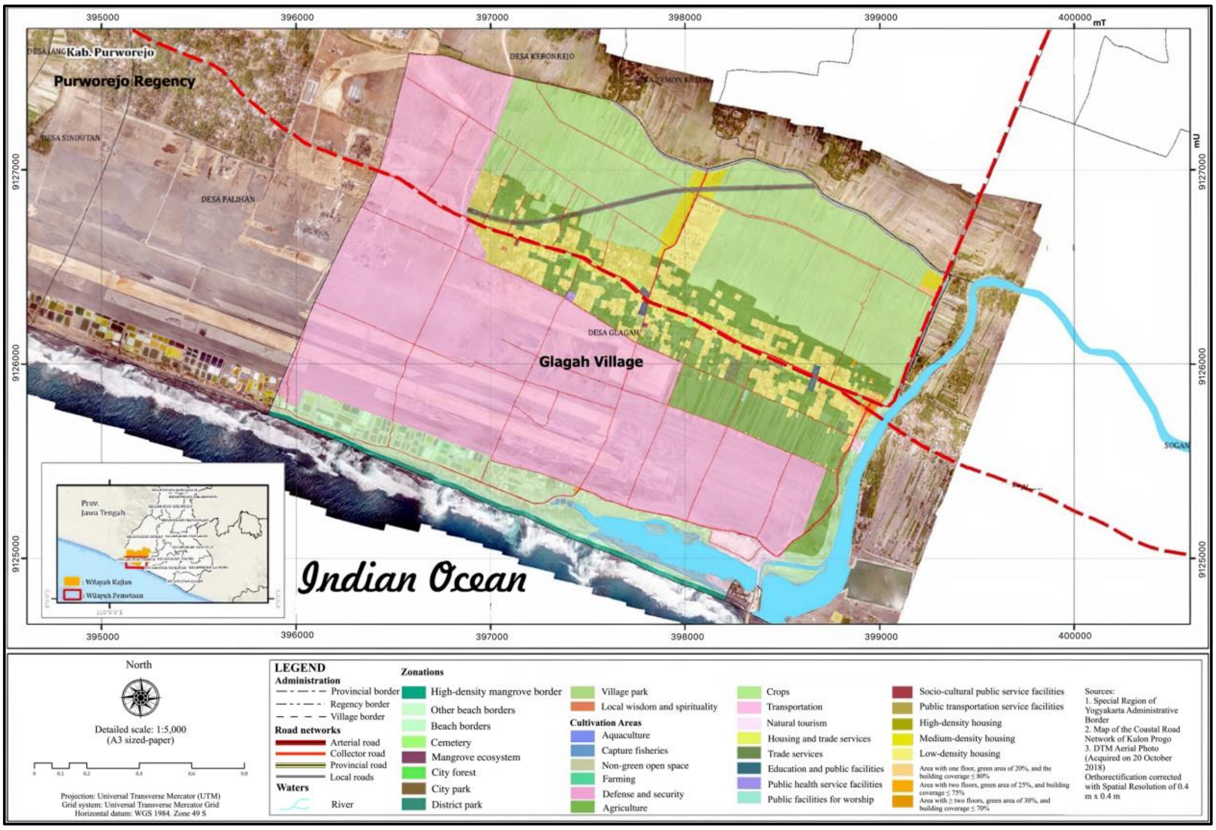


Figure 12. Map of the spatial design plan of Glagah Village on a scale of 1:5,000

Reducing the threat of tsunami hazards requires strategic steps. The 5 m scenario tsunami wave inundated 53.83 ha of Glagah Village. Besides, the total area exposed to tsunami hazards in the 11-m wave scenario was 168.65 ha (Figure 12). Thus, the vulnerability and risk of Glagah Village with 5 and 11 m wave scenarios are spread into all categories (low, moderate, and high)

(Figures 6 and 8). Although some areas fall into the low index in vulnerability and risk, it is crucial to reduce the community's exposure to tsunami threats by reconfiguring areas into the best possible distribution, especially when it comes to human settlements. This effort is critical as it can increase the capacity of the community when evacuation and mass movement are needed. The phenomenon of urbanization cannot be separated from the high population living in coastal areas. To continue accommodating these needs, the present study, through detailed spatial planning, allocates housing, support facilities, markets, supermarkets, and hotels less than 1 ha at each risk level.

According to Løvholt et al. (2014), coastal areas should be designed for non-settlements with lower densities. Furthermore, strict regulations must be applied to buildings that aspire to stand permanently or semi-permanently in the hazard zone. Because the concentration of people in coastal areas triggers economic development, which has a domino effect on development, resources, population, and traffic flow, this research assigns transportation (airport), agriculture/food crops, roads, beach borders, river, and river borders at all risk levels more dominant than areas/buildings for human activities. Anfuso et al. (2021) argued that land configuration for protecting coastal communities must be planned by considering the level of danger, vulnerability, and risks that could arise when a tsunami hits. The threat of a tsunami is also exacerbated by the possibility of aftershocks and long periods of inundation. An optimal and targeted approach for better capacity can be taken by analyzing types of land uses and configuring them in certain exposure levels.

Analyzing and allocating human activities to specific areas based on specific goals requires satisfactory coastal area management. According to Chang & Mori (2021), green infrastructure, including mangrove forests, agriculture, gardens, and shrubs, is a nature-based solution that can reduce tsunami disasters. Many studies (Dissanayaka et al., 2022; Haldar et al., 2024; Kurosawa, 2021; Song et al., 2023; Tashiro, 2021) have proven that green infrastructure effectively reduces disaster risk. A study by Faria de Deus and Tenedório (2021) evaluating land-use and land-cover change trajectories between 1947 and 2018 found that land-use management prioritizing environmental sustainability will bring fruitful ecosystem services. These efforts can be achieved by following sustainable design principles such as livability, community engagement, greener urban planning with mixed land use, and land use optimization.

Furthermore, various studies (Al Sayah et al., 2022; Castellar et al., 2024; Davies et al., 2021; de Luca et al., 2021; Sudmeier-Rieux et al., 2021) have recommended the importance of conserving nature and considering sustainable ecosystem functions in disaster risk management. By considering procedural planning guidelines and previous research recommendations, the present study believes that types of land use that rarely coincide with intense community activities should be placed at a high-risk level. Therefore, the present study assigns beach borders, low-density perennials/mangroves, medium-density perennials/mangroves, rivers, and river borders as the dominant land use types at the high-risk level in the exchange that the impact of the tsunami can be reduced.

Detailed spatial planning on a scale of 1:1,000

Getting further detailed than a scale of 1:5,000, detailed spatial planning with a scale of 1:1,000 extensively minimizes housing, support facilities, worship areas, markets, supermarkets, and hotels at high-risk levels. Furthermore, green and gray infrastructure to protect coastal areas such as beach borders, low-density perennials/mangroves, medium-density perennials/mangroves, and river borders are placed massively in areas with high-risk levels, as shown in Table 5.

Table 5. Spatial Design Plan of Glagah Village on a Scale of 1:1,000

No	Low risk		Moderate risk		High risk		Unexposed	
	Land use	**Area (ha)**	**Land use**	**Area (ha)**	**Land use**	**Area (ha)**	**Land use**	**Area (ha)**
1	Road	1.1	Road	2.6	Road	0.18	Road	10.43
2	River	0.68	River	19.19	River	1.85	River	2.33
3	Housing and support facilities	0.49	Housing and support facilities	0.23	Housing and support facilities	0.18	Housing and trade/services	10.48
4	Tourism and recreation facilities	0.51	Natural tourism	3.35	Nature tourism facilities	1.14	Manmade tourism	0.01
5	Housing and support facilities	0.01	Market, supermarket, malls, shops, hotels	0.04	Housing and support facilities	0.01	Trade and services	1.09
6	Rice field and farming	6.27	Medium-density mangroves and fisheries	0.45	Housing and support facilities	0.02	Capture fisheries	0.02
7	Low-density perennials	1.52	Defense and security	0.04	Low-density perennials	12.19	Office	0.25
8	Housing and support facilities	1.02	Plantation land	2.44	Medium density perennials	3.85	Plantation farming	51.68
9	Worship area	0.04	Rice field and farming	3.19	Housing and support facilities	0.08	Food crop farming	107.87
10	Airport	21.9	Housing and support facilities	0.18	Airport	0.15	Low-density housing	41.53
11	Cemetery	0.25	Airport	35.06	Cemetery	0	Medium-density housing	4.38
12	Other beach borders	2.23	Cemetery	0.01	Other beach borders	14.06	Public health service facilities	0.19
13	River border	0.06	High-density mangrove border	6.22	River border	3.5	Education public service facilities	0.58
14			Other beach borders	18.63			Public service facilities of worship	0.11
15			River border	3.57			Socio-cultural public service facilities	0.12

No	Low risk		Moderate risk		High risk		Unexposed	
	Land use	**Area (ha)**	**Land use**	**Area (ha)**	**Land use**	**Area (ha)**	**Land use**	**Area (ha)**
16	-	-	-	-	-	-	Public transportation service facilities	202.81
17	-	-	-	-	-	-	The protected area of local wisdom and spirituality	0.07
18	-	-	-	-	-	-	Village park	0.19
19	-	-	-	-	-	-	Cemetery	1.05
20	-	-	-	-	-	-	District park	3.78
21	-	-	-	-	-	-	Sub-district park	0.23
22	-	-	-	-	-	-	Other beach borders	0.67
23	-	-	-	-	-	-	River border	1.4

The land use distribution for Glagah Village with a 1:1,000 scale based on the risk level was divided into four classes: low, medium, high, and unexposed. Spatial plans with low risk (0.01-21.90 ha) are spread into 14 utilizations, for example, the airport area (21.90 ha) and rice fields (6.27 ha). There are also types of utilizations with an area of 1-2 ha (Table 5). Besides, the remaining nine areas were less than 1 ha each, such as human settlements and supporting facilities.

The type of land use within medium risk was getting narrower, consisting of high-density mangrove borders, river banks, rice fields, agricultural land, and roads ranging from 2-6 ha each. For high tsunami risk areas, it was found to be dominant on the coastal border (14.06 ha), followed by land with low-density perennials (12.19 ha), medium-density perennials, and river bodies with approximately 4 ha each. Nine other land uses are also at high risk, with each area being less than 1 ha. The spatial distribution for areas unexposed to tsunami risk was quite dominant on transportation facilities (airport) of 202.81 ha, followed by food crop farming, plantation/agriculture, and low-density housing. Improving awareness of future-oriented spatial planning schemes can guide sustainable development, especially when confronted with the increasing expansion of cities in areas at risk of tsunamis.

Policymakers need to pay attention to the function of protected areas, management of coastal resources, and protection of the coastal regions in addition to improving the nearshore economy. Policymakers must resettle and reconfigure land use from risky areas to secure places to protect people when a tsunami occurs. Although zones without exposure to disasters cannot be entirely relied on, areas delegated as safe places can give people more time to escape to much better areas. Hazard, vulnerability, and risk in Glagah Village with 5 and 11 m tsunami wave scenarios are spread into low, moderate, and high categories (Figures 6 and 8). Therefore, efforts to suppress vulnerability through better land configuration in this research are exceptionally reasonable.

According to Rafliana et al. (2022), harmonizing land use types that consider the location of building groups, building types, road access, and ecosystem functions can improve community capacity. In specific steps, capacity can be increased through emergency response training, familiarization with disaster hazards, proper regulation, and availability of disaster response information. Generally, 23 types of spatial utilization found in Glagah Village were set to be unexposed to the tsunami, as shown in Figure 9.

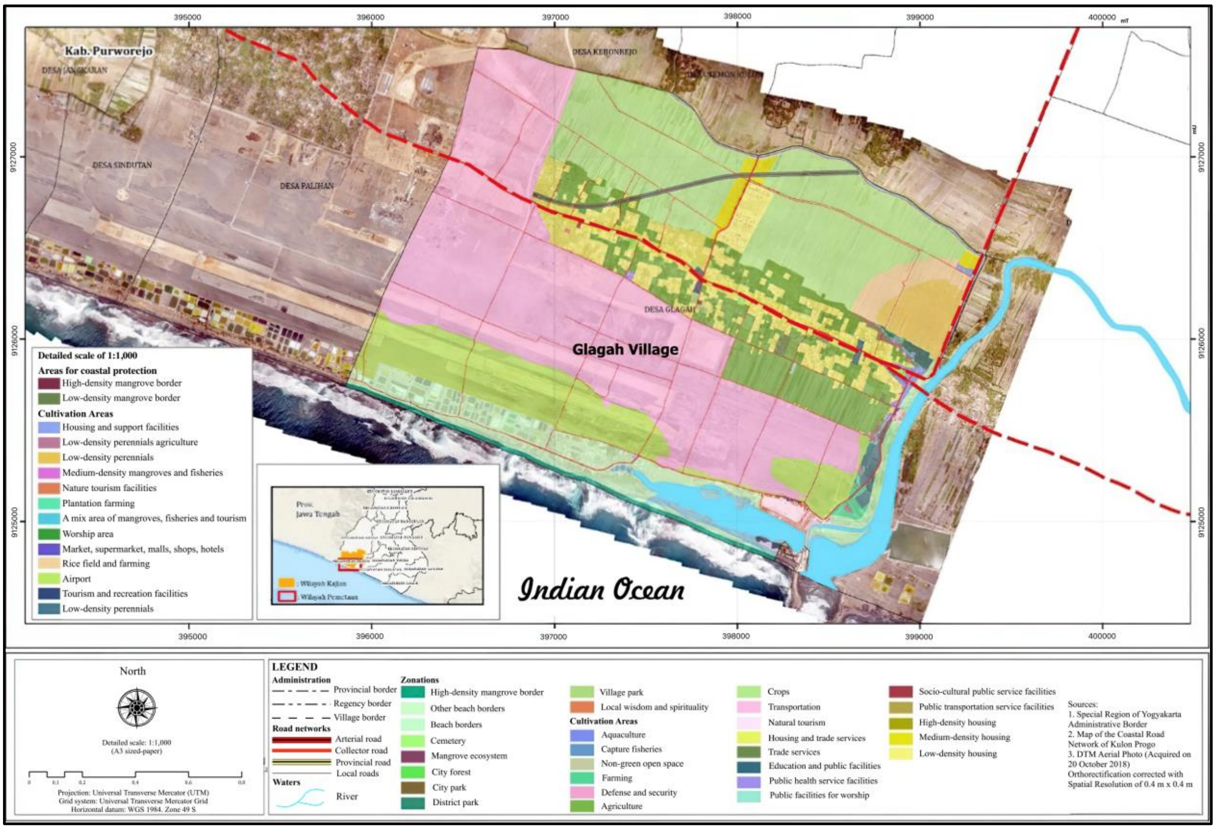


Figure 13. Map of the spatial design plan of Glagah Village on a scale of 1:1,000 in 2019

Considering coastal areas are vulnerable to various disasters, especially tsunamis, development for various activities must be projected towards development that prioritizes protection. When evaluating land use allocation, the combination of green and gray infrastructure must be carried out appropriately and sustainably (Esteban et al., 2020; Fukui et al., 2022; Ishii et al., 2021; Kumar et al., 2021; Mabrouk et al., 2023). Sustainable management of green infrastructure can protect communities, settlements, and supporting infrastructure in all zones. As essential mitigation components, natural ecosystems have a robust role in protecting against hazards. However, the resilience of ecosystem services depends on how healthy they are in their surroundings (Moos et al., 2019).

A study by Young and Jorge Papini (2020) regarding land use/cover changes in Sao Paulo, Brazil, found that untreated ecosystems were correlated with increased disasters, vulnerability, and exposure to hazards. On the other hand, healthy and well-managed ecosystems provide many benefits for human well-being. Therefore, creating green space in coastal areas is an effective strategy to protect against tsunami disasters. Apart from positioning green infrastructure in the frontline of coastal areas, it is essential to assess, restore, and strengthen the foundations of the ecosystem so that they can actively participate in risk reduction. In the long term, ecosystem services for coastal protection can deliver a more significant impact (Cooper et al., 2020).

In the present study, public spaces where community activities are intensely taking place are positioned in the unexposed area to a tsunami with more detailed (441.27 ha), consisting of public transportation service facilities, high-density housing, food crop farming, low-density housing, trade /services areas, and medium-density housing. On the other hand, green and gray infrastructure to protect coastal areas such as beach borders, low-density perennials/mangroves, medium-density perennials/mangroves, and river borders are placed more massively in areas with high-risk levels. Dolan (2020) found that natural borders can reduce physical exposure to storm waves. These findings are supported by several studies (Endter-Wada et al., 2020; Norman et al., 2022; Sudmeier-Rieux et al., 2021; Walz et al., 2021), which found that forests, wetlands, coastal ecosystems, and drylands help mitigate the danger.

Inundation caused by tsunamis can damage various functions in adversely influenced areas, such as protective structures, infrastructure, water resources, drainage systems, cultural and historical facilities, and sanitation systems. In the long term, exposure to tsunamis and high-intensity inundation will damage sources of livelihood that are directly related to the community's quality of life, such as agriculture, offices, plantations, fields, and tourist areas. Disaster setbacks can position communities vulnerable to disease and permanent loss of livelihoods (Parven et al., 2022). Therefore, coastal environmental management is a holistic issue that must take into account physical, social, economic, and cultural aspects. Taking steps to improve the coastal management framework requires an integral approach without disputes to maintain the quality of life, environmental sustainability, and economic fitness of coastal areas.

An excellent spatial plan must set high protection standards for land uses inseparable from community activities, such as hospitals, schools, recreation areas, and transportation access. Apart from that, the development of coastal areas must focus on making evacuation easier for anyone living in coastal zones. The types of buildings, road networks, and population distributions in coastal areas are essential elements that can help improve the evacuation process at various levels. The study by Takabatake et al. (2022) through an evacuation simulation model that can consider changes in evacuation behavior due to road blockages when a tsunami occurs in three coastal cities in Japan (Kamakura, Zushi, and Fujisawa) found that a high number of fatalities could occur due to building collapses even though the area was near the evacuation site and was affected by a minor tsunami inundation. They also emphasized that the spatial distribution alone is insufficient to provide information to reduce fatalities. It is crucial for regional planning to configure land use that takes into account building proportions (height and width), ease of accessing safe areas, and the availability of a proper road network.

Considering the vital role of coastal ecosystems (Chang & Mori, 2021; Dissanayaka et al., 2022; Haldar et al., 2024; Kurosawa, 2021; Song et al., 2023; Tashiro, 2021), evaluating land use types with an emphasis on environmental sustainability will contribute to solid ecosystem planning. These efforts can be achieved by following sustainable design principles such as neat urban planning, revitalization of green areas, and mixed land use. In addition to green infrastructure, gray infrastructure can support and protect coastal areas. A study by Yamanaka & Shimozono (2022) regarding tsunami inundation characteristics along the Japan Sea coastline found that the number of people affected by the tsunami decreased moderately with the presence of coastal protection buildings and breakwaters. The proximity of an activity-dense area to the coast correlates with high vulnerability. As a result, severe damage due to tsunami inundation is inevitable (Woessner & Farahani, 2020). According to Anfuso et al. (2021), coastal areas are dynamic and vulnerable to natural disasters (tsunamis, floods, high waves, storms, tidal changes, and sea level variations). Therefore, positioning people in areas not directly adjacent to the tsunami's first hit point is serious work.

Tsunamis can spread to rivers and streams directly connected to the ocean, leading to more significant momentum for inundation (flooding) further inland (US National Oceanic and Atmospheric Administration, 2024). Therefore, rivers and river borders in the present study are not prioritized in areas unexposed to tsunamis. Gray infrastructure prioritized for protecting settlement areas must block channels directly connecting the mainland and the sea. In this way, gray and green infrastructure functions can collaborate to minimize disasters in coastal areas. Although the inundation caused by the tsunami usually reached 300 m from the coastline, the most severe damage to housing was those closest to the coastline. Therefore, places, spaces, people, and well-being must be unexposed to hazard to the best possible effort. Birkmann & Fernando (2008) confirmed the present study justification as they found that around 50% of the houses within the 100 m zone in the Galle District, Sri Lanka, suffered total and partial damage. Furthermore, their investigation of the 2004 Indian Ocean earthquake and tsunami found that people within a zone less than 100 m from the shoreline were more likely to die and be seriously injured than those outside the zone.

A safe distance from the shoreline will buy more time for people to save themselves, amplifying their resilience in saving themselves from the negative impacts of the tsunami. In addition, people will increasingly have the ability and opportunity to access resources to save others. Therefore, mandatory tsunami mitigation strategies need to consider how exposure to tsunami hazards relates to the profile of communities in potentially affected areas. Exposure analysis by Paulik et al. (2020) in New Zealand using the exposure component of a risk model framework found that coastal populations in low-lying areas have the potential to experience higher exposure to tsunamis and inundation. Furthermore, their worst-case scenario found that the area closest to the source of the incident would require complicated evacuation because the community only had less than 30 minutes of evacuation time before the wave arrived.

It is wise to consider sufficient evacuation time in each type of situation. The government needs to use rich data to identify the spatio-temporal impact of disasters on coastal areas, reduce losses, and maximize mass complex movement during evacuation times. Several studies (González-Riancho et al., 2015; Paulik et al., 2020; Vázquez-González et al., 2021) found that the response of population age groups in the evacuation process varied as they found that children and senior citizens had difficulty evacuating. When a disaster is combined with limited evacuation time, groups of children, the elderly, people with special needs, and pregnant women have relatively limited movement, causing them to undergo higher impacts. According to the Pacific Tsunami Museum (2024), in extreme cases, flooding caused by a tsunami can cover land with water and debris up to more than 305 m. The time it takes for a tsunami to reach the coast depends on the location of the source, meaning that a tsunami's source near the coastline can reach the seaside in less than an hour to a few minutes. A tsunami that reaches the shoreline quickly can have the most destructive impact because there is little time to spread warnings and carry out evacuations.

The impact of tsunami currents can continue for days. Worse still, massive water flows can carry objects and people into the sea as they revert (US National Oceanic and Atmospheric Administration, 2024). Therefore, a proactive combination of governments, practitioners, and civil society in mitigation roles is urgently needed to reduce disaster risk. Excellent and appropriate coastal policies must be adopted through appropriate regional configuration, ecosystem services revitalization, gray infrastructure optimization, and capacity building through various preparedness activities.

Even though land use planning through guidelines developed based on hazard identification has been carried out, implementation of these guidelines still encounters many obstacles due to inconsistencies in program execution. Fleeing from the tsunami appeared as a mass movement from a risky area to a safer one should have persisted. However, many problems can be seen from the policies in several affected locations that tend to build resettlement rather than relocate. According to Løvholt et al. (2014), the inconsistency between relocating and rebuilding occurs due to a trade-off between cost and security. Therefore, the disaster measures, starting from preventive to bold actions during and after a disaster, must be assessed so that the guidelines that have been prepared can be executed sustainably.

CONCLUSION

The tsunami hazard assessment using two wave height scenarios (5 and 11 m) showed that the tsunami hazard index in Glagah Village was in a low category, dominated by vacant land and sandy land, accounting for up to 25.38% of the total area. Regarding vulnerability based on physical, social, economic, and environmental vulnerabilities, Glagah Village is dominated by a medium-vulnerability index with a high-capacity category because the village already has an evacuation route. Besides, Glagah Village has a functioning tsunami early warning system, accompanied by the availability of safety gear. Furthermore, by combining the index values for hazard, vulnerability, and capacity, the tsunami disaster risk in Glagah Village is categorized as a moderate index. Planning for mitigating disaster risk is determined by mitigation factors. Therefore, spatial planning in Glagah Village on a scale of 1:5,000 and 1:1,000 recommends that the main facilities related to community activities, such as human settlements and supporting facilities, be located in areas unexposed to the tsunami. This plan allows everyone to evacuate themselves while being reinforced by a functioning warning system that stays on alert. This research is limited in considering regional morphology and various social dimensions in fully understanding wave dynamics and tsunami inundation in the study area. Therefore, future research needs to consider these aspects to gain a broader perspective, such as how rivers can worsen inundation from tsunami disasters.

DECLARATIONS

Conflict of Interest

We declare no conflict of interest, financial or otherwise.

Ethical Approval

On behalf of all authors, the corresponding author states that the paper satisfies Ethical Standards conditions, no human participants, or animals are involved in the research.

Informed Consent

On behalf of all authors, the corresponding author states that no human participants are involved in the research and, therefore, informed consent is not required by them.

DATA AVAILABILITY

Data used to support the findings of this study are available from the corresponding author upon request.

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