http://journal.uir.ac.id/index.php/JGEET

E-ISSN : 2541-5794
P-ISSN : 2503-216X

Journal of Geoscience,
Engineering, Environment, and Technology
Vol xx No xx 20xx

RESEARCH ARTICLE

An Integrated GIS-Based Framework for Tsunami Evacuation Planning: Shelter Accessibility and Route Network Analysis in Palabuhanratu, Indonesia

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Received:
Received: Oct 1, 2016; Accepted: Nov 20, 2016.
DOI: 10.24273/jgeet.2016.1.2.001

Abstract
Palabuhanratu is located along the southern coast of Java and is at high risk of tsunami disasters owing to seismic gaps along the Sunda subduction zone. The seismic gap could generate earthquakes up to 9.1 Mw, potentially triggering tsunamis as high as 20.2 meters. Mitigation efforts require evacuation sites that can be reached within a limited evacuation time, yet existing temporary evacuation sites are moderately to poorly accessible, with a substantial proportion of the affected population unable to reach them within 30 minutes. This study develops an integrated GIS-based framework linking tsunami hazard mapping and inundation modeling with affected-population assessment, shelter location planning, and evacuation route analysis. The methodological approach uses existing evacuation sites as a baseline and progressively evaluates alternative shelter configurations based on population coverage within a 30-minute travel-time constraint, followed by network-based evacuation route analysis for the selected shelter configuration. GIS-based spatial analysis estimated inundation areas of 3.57 km^2 and 6.44 km^2 under 10- and 20-meter tsunami scenarios, affecting 13,553 and 23,574 people, respectively. Existing evacuation sites were reachable by only 38% of the affected population under the 20-meter inundation scenario. The addition of three proposed shelter locations increased the modeled accessibility to 100% within the 30-minute travel-time threshold. Network analysis subsequently identified 55 evacuation routes connecting tsunami-affected areas to designated evacuation sites. The integrated framework provides a systematic basis for comparing shelter configurations and linking shelter planning with evacuation route development, thereby supporting comprehensive tsunami mitigation planning in vulnerable coastal communities.

Keywords: Evacuation routes, hazard mapping, Palabuhanratu, shelter planning, tsunami

1. Introduction

Indonesia is an archipelagic country consisting of 17,504 islands, with the second-longest coastline in the world, stretching 95,181 km (Dirhamsyah et al., 2022). A significant portion of Indonesia lies in earthquake- and tsunami-prone areas. According to the PVMBG, 28 points along Indonesia's coastline are vulnerable to earthquake and tsunami disasters, including the coasts of Sumatra, the southern coast of Java, Bali, and the Nusa Tenggara Islands (Kozin 2016). Approximately 4.35 million people residing along the coasts of Java, Sumatra, and Bali are at risk of tsunami disasters (Harris dan Major, 2016). The high population density in coastal areas makes them among the most vulnerable regions to tsunami hazards worldwide.

Approximately 90% of tsunami events are caused by underwater earthquakes (Benazir et al. 2023). According to the USGS (2017), earthquakes with a magnitude of > 6.5 Ms have the potential to trigger tsunamis. Many tsunamis in Indonesia are caused by seismic activity around the subduction zones at the convergence of the Indo-Australian and Eurasian plates (Irsyam et al., 2020). Over the last three decades, significant tsunamis caused by seismic activity in the Sunda subduction zone have occurred, such as the 2004 Aceh tsunami with 227,898 fatalities due to a 9.0-magnitude earthquake, the 2006 Pangandaran tsunami with 664 fatalities caused by a 7.7-magnitude earthquake, and the 2010 Mentawai tsunami with 456 fatalities due to a 7.7-magnitude earthquake (Triyono et al. 2019).

Subduction zone earthquakes are caused by locked plate interfaces, where accumulated stress and strain result in energy release, generating seismicity. Plate movement in subduction zones leads to periodic seismic activity. The absence of earthquakes in such zones, known as seismic gaps, holds the potential for large earthquakes and tsunamis (Adventari et al. 2021). According to data from the Meteorology, Climatology, and Geophysics Agency (BMKG), seismic gaps have been identified along the southern coast of Java (Widiyantoro et al. 2020).

The seismic gap along the southern coast of Java is divided into two regions: the southern coasts of Lampung to West Java and the southern coasts of Central Java to East Java. This seismic gap has the potential to cause earthquakes with magnitudes of 8.9 Mw in Southern coast West Java, 8.8 Mw in Southern Coast East Java, and up to 9.1 Mw if occurring simultaneously (Widiyantoro et al. 2020). Research by Adventari et al. (2017) predicts that such earthquakes could trigger tsunamis as high as 20.2 meters in West Java and 11.7 meters in East Java.

The tsunami risk along the southern coast of Java is highest in Sukabumi District, classified as extremely high risk, as noted in the 2023 Indonesian Disaster Risk Book (IRBI). The high-hazard area covers 6,566.88 hectares, with estimated losses reaching USD 258,038,100 and social vulnerability affecting 71,931 people. Palabuhanratu, a sub-district in Sukabumi located on the coast, has the highest social vulnerability, with 24,599 residents (W. Adi et al. 2023). The tsunami risk in Palabuhanratu is exacerbated by geomorphological factors such as its bay-shaped coastline, steep seabed and slopes, and proximity to the subduction zone in the Indian Ocean, which significantly influence the height and velocity of tsunami waves reaching the shore (Pramana, 2015). Thus, tsunami mitigation efforts are crucial for minimizing the impacts on coastal communities.

Mitigation efforts according to the National Disaster Management Agency (BNPB) in 2012 include providing temporary evacuation sites, as outlined in the government's primary program detailed in the Tsunami Disaster Risk Reduction Master Plan for 2013-2019 (BNPB 2012). Temporary evacuation sites are divided into two types: natural sites, such as mountains, hills, and highlands, and artificial sites, such as multi-purpose buildings and dedicated shelters (Arifal dan Ashar 2021). In Palabuhanratu, mitigation measures include temporary and final evacuation sites located outside the tsunami hazard zone. Ideally, evacuation sites should be accessible within 20 minutes (BNPB 2013). According to research by Habibie (2022), the reachability of temporary evacuation sites ranges from moderate to far, with evacuation times of 10-20 min and more than 20 min. The availability of high-rise buildings for vertical evacuation should be considered to improve community access to evacuation sites.

Previous studies in Palabuhanratu have addressed tsunami hazard assessment, inundation modeling, and evacuation planning from different perspectives. Tanioka et al. (2012) investigated tsunami inundation and hazard mitigation in Palabuhanratu, while Isya et al. (2021) assessed tsunami risk and inundation in the Palabuhanratu Bay area using tsunami modeling. Habibie (2022) evaluated the accessibility of existing temporary evacuation sites, and Suri and Syafiudin (2024) examined tsunami evacuation routes in Palabuhanratu. However, these studies primarily addressed tsunami hazards, shelter accessibility, or evacuation routes as individual components. The linkage between the modeled tsunami-affected population, alternative shelter configurations, and subsequent evacuation route planning has not been explicitly evaluated as an integrated framework. In particular, the improvement in population coverage resulting from additional shelter locations has not been quantitatively compared with the existing evacuation conditions before determining the corresponding evacuation routes. This study addresses this gap by integrating tsunami hazard mapping and inundation modeling with affected-population assessment, comparative shelter location planning, and network-based evacuation route analysis. Existing evacuation sites were treated as the baseline, while alternative shelter configurations were evaluated based on the proportion of affected residents who could reach a shelter within 30 minutes. The configuration that provided the highest modeled population coverage was subsequently used as the basis for evacuation route planning.

Vertical evacuation shelters should be located within tsunami hazard zones. According to the Federal Emergency Management Agency (FEMA 2019) guidelines on the design of structures for vertical evacuation from tsunamis, shelters should be habitable immediately after an earthquake, with no structural damage, intact non-structural components, and fully operational functions without requiring repairs. In addition to being resistant to tsunami loads, shelters must also withstand earthquake loads. Structural performance under tsunami loads can be analyzed using fragility curves, which depict the probability of structural damage due to tsunami forces (Mas et al. 2020). According to ASCE 7-16, tsunami-resistant structural performance should meet immediate occupancy levels, meaning no structural damage, intact non-structural components, and fully operational conditions without repair (Ashar et al. 2014).

2. Data and Methods

2.1. Tools and Materials

The research location was situated in Palabuhanratu, Sukabumi, West Java, at coordinates 7°03′00″ S, 106°27′00″ E. The location map of the study area can be viewed at Fig. 1. The tools used in this study included a laptop equipped with software for spatial data processing, such as ArcGIS 10.8 and QGIS. ArcGIS is a software system developed by ESRI (Environmental Systems Research Institute) that includes various products and functions for spatial data processing. This application can be used for map creation, spatial data analysis, spatial data modeling, and more (Fauzi et al. 2022). The primary application of ArcGIS is ArcMap, which is used for displaying and editing spatial data, creating and editing maps, querying, and modeling (Budiarto 2019).

The materials used in this study include the Indonesian Land Use Map (Peta Rupa Bumi Indonesia) and the Digital Elevation Model (DEM) from the Geospatial Information Agency (Badan Informasi Geospasial), tsunami hazard zone boundary maps, and population data. The study involved processing primary data obtained using GIS software on a laptop to derive various parameters needed to achieve the research objectives, such as the affected area, elevation maps, slope, distance from the shoreline, land cover, vulnerability level, affected population, tsunami shelter planning, and evacuation routes, as well as structural disaster mitigation planning. Additionally, secondary data from literature reviews, previous research, and documents from relevant agencies were utilized.

Fig. 1 Reasearch Location Map

2.2. Developing Hazard Map

The tsunami hazard index map refers to the Guidelines for Preparing Tsunami Risk Maps at the city level issued by the National Disaster Management Agency (BNPB 2014). The level of tsunami hazard was determined based on elevation and distance from the shoreline, as illustrated in the map in Table 1. The elevation map was created using DEM data developed by the Indonesian Geospatial Information Agency (BIG), with the reclassified feature applied to adjust the elevation classification as needed. The shoreline distance map was generated using the land use map (RBI), employing the buffer feature and categorizing it into several distance categories. Subsequently, the tsunami hazard index, based on elevation and distance from the coastline, was calculated using a matrix to classify the tsunami hazard level for a given area. The matrix used for calculating the tsunami hazard levels. Subsequently, the tsunami hazard levels can be viewed at Table 2.

Table 1. Index value for hazard map parameters

Elevation (masl)	Index Value	Distance from Coast	Index Value
0-15	4	0-100	4
15-50	3	100-500	3
50-100	2	500-1000	2
>100	1	>1000	1

Table 2. Tsunami hazard levels

Calculate Composite Hazard Index Value	Hazard Levels
1-2	Very Safe
3-4	Safe
5-9	Risk
10-16	High Risk

2.3. Tsunami Inundation Map

The elevation–distance index was used as a preliminary index-based tsunami hazard assessment following BNPB (2014), whereas the spatial extent of tsunami inundation was subsequently estimated using the empirical inundation model developed by Berryman (2006). The Berryman (2006) approach estimates inland tsunami inundation based on the initial tsunami run-up height and the reduction in water height associated with terrain slope and surface roughness. In this study, the model was applied to estimate the inland inundation extent under tsunami run-up scenarios of 10 m, 15 m, and 20 m using the formulation presented in Equation (1). The model assumes that tsunami inundation can be approximated from these spatial parameters and does not explicitly simulate time-dependent tsunami generation, offshore wave propagation, flow velocity, or complex hydrodynamic interactions. Therefore, the approach is used for GIS-based screening of potential inundation extent and subsequent evacuation planning rather than as a substitute for detailed numerical tsunami propagation and hydrodynamic modeling.

$$Hloss = \frac{167n^2}{H0^{1/3}} + 5 \sin S \quad (3)$$

Slope and surface topography are required as input data for inundation modeling. Slope data were derived from raster DEM data obtained from the Ina-Geoportal of the Geospatial Information Agency (BIG). The DEM was processed in ArcMap using the Slope tool, with the resulting slope expressed in degrees. Surface roughness coefficients were assigned according to land-cover types based on Berryman (2006). These parameters were incorporated into the inundation model to account for the influence of local terrain and surface characteristics on tsunami inundation.

The analysis of the population affected by the tsunami was performed using QGIS, specifically with the InaSAFE feature. The data used for this analysis included raster population density data from the Central Statistics Agency (BPS) Sukabumi, a map of Palabuhan Ratu, and tsunami inundation maps with wave height scenarios of 10 and 20 meters, as predicted by Adventari et al. (2017). The results of this analysis provide the number of people affected by the tsunami under the inundation scenarios of 10 and 20 meters. Population density and community activities in the affected areas influence the planning of shelter locations and the division of evacuation zones according to the planned shelter capacities

2.4. Analysis of Reachability Existing Evacuation Center and Shelter Planning Recommendation

The analysis of the reachability of existing evacuation sites was conducted to determine the range of coverage area as a basis for determining the location of new shelters. The planning of new shelters is prioritized in areas that are not covered by evacuation sites and regions near residential areas/activity centers. The coverage analysis used the multiple ring buffer feature in ArcMap. Accessibility to the shelter locations was evaluated based on the distance and travel time to the shelter, calculated using the lowest average human walking speed of 0.751 m/second (The Japan Institute for Fire Safety and Disaster Preparedness 1987, in (Muhajir and Cahyono 2013). The travel distance was calculated using equation (2). Travel time classification for reaching shelter locations follows the research by Ashar, Amaratunga, and Haigh (2014b). The reachability classification is detailed in Table 3.

$$S = v \, x \, t \quad (2)$$

Table 3. Shelter reachability classification

Reachability	Travel time (minute)	Distance (meter)
Very Close	< 5	<225
Close	5-10	225-450
Moderate	10-20	450-900
Far	20-30	900-1350
Very Far	>30	>1350

The location of the shelter is determined using the guidebook on planning techniques for temporary evacuation sites. The criteria for planning the location consider sufficient time for evacuation, height above tsunami waves, location away from sources of hazardous and toxic materials (B3), away from cliffs that have the potential for landslides/collapse, and preferably planned on land owned by the government or have an agreement with residents or private parties as landowners (BNPB 2013). The same criteria were also expressed by Stefanus et al. (2022), if the shelter is located in a tsunami inundation area, it must be resistant to earthquake shocks and tsunami waves, have a height above the tsunami inundation (at least 20 m and four floors), have good access, and have sufficient capacity to accommodate refugees.

2.5. Analysis of shelter planning and evacuation routes

The determination of evacuation zones is carried out to divide evacuation areas based on the distance and travel time to the nearest planned shelters. The zoning process utilizes the Service Area feature in the Network Analysis tool by incorporating road network data and designated shelter points. This process results in service areas defined by travel times along the road network and affected areas divided into several evacuation zones.

The planning of evacuation routes to the nearest shelter is carried out using the Network Analysis tools in ArcGIS. The routes generated from the network analysis process were designed to identify the shortest and most efficient travel paths. In addition, the determination of evacuation routes refers to the Indonesian National Standard (SNI) 7766:2012 (BSN 2012). The results of this analysis included the division of evacuation zones and maps of evacuation routes to the nearest planned shelters in areas likely to be impacted by a tsunami.

3. Result and Discussion

3.1. Tsunami Vulnerability

The tsunami hazard map was developed based on the Guidelines for Tsunami Risk Map Preparation at the District/City Level, issued by the National Disaster Management Agency of Indonesia in 2014 (BNPB 2014). This map incorporates data on land elevation, representing the height or depth of an area relative to sea level, and distance from the coastline, indicating how far a region is from the shore. The maps of the coastline buffer, land elevation, and data interpretation are shown in Figure 2 (a) and (b).

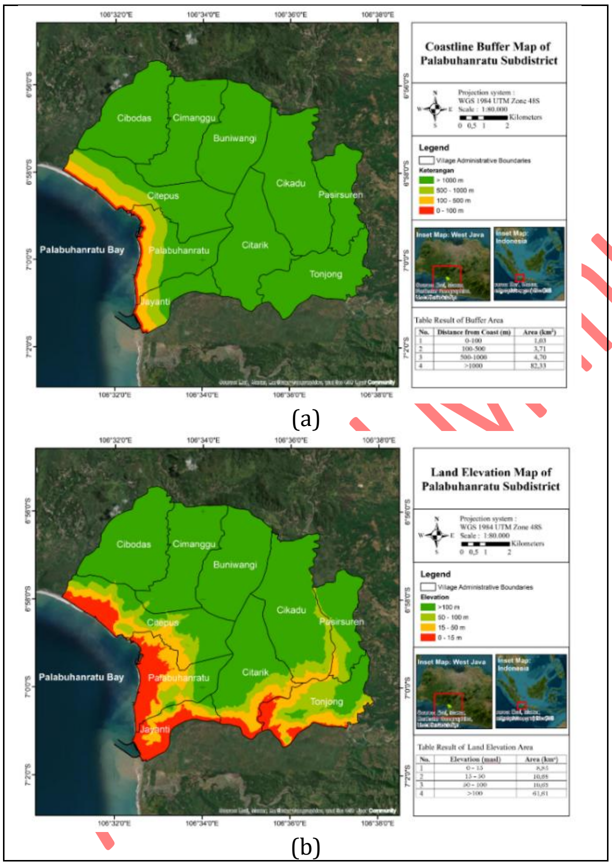


Fig. 1 (a) Coastline buffer map (b) Land elevation map

The land elevation in Palabuhanratu Subdistrict varies significantly, as shown in Figure 2 (b). Seven villages have varying land elevations, categorized into 0 – 15 m above sea level (masl), 15 – 50 masl, and 50 – 100 masl. These villages include Citepus, Palabuhanratu, Jayanti, Citarik, Cikadu, Pasirsuren, and Tonjong. Meanwhile, areas with land elevation >100 masl are generally located in the northern and eastern parts of Palabuhanratu Subdistrict, specifically in the villages of Cibodas, Cimanggu, and Buniwangi, with a total area of 61.61 km^2. The area with land elevation >100 masl represents the largest land coverage, whereas the smallest area is found at an elevation of 0–15 masl, covering only 8.85 km^2. The low-elevation area (0 – 15 masl) is at the highest risk of damage in the event of a tsunami because of its low altitude and proximity to the sea level. As shown in Fig. 2 (a), three villages directly border the coastal area: Citepus, Palabuhanratu, and Jayanti. The area within 0 – 100 m from the coast covers 1.03 km^2, the area within 100 – 500 m covers 3.71 km^2, the area within 500 – 1000 m covers 4.7 km^2, and the farthest distance, >1000 m from the shoreline, spans 82.33 km^2, making it the largest area. The closer a region is to the shoreline, the greater the potential for damage in the event of a tsunami. The results of the tsunami hazard zone and the data regarding the classification and area extent of the hazard zone are shown in Fig. 3.

Figure 3. Figure 3 Fig 3 Fig 3 Fig 3 shows that villages classified as having "Risk" and "High Risk" tsunami hazard levels are located in the western part of Palabuhanratu Subdistrict, specifically Citepus, Palabuhanratu, and Jayanti Villages, with respective areas of 4.64 km^2 and 4.00 km^2. This is attributed to their proximity to the shoreline and low land elevation. Meanwhile, the northern, eastern, and southern parts of Palabuhanratu Subdistrict are classified as "Very Safe" covering an area of 71.37 km^2 and "Safe" with an area of 11.76 km^2. The farther a region is from the shoreline and the higher its elevation, the safer it is from potential tsunami damage.

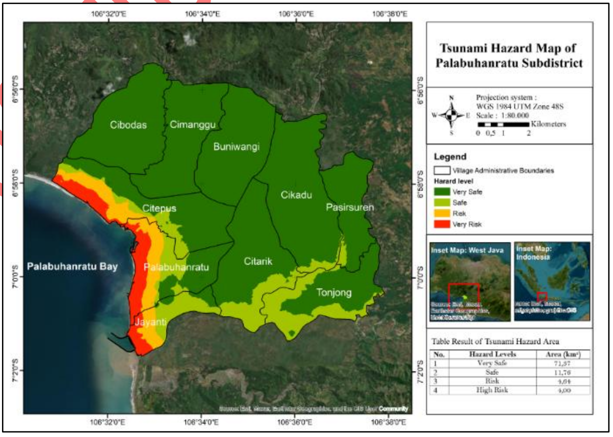
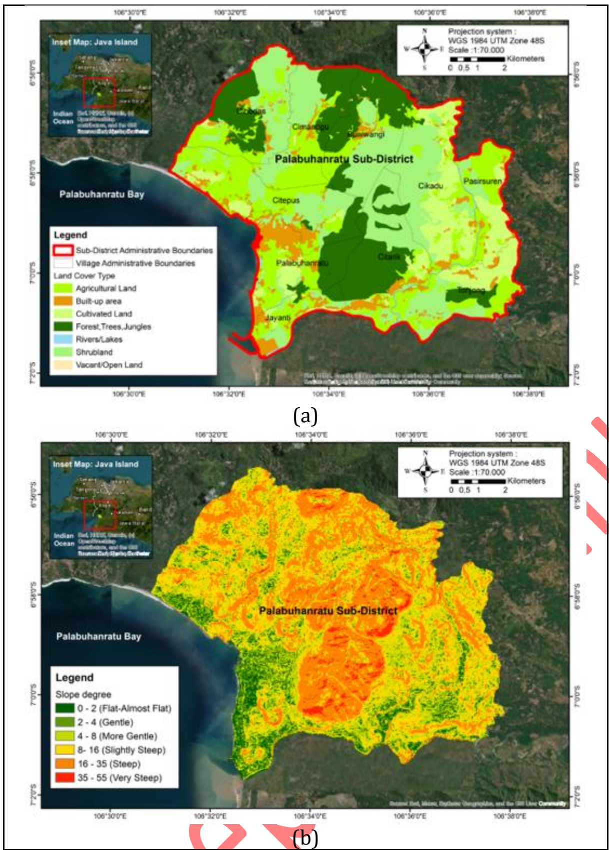


Fig. 3 Tsunami hazard map

Fig 3. shows that villages classified as having "Risk" and "High Risk" tsunami hazard levels are located in the western part of Palabuhanratu Subdistrict, specifically Citepus, Palabuhanratu, and Jayanti Villages, with respective areas of 4.64 km^2 and 4.00 km^2. This is attributed to their proximity to the shoreline and low land elevation. Meanwhile, the northern, eastern, and southern parts of Palabuhanratu Subdistrict are classified as "Very Safe" covering an area of 71.37 km^2 and "Safe" with an area of 11.76 km^2. The farther a region is from the shoreline and the higher its elevation, the safer it is from potential tsunami damages.

3.2. The Impact of Tsunami Inundation Height

Tsunami modeling was conducted using two initial wave heights of 10 and 20 m from the shoreline. Tsunami modeling refers to the study by which states that the southern coast of West Java is potentially exposed to a tsunami as high as 20.2 meters due to seismic gaps in the Sunda Megathrust subduction zone. Additionally, the tsunami wave heights were based on recurrence period predictions of 100 and 500 years with a tsunami potential of 5–20 m, as examined by the National Tsunami Hazard Assessment for Indonesia in 2013 (Horspool et al. 2013). According to Berryman's (2006), tsunami inundation is significantly influenced by variations in land cover and slope gradient at specific locations (Berryman 2006). Variations in land cover and slope gradient are illustrated in Figure 4. Berryman's (2006) inundation calculation considers the loss of tsunami height per 1 meter of inundation distance through land cover roughness and slope parameters, which can act as obstacles to wave velocity when reaching the land and reduce the tsunami wave height. Additionally, the initial tsunami wave height also affected the inundation distance in Palabuhanratu. The results of the inundation analysis were conducted using an initial wave run-up of 10 and 20 m from the shoreline, as shown in Figure 5. Table 4 shows the affected area of the tsunami and the number of casualties.



(a)

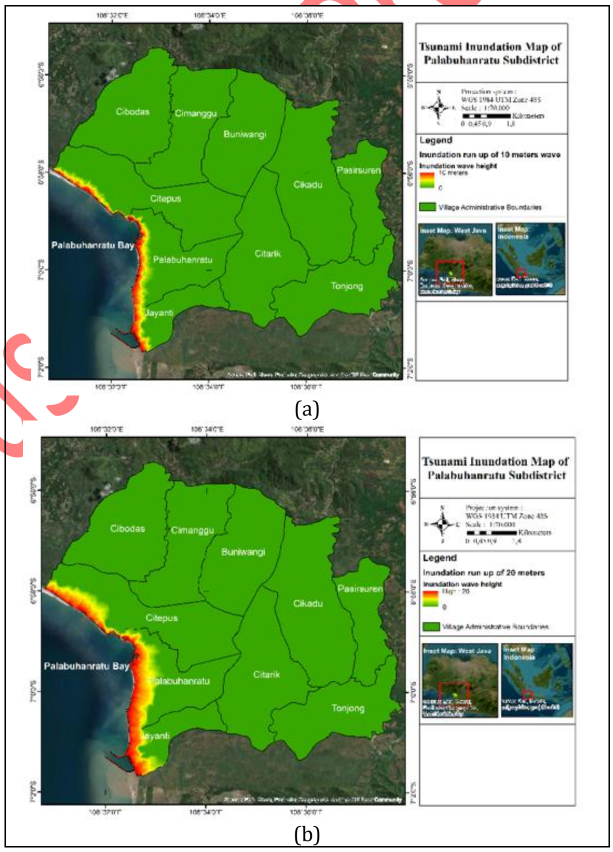
(b)

Fig. 4 (a) land cover map (b) land slope map

Table 4. Result of the tsunami inundation area and population affected

Sub-District	Tsunami Inundation area affected (km²)		Population affected by Tsunami (person)	
	10 Meter	20 Meter	10 Meter	20 Meter
Citepus	0.89	1.81	907	1,842
Jayanti	0.77	1.34	1,075	1,870
Palabuhan Ratu	1.91	3.29	11,571	19,862
Total	3.57	6.44	13,553	23,574

Fig. 5 shows the results of the tsunami inundation area with 10- and 20-meter run-up. The tsunami modeling with a 10-meter wave run-up can reach as far as 704 meters with an inundation area of 3.57 km^2 or 3.89% of the total area of the Palabuhanratu subdistrict. The average range of the 10-m tsunami wave is within a radius of 300–500 m from the coastline. A total of 13,553 people were affected in the 10-m inundation area. The affected areas are located in three coastal villages: Citepus, Jayanti, and Palabuhanratu. Palabuhanratu has the largest affected area of 1.91 km^2, accounting for 53% of the inundation area. The highest number of affected residents was in Palabuhanratu, with 11,571 people, or approximately 85% of the total affected population. The tsunami modeling with a 20-meter run-up can reach as far as 1,162 meters, affecting an area of 6.44 km^2 or approximately 7.0% of the total area of the Palabuhanratu subdistrict. The average range of tsunami inundation is within a radius of 500–1, 000 m from the coastline. The tsunami inundation affected 23,574 residents spread across three coastal villages. Palabuhanratu has the largest inundated area of 3.29 km^2 or 51% of the inundation area. The highest number of affected residents was in Palabuhanratu, totaling 19,862 people or 85% of the total affected population.



(a)

(b)

Fig. 5 (a) Tsunami hazard map at 10 meters inundation (b) Tsunami hazard map at 20 meters inundation

The inundation radius of 10 meters initial wave run-up is in line with the findings of a tsunami inundation study by Tanioka et al. (2012), where the maximum inundation distance ranged from 400 to 800 m with tsunami wave heights between 5.4 and 15 m, using Mw8.0 and Mw8.5 earthquake models. The study by Isya et al. (2021) on inundation in Palabuhanratu, tsunami modeling with a magnitude of 9.3 SR using the ComMIT software produced tsunami wave heights reaching 25.6 meters up to 35 meters in steep slope areas. The inundation area along the coastal zones of Palabuhanratu, Jayanti, and Citepus villages was approximately 10.25 km^2. This result is notably larger than the findings of an inundation study with an initial wave run-up of 20 meters, which reported an inundation area of only 6.44 km^2. The discrepancy in inundation extents can be attributed to differences in modeling approaches, initial tsunami wave heights (Pradjoko et al. 2023), and the resolution of the data employed. It is well established that the use of higher-resolution DEM data with higher point densities and better geometric accuracy leads to more accurate inundation predictions (Septiangga et al. 2019). This study utilized DEM data (DEMNAS) developed by the Indonesian Geospatial Information Agency, with a resolution of 8 x 8 meters (0.27 arc seconds).

Based on the two tsunami inundation run-up models shown in Fig. 5, it is evident that the affected area increases with the rise in tsunami wave height. Despite the fact that the inundation from the 10-meter run-up (3.57 km^2) is smaller than that of the 20-meter run-up (6.44 km^2), almost twice the area. As stated in Equation 1, tsunami modeling calculates the wave height loss (Hloss), which is influenced by the surface roughness coefficient (n), the tsunami run-up height along the coastline, and the slope gradient (S). An increase in the slope gradient (S) significantly reduces the tsunami wave reach. The surface roughness coefficient (n) has a significant impact when it exceeds a value of 0.05 (Pradjoko et al. 2023). Palabuhanratu Village has a slope gradient ranging from 0 °to 4 °, categorized as flat to gentle according to slope classification by van Zuidam (1979). Its land cover consists of rice fields and farmland with roughness coefficient values of 0.025 and 0.035, respectively, which affect the tsunami wave reach and the extent of the inundation area.

3.3. The Reachability of Existing Shelter Evacuation Center and Shelter Recommendations

A temporary evacuation shelter (TES) can be established on a natural elevation of 20 meters above sea level outside the designated tsunami inundation zones. Alternatively, TES can be designed as multi-story buildings with elevations exceeding the predicted tsunami wave height within the inundation zones. The TES coverage was analyzed based on distances, as shown in Fig. 6 (a), to determine the number of residents and areas reachable by the natural hill TES. Subsequently, the results of the 10 m and 20 m inundation scenarios were overlaid on the TES coverage map, as shown in Fig. 6 (b), to identify the number of residents affected by the tsunami. The TES coverage due to 10- and 20-meter inundations is shown in Figure 7, calculating the number of casualties who can reach TES within a radius of <1350 m or 30 minutes assuming walking on the evacuation route.

The accessibility of tsunami evacuation shelters (TES) was categorized based on distance: very close (<225 m), close (225–450 m), moderate (450–900 m), and far (900–1350 m). The impact of a tsunami was assessed by the number of affected residents and the areas within the 10 m and 20 m inundation zones, while TES coverage refers to the total population that can reach these shelters. According to Fig. 7, the accessibility of Temporary Evacuation Sites (TES) located on natural hills relies on horizontal evacuation schemes, which can only accommodate approximately 27% (3,764 individuals) and 38% (8,958 individuals) of the affected population in tsunami scenarios with wave heights of 10 and 20 meters. The graphic in Figure 7 indicates that more than 50% of the affected population lacks access to TES in horizontal evacuation due to their uneven distribution across the coastal areas. Therefore, vertical tsunami evacuation planning is essential to enhance evacuation accessibility, enabling the population to reach shelters before tsunami waves arrive.

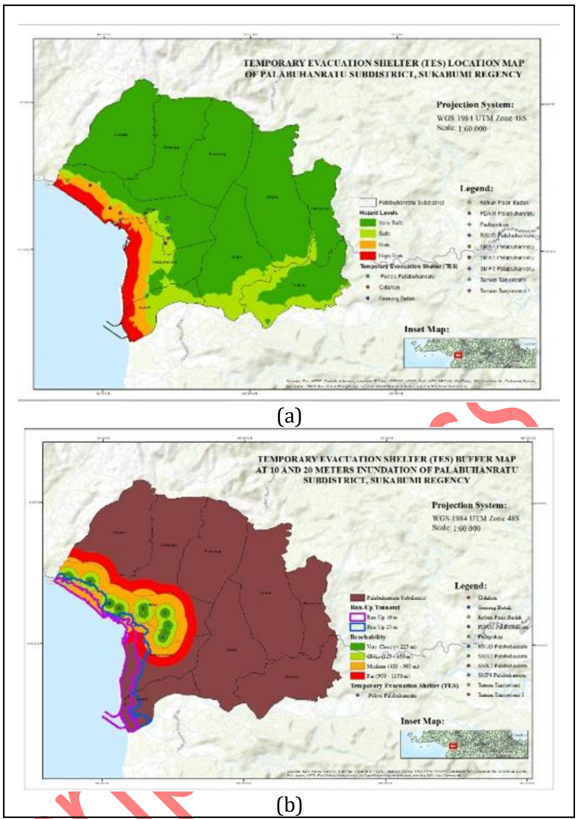


Fig. 6 (a) Temporary evacuation shelter (TES) location point (b) Temporary evacuation shelter (TES) buffer map

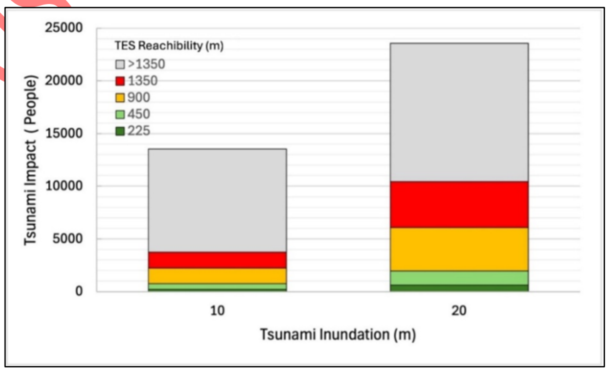


Fig. 7 Graphic reachability TES based on inundation variations

Table 5. Location of New Proposed Shelter Location

Name of Shelter	Address	Coordinate
First Shelter	Jl. Raya Pangsor	-6.985300, 106.544551
Second Shelter	Jl. Pelita-Cipatuguran	-7.017162, 106.542997
Third Shelter	Jl. Pelita-Cipaguturan	-6.999484, 106.543243

In the study area, there are no existing buildings structurally suitable for vertical tsunami evacuation in inundation zones, such as disaster-resistant multi-story buildings. Therefore, the identification of new shelter locations is necessary to enhance the evacuation site coverage. The analysis of the proposed vertical shelter locations based on the planning criteria issued by BNPB (2013), which include accessibility for affected communities, distance from hazard sources, and suitability of either vacant land or existing multi-story buildings. Based on these criteria, three recommended shelter locations have been identified in Table 5 and illustrated in Fig. 8.

To evaluate the effectiveness of the proposed shelter configuration, the existing TES condition was used as the baseline for comparison. Shelter accessibility was evaluated based on the proportion of the tsunami-affected population that could reach an evacuation shelter within 30 minutes, following the travel-time-based assessment of tsunami evacuation accessibility used in previous studies (Ashar et al. 2014). The assessment considered the accessibility of the existing natural-hill TES and the addition of the recommended shelters. Alternative shelter configurations were evaluated by progressively adding the proposed shelters to the existing TES network. This comparative assessment enables the improvement in population coverage associated with each additional shelter to be quantified and provides a basis for identifying the shelter configuration that provides the highest evacuation accessibility within the defined travel-time constraint. The results of this assessment are presented in Fig. 9.

Fig. 8 Location of existing TES and Shelter Recommendation

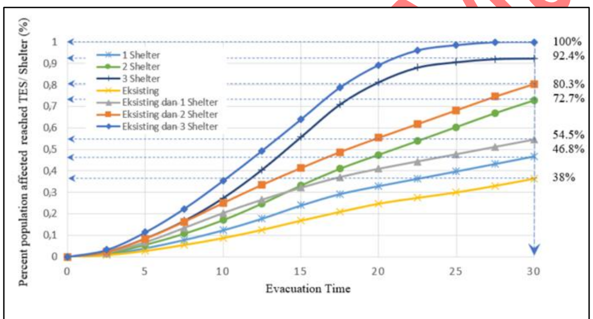


Fig. 9 TES and Proposed shelter Reachability

As shown in Fig. 9, the existing TES provided a baseline coverage of 38.0% of the affected population within an evacuation time of less than 30 min. The addition of one proposed shelter increased the coverage to 54.5%, representing an improvement of 16.5 percentage points relative to the baseline. The addition of two proposed shelters further increased the coverage to 80.3%, corresponding to an improvement of 42.3 percentage points. The configuration comprising three proposed shelters achieved the highest coverage of 100%, representing a 62.0 percentage point improvement compared with the existing TES condition. These results indicate that progressively adding shelter locations substantially improves evacuation accessibility within the defined 30-minute travel-time constraint. Among the evaluated configurations, the three-shelter configuration provided the highest population coverage and was therefore used for subsequent evacuation route analysis.

Following the identification of the three-shelter configuration as the configuration with the highest population coverage, evacuation routes were analyzed to connect tsunami-affected areas, including coastal regions, residential areas, and activity centers, with the designated evacuation sites. The designated evacuation sites consisted of six existing natural-hill TES and three proposed shelter locations. Evacuation routes were modeled using network analysis to identify accessible paths to the nearest designated shelter. Routes were evaluated based on a maximum evacuation time of 30 minutes, corresponding to a maximum travel distance of 1,350 m based on the assumed walking speed of 0.751 m/s for elderly evacuees (The Japan Institute for Fire Safety and Disaster Preparedness 1987). The resulting evacuation routes and their spatial accessibility are presented in Fig. 10.

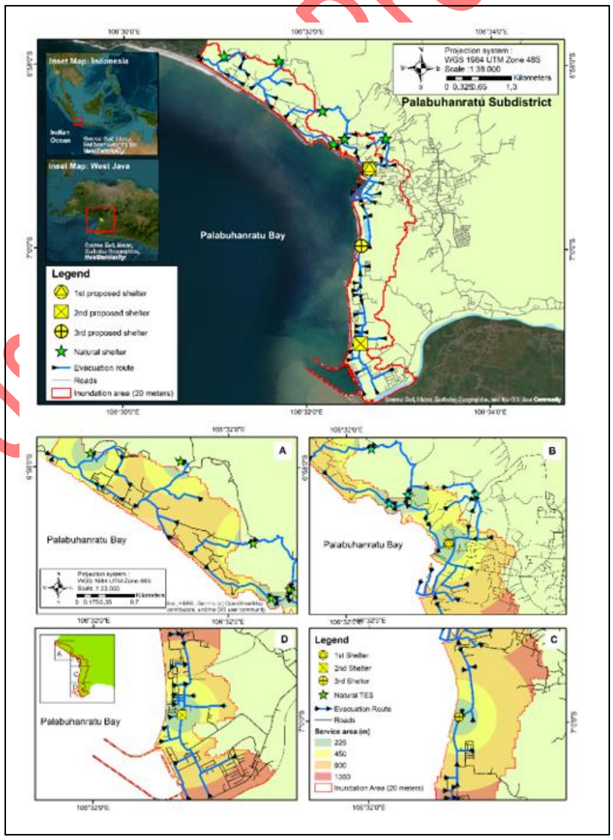


Fig. 10 Evacuation routes to nearest evacuation sites

Network analysis identified 55 evacuation routes, with travel times ranging from less than 15 min to 25–30 min. Eight routes fell within the 25–30-min range, primarily because of winding road segments and numerous intersections. Routes requiring more than 30 min would require further improvement of the road network or alternative routes to reduce travel distance and travel time. In addition, buffer analysis using radii of 225, 450, 900, and 1,350 m was conducted to evaluate the spatial coverage of the designated shelters. As illustrated in Fig. 10, the tsunami-affected area under the 20-m inundation scenario falls within the serviceable range of the designated shelters. Most areas of Citepus and Palabuhanratu Villages are located within a 900-m radius, while only small portions extend to 1,350 m. Based on the assumed walking speed and the 30-minute travel-time threshold, the network analysis indicates that the modeled inundation zone can be reached by the designated evacuation shelters.

The number of evacuation routes determined in this study is fewer than the 65 evacuation routes identified by Suri and Syafiudin (2024) for tsunami evacuation in Palabuhanratu. This discrepancy is influenced by the number of evacuation starting points considered and the destinations for these routes. In this study, modifications were made to the evacuation routes, directing them toward temporary evacuation sites, such as natural hills with elevations above 20 meters above sea level, and adjusting the routes to the planned multi-story shelter buildings. The development in this study focused on the addition of evacuation routes that ensure travel times are less than 30 min. Consequently, the accessibility of shelters improved significantly, with 100% coverage of the population within the natural hill shelter routes and three planned evacuation shelters.

The increase in modeled shelter accessibility from 38% to 100% should be interpreted within the assumptions of the evacuation model. The accessibility estimates were based on a walking speed of 0.751 m/s and a maximum travel time of 30 minutes, assuming that evacuees can move along the available road network without substantial delays. In an actual tsunami event, evacuation effectiveness may be lower because of earthquake-induced road damage, congestion, bottlenecks, bridge failures, crowd movement, and variations in individual walking ability. In addition, the simultaneous movement of a large number of evacuees may increase travel time compared with the modeled conditions. Therefore, 100% coverage represents the proportion of the affected population that is spatially reachable within the specified travel-time threshold under the model assumptions, rather than a guarantee of successful evacuation in an actual disaster event.

4. Conclusion

Tsunami hazard zone in Palabuhanratu subdistrict, covering 8.64 km^2, with 4 km^2 at high risk and 4.64 km^2 at moderate risk. The tsunami hazard map was developed following BNPB (2014) guidelines, considering land elevation and proximity to the coast. Tsunami inundation modeling based on Berryman (2006) using initial wave heights of 10 and 20 meters resulted in impacted areas of 3.57 km^2 and 6.44 km^2, respectively. The modeling shows that higher initial wave heights correspond to larger inundation extents. Affected areas mainly consist of low elevation, gentle slopes, and smooth land cover, which facilitate tsunami spread. The estimated affected population numbers were 13,553 and 23,574 for the 10- and 20-meter scenarios, respectively.

The analysis of existing Temporary Evacuation Sites (TES) revealed coverage gaps. Currently, existing TES coverage only reaches 38% of the affected population. The proposed shelter locations were strategically planned to ensure accessibility within an evacuation time of less than 30 min. Shelter planning was based on factors such as population density, community activity centers, and evacuation distances, resulting in three proposed multi-story shelter locations. With these additions, the accessibility of TES can be increased to 100%, significantly reducing the risk and potential casualties from a tsunami. Additionally, evacuation routes were optimized, with 55 routes designed to ensure evacuation within 30 minutes, thereby significantly reducing tsunami risk and potential casualties.

Acknowledgements

This study was funded by the Directorate of Research and Innovation of IPB University through the Riset Kolaborasi Indonesia PTN-BH scheme (Grant number: 35235/IT3.D10/PT.01.03/P/B/2024).

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