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RESEARCH ARTICLE

Mapping of Tsunami Vulnerability Levels and Planning of Shelter Points and Evacuation Routes along the Palabuhanratu Coastline

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Abstract

The Palabuhanratu Subdistrict, located in the Sukabumi Regency, is a high-risk area for tsunami disasters owing to tectonic activity along the Indo-Australian and Eurasian Plate subduction zones. The tsunami vulnerability level in this subdistrict is further heightened by the relatively dense population in its coastal areas, which increases the potential for loss of life and material losses. Therefore, an analysis of tsunami vulnerability levels and the planning of structural mitigation measures—such as shelters and evacuation routes—are crucial to protect communities from tsunami threats. This study aims to analyse the inundation area and affected population under tsunami scenarios with wave heights of 10, 15, and 20 m; identify the coverage of the proposed tsunami shelters; and evaluate the effectiveness of evacuation routes leading to the shelters in the Palabuhanratu Subdistrict. The methods employed include scoring and weighting techniques, Model Builder tools, and Network Analyst. The results indicate that coastal villages, such as Citepus, Jayanti, and Palabuhanratu, are highly vulnerable to tsunamis. Based on inundation modelling, Palabuhanratu Village had the largest inundated area and the highest number of affected residents. Most residents of Citepus and Jayanti Villages are located more than 1,350 m from the nearest shelter, with travel times exceeding 30 min. In contrast, the majority of residents in Palabuhanratu Village can reach shelters within 20 min, although some are still categorised as being in distant and very distant zones. A total of 11 evacuation routes were designed to connect the initial evacuation points to the shelters. However, 2 of the 11 routes, from Point 5 and 6, still exceed 1.000 m in distance and require more than 20 min of travel time.

Keywords: Evacuation route, Palabuhanratu, risk levels, shelter, tsunami.

1. Introduction

Situated at the convergence of three active tectonic plates, Indonesia is recognised as a triple-junction convergent country, bordered by the Eurasian Plate to the north, the Indo-Australian Plate to the south, and the Pacific Plate to the east (Murjaya, 2023; Harijoko et al., 2024). The interaction between these plates, involving friction and pressure on the Earth's crust, triggers the release of energy that causes earthquakes (Yuwanto, 2018). When such earthquakes occur offshore with significant magnitudes, they can generate tsunamis, characterised by run-up, inundation, and strong currents (BNPB, 2014). The southern part of Java Island has a recorded history of earthquakes and tsunamis owing to the presence of a subduction zone, with 48 major earthquakes documented between 1612 and 2014, some exceeding a magnitude of 7 (Meilano et al., 2020). One notable event was the Cianjur earthquake (Mw 5.6) on 21 November 2022, which was followed by 140 aftershocks and resulted in 268 deaths. Other significant earthquakes, such as the Tasikmalaya earthquake (Mw 7.0), have caused widespread damage in the West Java region. Several tsunamis have also occurred due to major earthquakes, including the 2006 Pangandaran tsunami (Mw 7.7), which reached a wave height of 7 m within 40 min, and the 1994 Banyuwangi tsunami, which reached 13.9 m in just 38 min, causing extensive destruction (Subardjo et al., 2017).

The Palabuhanratu Subdistrict, located in the Sukabumi Regency, lies along the southern coast of Java and is classified as a tsunami-prone area owing to tectonic activity. The 2023 Disaster Risk Index reported that Sukabumi Regency has a high risk of earthquakes (score of 12.28) and tsunamis (score of 16.43) (BNPB, 2023). This is attributed to its proximity to the Eurasian and Indo-Australian Plates, and the presence of the Cimandiri Fault. Historical records indicate several earthquakes associated with the Cimandiri Fault, including the Palabuhanratu (1900), Padalarang (1910), Conggeang (1948), Cibadak (1973), Gandasoli (1982), and Sukabumi (2001) earthquakes, all of which highlight the high tsunami potential in the region (Setyani, 2017). The tsunami vulnerability in the Palabuhanratu Subdistrict is further exacerbated by the relatively large population living in its coastal areas, increasing the risk of material losses and casualties. According to data from the Department of Population and Civil Registration of Sukabumi Regency in 2024, the subdistrict's population reached 120,488 residents (BPS, 2024). Palabuhanratu Village has the highest population density (6,042 people/km^2), whereas Cimanggu Village has the lowest (553 people/km^2). High population density elevates the potential for casualties during a tsunami disaster, particularly in areas with dense infrastructure and high mobility, which can impede evacuation efforts (Puspitotanti & Karmilah, 2022). Therefore, tsunami vulnerability mapping is crucial for effective mitigation planning and developing evacuation strategies.

To address the significant tsunami hazard potential, inundation modelling is required using run-up scenarios of 10, 15, and 20 m heights. The 10 m and 15 m scenarios were based on the Pangandaran tsunami (7 m) and the Banyuwangi tsunami (13.9 m), respectively, both of which reflect the potential impact of large tsunamis along the southern coast of Java. The 20 m scenario was selected as a precautionary and anticipatory measure in response to the possibility of a megathrust earthquake capable of generating an extreme tsunami in the region. GPS-based studies have identified a seismic gap zone south of Java, that may serve as the source of a major earthquake (Widiyantoro et al., 2020).

Structural mitigation efforts, such as tsunami shelters, are crucial for reducing casualties, as they serve as vertical evacuation points for affected residents (Eisner et al., 2001). However, the Palabuhanratu Subdistrict currently lacks dedicated tsunami shelters, making evacuation efforts reliant on temporary evacuation sites located on hills with elevations above 20 m above sea level. Unfortunately, these locations are less effective because of their considerable distance, requiring 10–20 min of travel time, which poses challenges for vulnerable groups such as children, pregnant women, and the elderly (Habibie, 2022). Furthermore, supporting facilities such as access to clean water, sanitation, lighting, and electricity are not yet available, rendering these sites unsuitable for prolonged refuge during disasters.

Ideally, tsunami shelters should be reachable within 20 min on foot, located within 2–3 km, and situated at elevations above 20–30 m above sea level. In addition, shelters must be equipped with essential facilities, such as a clean water supply, sanitation infrastructure, emergency food stocks, and first-aid equipment (Budiarjo, 2006). To ensure effective evacuation, an analysis of the fastest evacuation routes and strategic placement of accessible shelter locations is necessary. Therefore, identifying optimal shelter points and tsunami evacuation routes in the Palabuhanratu Subdistrict is a critical step in mitigation efforts to reduce the risk of casualties during a disaster. This study aimed to analyse the inundated area and affected population under tsunami scenarios of 10, 15, and 20 m wave heights, identify the coverage of the proposed tsunami shelter points, and assess the effectiveness of evacuation routes leading to the tsunami shelters in Palabuhanratu Subdistrict.

2. Data and Methods

2.1. Tools and Materials

This study utilised various tools, including hardware such as laptops or computers and software such as ArcMap 10.8, Quantum GIS, InaSafe, and Google Earth Pro, which played a key role in data analysis and visualisation. Secondary data were also employed, including the Indonesian Topographic Map and Digital Elevation Model (DEM) for the Palabuhanratu Subdistrict area obtained from the Ina Geoportal, demographic information collected from the Central Bureau of Statistics (Badan Pusat Statistik), and shapefile (shp) data of buildings and road networks acquired from OpenStreetMap.

2.2. Tsunami Vulnerability

Tsunami vulnerability was determined using five parameters: land elevation (weighted at 25%), land slope (20%), land cover (15%), distance from the coastline (20%), and distance from rivers (20%). All param were classified into five vulnerability levels, ranging from very high to very low (Faiqoh et al., 2013). Land elevation was classified as <5, 5–10, 10–20, 20–30, and >30 m above sea level (Sambah & Miura, 2014). Land slope classification includes <2%, 2–6%, 6–13%, 13–20%, and >20% slopes (Sambah & Miura, 2014). Land cover was categorised into settlements and rivers, agricultural land, open land, shrubs and plantations, and forests and rocky areas. Distance from the coastline was classified as <500, 500–1,000, 1,000–1,500, 1,500–3,000, and >3,000 m. Distance from rivers is classified as <100 m, 100–200 m, 200–300 m, 300–500 m, and >500 m (Faiqoh et al., 2013). Eqn. 1 was used to obtain the total weighted score in tsunami vulnerability mapping, where N is the total weighted score, Bi is the weight of each parameter, and Si is the score of each parameter. Meanwhile, Eqn. 2 is used to determine the interval classes for the tsunami vulnerability levels.

$$N = \sum Bi \times Si \tag{1}$$

$$Interval\ class = \frac{Highest\ score - Lowest\ score}{Total\ class} \tag{2}$$

2.3. Inundation Modelling

Inundation modelling is one of the primary impacts of a tsunami event, which occurs when seawater strikes and floods coastal areas. The Model Builder tool can be applied to ArcGIS software for inundation modelling. For inundation modelling, each type of land cover has its own roughness coefficient. Water and forest have a roughness value of 0.070, shrubs have 0.040, plantations have 0.035, open or vacant land has 0,015, mangroves and agricultural land have 0.025, residential/built-up land has 0.045, and ponds, pools, and fishponds have 0.010. The equation used in inundation modelling is presented in Eqn. 3, where Hloss is the wave height loss per 1 meter, n is the land cover roughness coefficient, H0 is the initial wave height (run-up), and S is the surface slope (Berryman, 2005).

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

The analysis of the inundated area and the number of people affected by the tsunami is crucial for assessing risk and designing effective mitigation and evacuation measures. The area calculation was performed by processing the inundation shapefile, while the estimation of casualties used the building shapefile (shp) data from OpenStreetMap, with tsunami run-up scenarios of 10, 15, and 20 m. Each building is converted into a point, assuming that one point represents three family members, based on the 2023 BPS data, which states that the average family size in Sukabumi Regency is 2.87, rounded up to 3 (BPS, 2023).

2.4. Tsunami Shelter Reach and Evacuation Route Effectiveness

Shelter locations were prioritised in areas with moderate to very high tsunami vulnerability, considering accessibility for the population. The average walking speed is only 0.751 m/s, so shelters that are too far or difficult to reach can increase the risk of casualties. The classification of travel time and distance to shelter locations was divided into five categories: very close (<5 min and <225 m), close (5–10 min and 225–450 m), moderate (10–20 min and 450–900 m), far (20–30 min and 900–1,350 m), and very far (>30 min and >1,350 m) (Ashar et al., 2014). Evacuation routes are designed to allow the quickest possible evacuation, thus increasing the chances of safety during a tsunami. Planning can be carried out using the Network Analyst method, which determines the route with the least impedance (Sahputra et al., 2017). The Remaining Safe Time calculation must be performed first to determine how much time remains for evacuation before the tsunami arrives. The Remaining Safe Time can be determined using Eqn. 4, where RST is the remaining safe time, ETA is the estimated time of arrival, IDT is the initial detection time, and RT is the reaction time. The travel distance for evacuees can be calculated using Eqn. 5, where S is the travel distance, v is the average walking speed, and t is the evacuation time.

$$RST = ETA - (IDT + INT) - RT \quad (4)$$

$$S = v\ x\ t \quad (5)$$

3. Result and Discussion

3.1. Tsunami Vulnerability

The tsunami vulnerability in the Palabuhanratu Subdistrict was analysed using a scoring and weighting method by integrating five parameter maps. Each parameter contributes to the overall vulnerability index, allowing for a comprehensive spatial representation of tsunami vulnerability in the study area. These maps are shown in Fig. 1 and Fig. 2.

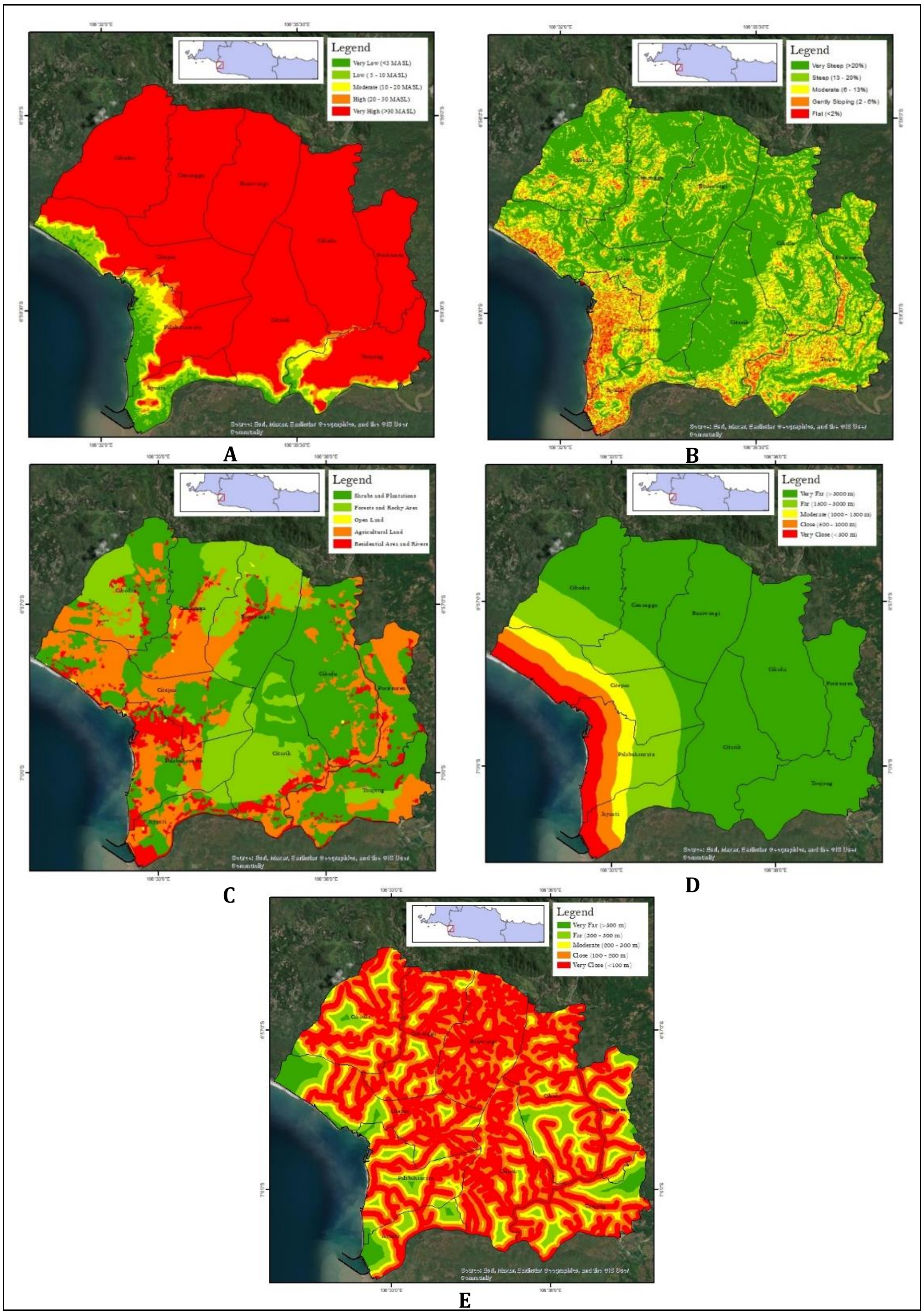

Fig. 1 Spatial parameters for tsunami vulnerability assessment (A) land elevation, (B) land slope, (C) land cover, (D) distance from the coastline, (E) distance from the rivers.

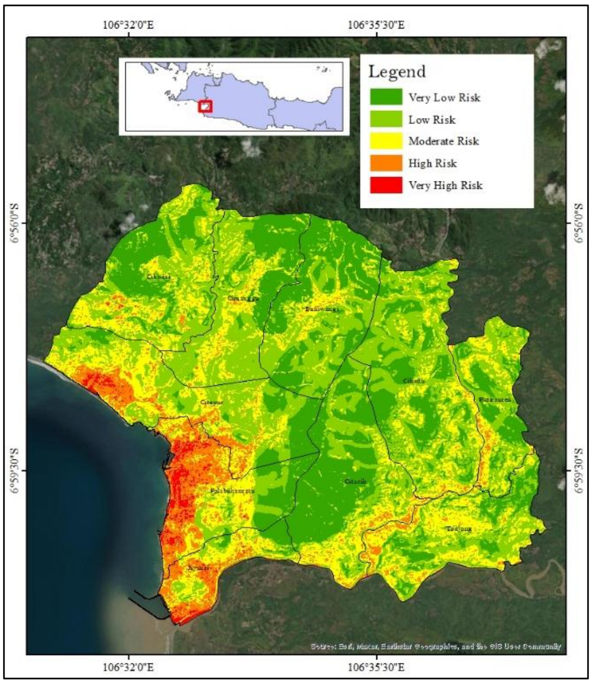

Fig. 2 Vulnerability map.

High-risk areas (orange) cover 7.58 km^2 or 8.29% of the total area, primarily along the coastal zone. Meanwhile, very high-risk areas (red) account for only 1.27 km^2 or 1.39% of the total area, yet still require full attention due to their high vulnerability potential. Citepus, Palabuhanratu, and Jayanti Villages fall into the high to very high-risk categories. This is due to their proximity to the coastline, low and flat land characteristics, presence of rivers that flow into the sea, and densely populated residential areas (Sambah & Miura, 2014).

Previous studies conducted by Kultsum (2017) and Habibie (2022) assessed tsunami vulnerability in the Palabuhanratu Subdistrict using a topographic and coastal proximity-based approach, relying primarily on elevation and distance from the shoreline as key indicators. These studies classified vulnerability levels based on proximity zones, assuming that areas closer to the coastline are more exposed to tsunami hazards. Although such methods offer advantages in terms of simplicity and rapid application over large areas, they inherently overlook other critical factors that significantly influence inland tsunami propagation, such as land slope, land cover, and proximity to river systems. To address these limitations, the present study adopted a more comprehensive and integrative approach by incorporating five spatial parameters (elevation, slope, land cover, distance from the coastline, and distance from rivers) into the vulnerability assessment. This multidimensional framework allows for a more realistic and spatially nuanced representation of the tsunami risk. The resulting vulnerability map reflects the geomorphological and hydrological complexities of the study area and serves as a robust foundation for strategic shelter site selection and evacuation route design. By prioritising low-risk zones near densely populated areas and ensuring that evacuation paths avoid steep terrain, the proposed method enhances the effectiveness and inclusivity of disaster mitigation planning, particularly for vulnerable populations, such as the elderly, children, and individuals with limited mobility.

3.2. Inundation Modelling

Inundation modelling in the Palabuhanratu Subdistrict was conducted using run-up height scenarios of 10, 15, and 20 m. The simulation maps for these run-up scenarios are presented and the inundated area and estimated affected population are shown in Fig. 3.

Fig. 3 shows that only Citepus, Jayanti, and Palabuhanratu Villages are inundated by tsunami waves under the 10 m, 15 m, and 20 m run-up scenarios. In Citepus Village, the affected area was 0.88 km^2 for a 10 m tsunami, increasing to 1.45 km^2 at 15 m, and 1.79 km^2 at 20 m. The affected population was 231 people at 10 m, increasing to 306 people at 15 m, and remained at 306 people at 20 m. In Jayanti Village, the inundated area covers 0.66 km^2 at 10 m, growing to 0.92 km^2 at 15 m, and 1.20 km^2 at 20 m. The affected population included 1,224 people at 10 m, increasing to 1,260 at 15 m, and 1,263 at 20 m. In Palabuhanratu Village, the inundated area was recorded at 1.78 km^2 at 10 m, rising to 2.53 km^2 at 15 m, and reaching 3.11 km^2 at 20 m. The affected population totals 4,758 people at 10 m, increases to 7,782 at 15 m, and reaches 11,280 when the tsunami height reaches 20 m.

Tsunami inundation modelilng considers the coastline, land cover, and land slope, all of which influence tsunami wave movement. The coastline determines the initial point of wave impact, whereas surface roughness from various land cover types can either slow down or accelerate water flow. Reefs, levees, forests, and buildings can obstruct or dissipate wave energy (Gayer et al., 2010). The land slope also plays a role, as steep areas tend to limit inundation, whereas flat areas allow for wider dispersion. The modelling conducted in the Palabuhanratu Subdistrict shows that densely populated and steep regions are generally more protected, whereas low-lying coastal areas are more vulnerable to tsunamis.

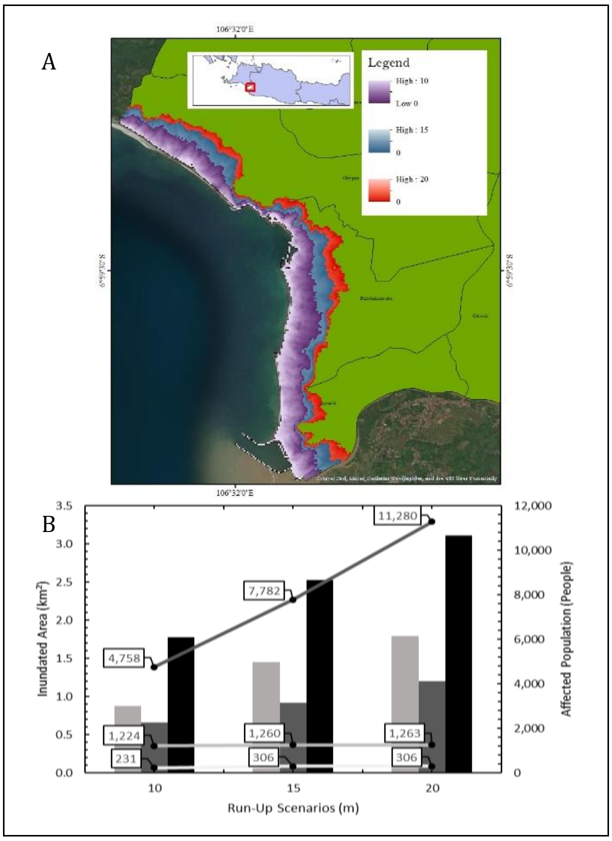

Fig. 3 Inundation modelling (A) simulation results of 10 m, 15 m, and 20 m inundation (B) Inundated area and affected population data.

3.3. Tsunami Shelter Reach and Evacuation Route Effectiveness

The tsunami shelter in the Palabuhanratu Subdistrict is planned to be located at Palabuhanratu Terminal, with coordinates of -6.985333° S and 106.544689° E. The shelter location was selected based on its proximity to the coastal area of Palabuhanratu Subdistrict and its position in a tsunami-prone zone. Shelter coverage analysis was conducted using the Multiple Buffer Ring tool in ArcGIS, with parameters based on the classification of travel time and distance from the nearest shelter. The shelter coverage map and data for 10 m, 15 m, and 20 m inundation scenarios are presented in Fig. 4 and Table 1.

Table 1. Shelter coverage data

Village	Distance (m)	Inundation (10 m)		Inundation (15 m)		Inundation (20 m)	
		Area (km^2)	Population	Area (km^2)	Population	Area (km^2)	Population
Citepus	450–900	0,004	0	0,015	0	0,015	0
	900–1.350	0,039	0	0,060	0	0,060	0
	>1.350	0,835	231	1,378	306	1,378	306
Jayanti	>1.350	0,660	1.224	0,918	1.260	0,918	1,263
Palabuhanratu	<225	0,111	906	0,147	1.860	0,147	2,010
	225–450	0,154	1.296	0,248	2.796	0,248	3,558
	450–900	0,294	1.056	0,500	1.626	0,500	3,960
	900–1.350	0,218	30	0,367	30	0,367	282
	>1.350	1,001	1.470	1,267	1.470	1,267	1,470

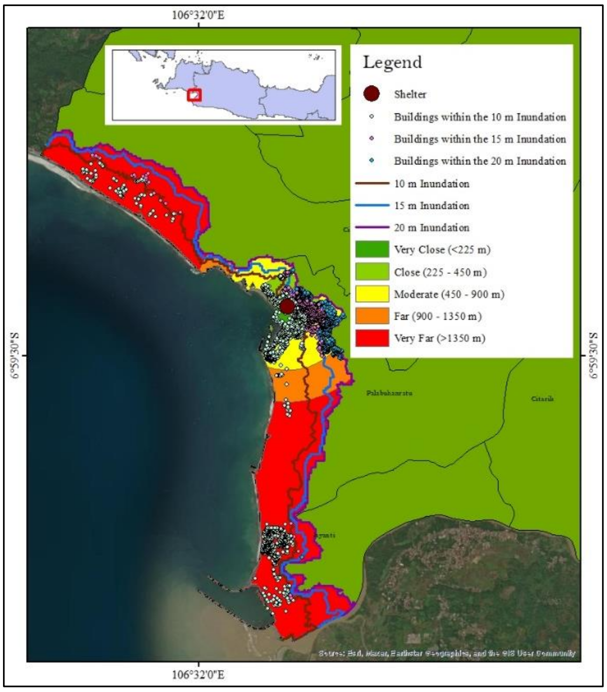

Fig. 4 Tsunami shelter reach map

The analysis of shelter accessibility under 10 m, 15 m, and 20 m inundation scenarios revealed varying levels of accessibility among villages in the Palabuhanratu Subdistrict. In Citepus Village, the majority of the population falls into the very far category (>1,350 m) and would require more than 30 min to reach the shelter in all inundation scenarios. This indicates the limited availability of evacuation facilities. A similar condition was found in Jayanti Village, where most residents also need more than 30 min to reach the shelter. In contrast, accessibility in Palabuhanratu Village is better than that in Citepus and Jayanti Villages. Most of the population can reach the shelter in less than 20 min, especially in the 15 m and 20 m scenarios, with an increase in the number of people in the very close (<225 m) and close (225–450 m) categories as the inundation height increases. However, there are still residents in the very far category in the 15 m and 20 m scenarios. Based on the Remaining Safe Time calculation, using the tsunami arrival time from the 1994 Banyuwangi event, the feasible evacuation time is 20 min (Post et al., 2009; BMKG 2013). Therefore, evacuation efforts must focus on areas within a 450–900 m range or 10–20 min from the shelter.

The analysis further indicates that in the absence of strategically planned shelter locations, there is a significant risk that residents may attempt to evacuate toward existing Temporary Evacuation Sites (TES) in Palabuhanratu Subdistrict, many of which fall within tsunami inundation zones, particularly under the 20-meter wave height scenario. This poses a critical safety concern, as most of these TES facilities were not structurally designed to withstand tsunami forces and do not meet the established standards for disaster-resilient infrastructure. Consequently, the development of designated tsunami shelters is essential to reduce the potential loss of life owing to the inadequacy of existing evacuation sites in terms of location and structural quality.

Previous studies have made important contributions to tsunami-evacuation planning. For instance, Sutikno & Mukarami (2015) employed a network-based service area analysis in Pacitan, considering evacuation times of up to 30 min. However, their approach was limited to a single tsunami scenario and did not differentiate shelter accessibility based on travel time or distance. Similarly, Ismiati et al., (2020) applied Network Analyst tools to identify Temporary Evacuation Sites (TES) in Makassar with a maximum allowable travel time of 12 min. Although this study established a strong foundation for using network analysis in tsunami mitigation, it did not incorporate multiple inundation scenarios or provide a detailed classification of shelter reachability based on distance or time thresholds. In contrast, this study integrates spatial analysis with multiple tsunami inundation scenarios (10 m, 15 m, and 20 m) to produce a more refined and context-specific shelter accessibility map. The categorisation of affected populations into five proximity classes (very close, close, moderate, far, and very far) enables a more accurate evaluation of shelter demand and highlights critical gaps in the current evacuation planning. Moreover, the analysis incorporates realistic evacuation time constraints based on historical tsunami events, thereby offering technically sound and actionable recommendations for local disaster management agencies, such as BPBD and regional governments in Palabuhanratu.

The evacuation starting points were determined based on the population density in residential areas, aiming to cover as many residents as possible in tsunami-prone zones affected by a 20 m wave. Although not all residents must go to the starting points before reaching the shelter, these points serve as a reference for assessing accessibility and travel time to the planned shelter. There are 11 evacuation routes from the starting points, which are distributed around the shelter in Palabuhanratu Village. The evacuation route map is shown in Fig. 5.

The Network Analyst results indicate that there are ten main evacuation routes leading to the shelter in Palabuhanratu Village. Of the 11 routes, two—the route from Point 5 via Jalan Kaum Raya (1,036 m, 23 min travel time) and the route from Point 6 via Jalan Dewi Sartika (1,051 m, 23 min travel time)—require more than 20 min to reach the shelter. These exceed the optimal evacuation time limit of 20 min and fall short of the safe evacuation standard based on the 1994 Banyuwangi tsunami arrival time (38 min) (Post et al., 2009; BMKG 2013). To improve evacuation effectiveness, the construction of alternative and shortcut roads is necessary, particularly around Jalan Kaum Raya and Jalan Dewi Sartika, to reduce travel distances. Additional road development is also recommended at Points 1 and 8 to further reduce the distance and travel time. It is highly advisable to separate vehicle and pedestrian routes to avoid congestion and develop dedicated pedestrian pathways to increase mobility. Furthermore, evacuation signage should be installed at intersections to make routes easier to follow, and evacuation route awareness campaigns should be conducted to prevent overcrowding on specific paths and ensure a smooth evacuation process.

Fig. 5 Evacuation Route Map

Prior to the implementation of the Network Analyst, evacuation route planning in Palabuhanratu lacked a standardised baseline network that could serve as a reliable reference for emergency response. Informal or spontaneous evacuation pathways relied upon by the community tended to be unstructured, with numerous intersections and branching roads, potentially leading to varied and inconsistent route selection. This condition increases the likelihood of spatial misperceptions among residents, particularly given their limited understanding of the surrounding environment, which may prompt them to follow familiar but suboptimal paths rather than the safest ones recommended in the official guidelines. This phenomenon aligns with the findings of Isagawa & Ohno (2018), who observed that evacuation behaviour is often influenced more by familiarity with routes than by objective safety criteria.

Such uncertainty in movement patterns can result in delays, misdirection, or even entrapment in high-risk zones during a tsunami event. In this study, evacuation route optimisation was conducted using the Network Analyst tool, which identifies the shortest and most efficient paths to the designated shelters based on existing road networks. While empirical data on the effectiveness of prior evacuation behaviours are unavailable, the use of a Network Analyst offers a scientifically grounded approach to enhancing evacuation performance by prioritising distance minimisation and travel-time efficiency. This methodological framework provides a critical advancement toward structured, data-informed evacuation planning in tsunami-prone regions.

4. Conclusion

The coastal villages Citepus, Jayanti, and Palabuhanratu in the Palabuhanratu Subdistrict are highly vulnerable to tsunami hazards. The inundated area and number of affected residents increased with increasing tsunami wave height. In Citepus Village, the affected area reached 0.88 km^2 at a 10 m tsunami height, increased to 1.45 km^2 at 15 m, and expanded to 1.79 km^2 at 20 m. The affected population was 231 people at 10 m, increasing to 306 people at 15 m, and remaining at 306 people at 20 m. In Jayanti Village, inundation covers 0.66 km^2 at 10 m, expands to 0.92 km^2 at 15 m, and reaches 1.20 km^2 at 20 m. The affected populations were 1,224 people at 10 m, 1,260 people at 15 m, and 1,263 people at 20 m. In Palabuhanratu Village, the inundation area was recorded at 1.78 km^2 at 10 m, increased to 2.53 km^2 at 15 m, and reached 3.11 km^2 at 20 m. The affected population totalled 4,758 people at 10 m, rising to 7,782 at 15 m, and reaching 11,280 at 20 m. Most residents in Citepus and Jayanti Villages are located more than 1,350 m from the shelter, requiring over 30 min to reach it, indicating limited evacuation facilities. Meanwhile, in Palabuhanratu Village, the majority of residents can reach the shelter in less than 20 min, although some still fall into the far and very far categories. A total of 11 evacuation routes were designed to connect the initial evacuation points to the designated shelters. Two of the eleven routes, specifically those from Point 5 and Point 6, still exceed 1.000 m in length and require more than 20 min of travel time.

Additional shelters are needed in areas categorized as far and very far within coastal villages to accommodate more evacuees. Furthermore, public outreach regarding shelter allocation is essential to prevent overcrowding at a single location. The community must be educated about the designated evacuation routes to ensure an orderly evacuation process. In addition, the development of road access is necessary to separate motor vehicle lanes from pedestrian pathways to reduce traffic congestion risks. A thorough assessment of road conditions in the Palabuhanratu Subdistrict is also required so that evacuation routes can be adjusted based on road width, infrastructure, and potential obstacles such as congestion and surface conditions.

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