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Tsunami Hazard Level Mapping and Evaluation of Temporary Evacuation Sites (TES) on the Palabuhanratu Coast

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Abstract: *Indonesia is highly prone to disasters due to its location at the convergence of three active tectonic plates: the Eurasian, Pacific, and Indo-Australian plates. Sukabumi Regency ranks as the second-highest risk area in the country. In the coastal region, Palabuhanratu Urban Village has the highest population density in Palabuhanratu District, reaching 6,042 people/km². The high population density in coastal areas increases the potential for casualties in the event of a tsunami. Therefore, mitigation efforts in the form of Temporary Evacuation Sites (TES) are essential across the coastal areas of Palabuhanratu District. A reassessment of the existing TES locations is necessary to evaluate their effectiveness. This study aims to identify the affected area and population under tsunami scenarios with run-up heights of 10 m, 15 m, and 20 m. Additionally, it analyzes the coverage of TES locations and the effectiveness of evacuation routes in Palabuhanratu District. The analysis is conducted using ArcGIS and QGIS software through several stages, including tsunami hazard zoning, tsunami inundation modeling, TES coverage analysis, and evacuation route optimization using network analyst tools. The results indicate that 90.6% of the coastal area in Palabuhanratu District falls into the safe category. The tsunami inundation modeling shows an affected area of 3.32 km² (run-up 10 m), 4.9 km² (run-up 15 m), and 6.1 km² (run-up 20 m). The estimated affected population for these run-up heights is 6,123, 9,348, and 12,849 people, respectively. On average, 68% of the affected population can reach a TES. A total of 68 evacuation routes were generated, with 30 routes classified as highly safe, safe, or moderate, requiring 0–20 minutes of travel time. The findings suggest that additional TES locations should be strategically placed along the coastal areas, particularly near residential zones, to improve evacuation efficiency.*

Keywords: evacuation route; hazard zone; TES; tsunami

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1. Introduction

Indonesia, as an archipelagic country, is located at the convergence of three active tectonic plates: the Eurasian, Pacific, and Indo-Australian plates. The movement of these tectonic plates beneath the ocean floor generates underwater earthquakes, which in turn trigger fast-moving tsunami waves. The southern coast of Java is one of the areas with a high potential for tsunamis due to the presence of tectonic activity in the form of the Indo-Australian plate subduction beneath the Eurasian plate near the trench[1]. Palabuhanratu, situated in the coastal region of Sukabumi Regency, is also part of the subduction zone connecting the Indo-Australian and Eurasian plates.

According to the Indonesia Disaster Risk Index (2023), Sukabumi Regency ranks as the second-highest disaster-prone area in the country, with a risk score of 16.45[2]. Based on data from the Central Bureau of Statistics (BPS), the population of Palabuhanratu District reached 120,488 people in 2023, with the highest population density recorded in Palabuhanratu Urban Village at 6,042 people/km²[3]. The high population density in coastal areas increases the potential for casualties in the event of a tsunami. Therefore, tsunami mitigation efforts are necessary, including the establishment of Temporary Evacuation Sites (TES) across Palabuhanratu District. Additionally, tsunami inundation modeling is required to determine the affected zones under various tsunami height scenarios, which will aid in analyzing TES locations based on the criteria set by the National Disaster Management Agency (BNPB)[4].

A study conducted by Habibie[5] identified 15 locations that could serve as TES in Palabuhanratu District. The tsunami height assumption in the study ranged from 10 to 20 meters, and the selected TES locations consisted of buildings or natural hills with elevations between 10 and 100 meters above sea level. However, the existing 15 TES locations are still unevenly distributed along the coastline and do not adequately cover other areas classified as tsunami hazard zones. This lack of distribution also results in ineffective evacuation routes from residential areas to the nearest TES.

The planning of tsunami evacuation routes is analyzed based on the walking speed of the most vulnerable individuals, which BNPB has set at 3.22 km/h. By considering tsunami arrival time and evacuation speed, it is possible to predict the maximum distance people can travel to reach a TES and determine the optimal evacuation routes[6]. Therefore, a reassessment of TES locations in the coastal areas of Palabuhanratu District is necessary to ensure better coverage of tsunami hazard zones. This study aims to identify the affected area and population under tsunami scenarios with run-up heights of 10 m, 15 m, and 20 m, as well as analyze the coverage of TES locations and the effectiveness of evacuation routes in Palabuhanratu District.

2. Methods

2.1. Location and Materials

The study area is located in the coastal region of Palabuhanratu District, Sukabumi Regency, West Java. The tools used in this research include a laptop equipped with spatial data processing software, namely ArcGIS 10.8.1, Google Earth Pro, and QGIS. The data utilized in this study consists of Indonesia's Topographic Map (RBI), building data from OpenStreetMap (OSM) in QGIS, population data from the Central Bureau of Statistics (BPS), and Digital Elevation Model (DEM) data from the Geospatial Information Agency (BIG).

2.2. Research Procedures

2.2.1. Tsunami Hazard Zone

The elevation map was created using DEM data obtained from the Tanah Air Indonesia website, managed by the Geospatial Information Agency (BIG). The DEM data was processed by classifying elevation into different hazard levels using the Reclassify feature in ArcGIS. Meanwhile, the mapping of distances from the coastline was conducted using ArcMap with the Buffer feature. The classification of land elevation and distance from the coastline was determined based on BNPB guidelines, as shown in **Table 1**[7]. The resulting distance map was then overlaid with the land elevation map using ArcGIS to generate the tsunami hazard zone map for Palabuhanratu District.

Table 1 Tsunami hazard levels

Index	Hazard Levels	Elevation (masl)	Distance from Coast
4	High Risk	0 – 15	0 – 100 m
3	Risk	15 – 50	100 – 500 m
2	Safe	500 – 100	500 – 1000 m
1	Very Safe	>100	>1,000 m

2.2.2. Tsunami Inundation Modeling

The tsunami inundation modeling is based on the Berryman equation (2005), which estimates the decrease in tsunami height per 1-meter inundation distance upon reaching land, considering elevation and surface roughness[8]. The inundation modeling assumes run-up heights of 10, 15, and 20 meters. The equation used in this modeling was developed by[8] and is presented in **Equation** (1).

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

where,

$Hloss$: Losses of tsunami height per 1 m of inundation distance
n : Surface roughness coefficient
H_o : Tsunami wave height at coastline (m)
S : Slope (degree)

The surface slope used in **Equation** (1) was derived from spatial data processing of DEM raster data using ArcMap. Meanwhile, each land cover type has a different surface roughness coefficient. The roughness coefficient values listed in **Table 2** [8] were then assigned to each land cover dataset in ArcGIS.

Table 2 Surface roughness coefficient values based on land cover types

Land Cover	Surface Roughness Coefficient
Rivers	0.007
Empty area	0.015
Shrubland	0.040
Agriculture area	0.025
Urban/Built Up area	0.045
Forest	0.070
Garden/Cultivated Area	0.035

2.2.3. Mapping of Temporary Evacuation Sites (TES) Location

Temporary Evacuation Sites (TES) can be either a building or a hill that is easily accessible from areas with a high tsunami hazard level. The accessibility is classified into five categories based on distance and travel time to the evacuation sites: very close (<5 minutes and <225 m), close (5 – 10 minutes and 225 – 450 m), moderate (10 – 20 minutes and 450 – 900 m), far (20 – 30 minutes and 900 – 1,350 m), and very far (>30 minutes and >1,350 m)[9]. This analysis aims to evaluate the TES locations to ensure they are accessible to the entire community.

2.2.4. Analysis of the Affected Population

The calculation of the affected population was conducted using building data obtained from OpenStreetMap (OSM) in QGIS, focusing on structures within the tsunami inundation area at wave heights of 10, 15, and 20 meters. The identified number of buildings was then multiplied by the average household size in Sukabumi District. According to the 2023 West Java Population Profile, the average household size in Sukabumi Regency is 2.87 people, which was rounded to 3 people per household.

2.2.5. Effective Tsunami Evacuation Routes

The analysis of effective evacuation routes was conducted using the Network Analyst tool in ArcGIS 10.8.1. Network Analyst determines the shortest travel time from residential areas to the nearest TES, calculated using **Equation** (2)[10,11]. The fastest evacuation time was estimated using the Remaining Safe Time method, which determines the available evacuation time before the tsunami arrives.

$$RST = ETA - (IDT + INT) - RT \quad (2)$$

where,
RST : *Remaining Safe Time*
ETA : *Estimated Time of Arrival*
IDT : *Initial Detection Time*
INT : *Interval Notification Time*
RT : *Reaction Time*

The analysis was carried out for each subdistrict/village located within the tsunami hazard zone. The distance of each evacuation route was calculated using **Equation** (3). The walking speed used in this study corresponds to the lowest average human walking speed, specifically that of elderly groups walking together, measured at 0.751 m/s.

$$S = V \times t \quad (3)$$

where,
S : Distance (m)
V : Speed (m/s)
t : Time (s)

3. Result and Discussion

3.1. Land Elevation

The elevation data used in this study is sourced from DEMNAS provided by Ina-Geoportal and classified into four levels using the reclassify feature in ArcGIS, as referenced in **Table 1**. Based on data analysis, it was found that 67.1% of Palabuhanratu District's area is at a safe elevation from tsunami hazards. Additionally, low-elevation land (15 – 50 m) accounts for 11.7% of the area, medium-elevation land (50 – 100 m) comprises 11.6%, and very low-elevation land covers 9.7% of Palabuhanratu District. Coastal areas with low elevation have a higher vulnerability to tsunamis compared to other regions[12].

3.2. Distance From the Coastline

The distance map from the coastline was created using the buffer feature in ArcGIS, with classifications referenced in **Table 1**. The distance criteria were determined by the National Disaster Management Agency. The farther a location is from the coastline, the lower its tsunami hazard level. The total area of Palabuhanratu District is divided into different distance classifications as follows: 0 – 100 m from the coastline accounts for 1.2%; 100 – 500 m covers 4.1%; 500 – 1000 m comprises 5.2%; and areas beyond 1,000 m make up the largest portion at 89.6%.

3.3. Land Cover

The dominant land cover types in the coastal areas of Palabuhanratu District are shrubs and agriculture land, covering 30% and 25.7% of the district's total area, respectively. Other major land covers include forest (21.7%), cultivated land (13.6%), built-up area (7.9%), rivers (1%), and empty area (0.2%). These land cover data were then used to calculate surface roughness coefficients. The roughness coefficient of each land cover type is associated with the energy dissipation of tsunami waves upon interaction with the surface[13].

3.4. Slope

Slope analysis results indicate that 36.5% of the coastal areas in Palabuhanratu District fall within the flat classification (0 – 8%), 30.7% are categorized as gentle slopes (8 – 15%), 21.3% as moderately steep (15 – 25%), 10.5% as steep (25 – 45%), and 1% as very steep (>45%). The slope data are utilized in tsunami inundation modeling, as steeper coastal slopes are more likely to be significantly impacted by tsunamis.

3.5. Tsunami Hazard Zone

Tsunami hazard zone mapping was conducted using the overlay feature in ArcGIS, combining elevation and coastline distance data to generate a hazard map, as shown in **Figure 1**. The classification of tsunami hazard zones follows the hazard index established by BNPB, as detailed in **Table 1**. The results indicate that 77.7% of Palabuhanratu District is categorized as very safe, 12.8% as safe, 5.1% as at risk, and 4.4% as highly at risk. Distance from the coastline plays a crucial role in determining tsunami hazard potential. The closer an area is to the coastline, the higher its tsunami risk[14].

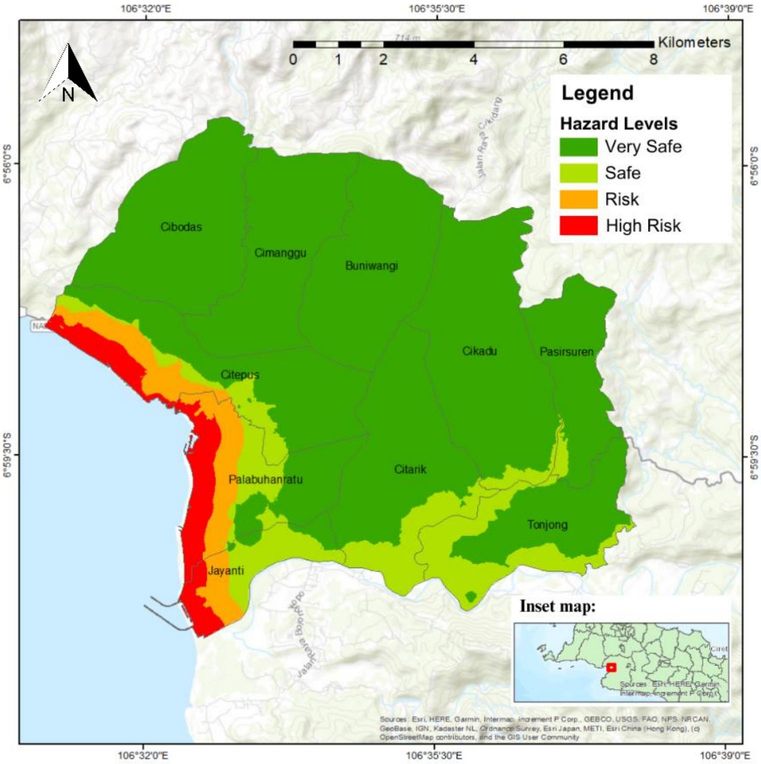


Figure 1 Tsunami hazard zone map of Palabuhanratu district

3.6. Tsunami Inundation Modeling

Tsunami inundation modeling utilized land cover, slope, and calculations from **Equation** (1), with wave heights of 10, 15, and 20 meters. These wave heights were selected based on the study by Widiyantoro *et al.*[15], which analyzed the implications of megathrust earthquakes and tsunamis in southern Java, Indonesia. Their findings suggest that a worst-case scenario with a 400-year recurrence period could result in a 9.1 Mw earthquake and a maximum tsunami height of 20.2 m in West Java. Therefore, tsunami modeling was conducted using 10, 15, and 20 m wave heights to assess potential impacts. Inundation simulations were performed using the model builder tool in ArcGIS. The results indicate that a 10-meter tsunami could inundate an area of 3.32 km², a 15-meter wave could affect 4.9 km², and a 20-meter wave could impact 6.1 km² of Palabuhanratu District. The most affected areas, based on tsunami inundation modeling, are Citepus, Jayanti, and Palabuhanratu Villages.

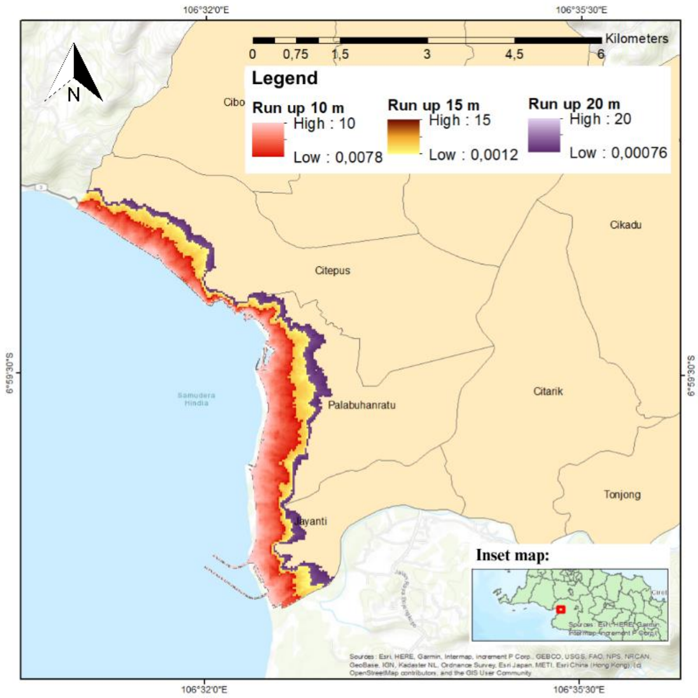


Figure 2 Tsunami inundation map with run-up heights of 10, 15, and 20 meters

3.7. Number of Tsunami-Affected Population

The affected population was estimated by analyzing the number of buildings within the tsunami inundation zones. Building data were obtained from OpenStreetMap (OSM) in QGIS, with each building representing three family members, based on the average household size in Sukabumi Regency, as calculated by the West Java Civil Registry Office in 2023[15]. The estimated tsunami-affected population for inundation scenarios with 10, 15, and 20-meter run-ups are 6,213, 9,348, and 12,849 people, respectively. Palabuhanratu Village has the highest number of affected residents in all run-up scenarios due to its high population density and proximity to the coastline.

3.8. Temporary Evacuation Sites (TES) Locations for Tsunami

Temporary Evacuation Sites (TES) locations in Palabuhanratu District were referenced from Habibie's study[5], which identified 15 TES in the district. This data was collected through field surveys and information from the Sukabumi Regency Disaster Management Agency (BPBD). The TES identified have varying elevations, ranging from 12 to 83 meters above sea level (m asl). Since the highest tsunami wave height used in this study is 20 m, only 12 TES with elevations above 20 m asl were reassessed. The reachability of each TES was analyzed based on distance and travel time, following the classification by Ashar *et al*.[9]. The 12 TES were grouped into five zones to avoid data redundancy regarding the affected population.

Zone 1 consists of a single TES located in Padepokan. Similarly, Zone 2 also contains one TES in Cidahon. Zone 3 includes four TES sites that are closely situated, namely Gunung Butak, Kebun Pasir Badak, PDAM Palabuhanratu, and Taman Tanjoresmi 1. Zone 4 comprises two TES locations, SMK 1 Palabuhanratu and Taman Tanjoresmi. In Zone 5, four closely located TES were selected: Polres Palabuhanratu, RSUD Palabuhanratu, SMA 1 Palabuhanratu, and SMP 3 Palabuhanratu. The TES coverage area is calculated based on distance classification, categorized as very close (<225 m), close (225–450 m), moderate (450–900 m), and far (900–1,350 m). This classification is used to determine the number of affected residents who can reach the Temporary Evacuation Sites (TES), as detailed in **Table 3.**

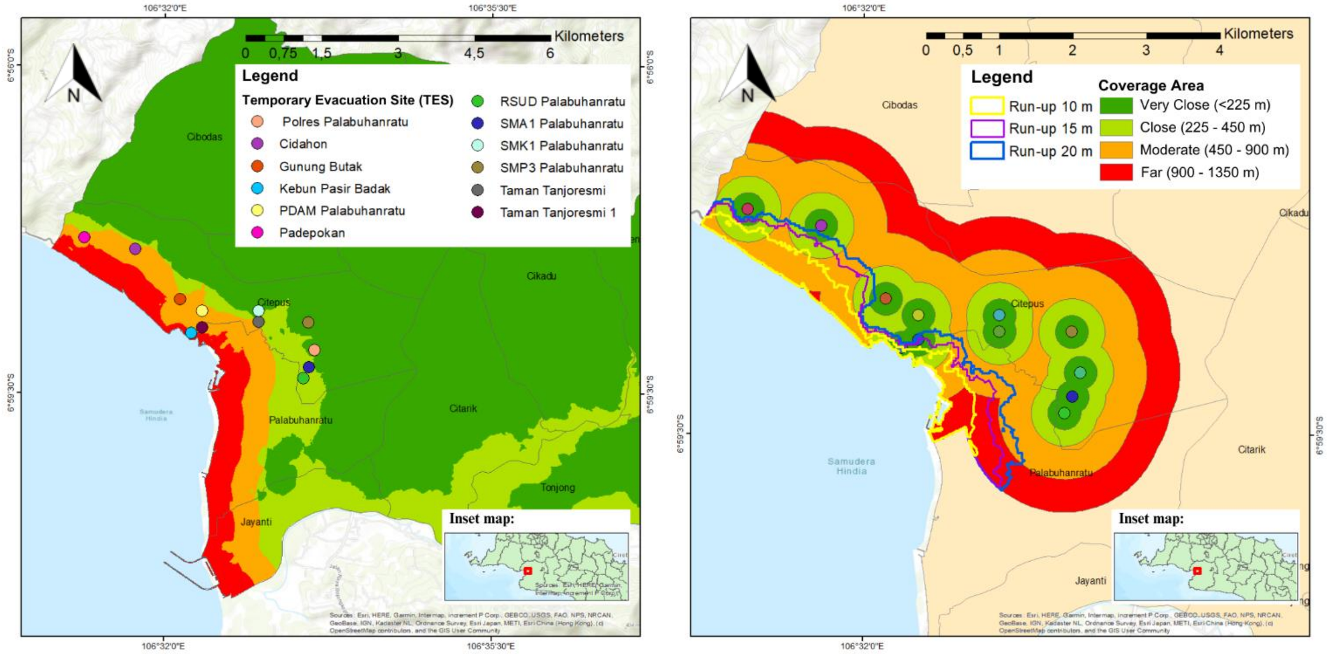
Table 3 The number of affected population and impacted area covered by TES

Distance (m)	Number of Tsunami-Affected Population Reached by TES (people)			Area Accessible to TES (km^2)
	***Run up* 10 m**	***Run up* 15 m**	***Run up* 20 m**	
		ZONE 1		
225	0	0	0	0.16
450	27	45	45	0.48
900	75	77	77	0.73
1350	0	0	0	0.31
		ZONE 2		
225	0	0	0	0.16
450	15	54	54	0.48
900	104	117	117	1.30
1350	0	0	0	0.89
		ZONE 3		
225	0	0	0	0.51
450	126	126	126	0.78
900	656	1070	1412	1.22
1350	1521	1842	1962	0.59
		ZONE 4		
225	0	0	0	0.25
450	0	0	0	0.58
900	237	2124	3282	0.57
1350	420	456	912	0.70
		ZONE 5		
225	0	0	0	0.56
450	0	0	0	1.07
900	0	0	804	2.45
1350	267	636	1254	3.04

The calculation results of the tsunami-affected population that can reach TES, as shown in **Table 3**, indicate that no residents fall within the very close range (0 – 225 m) in any zone. Residents who can access TES in Zone 4 and Zone 5 are located within the farthest distance range. This suggests that the available TES are still situated at a considerable distance from residential areas. Zone 3 has the highest number of tsunami-affected residents due to the presence of four TES within a single zone and their proximity to the coastline, resulting in a larger affected population compared to other zones. The coverage area of the Temporary Evacuation Sites (TES) and the inundation extent for run-up heights of 10, 15, and 20 meters can be seen in **Figure 3**. The number of affected residents and areas refers to those within TES coverage and classified as tsunami hazard zones based on inundation modeling at 10, 15, and 20 meters. Meanwhile, the total population and area covered by TES include all areas that fall within the evacuation site's reach.

The inundation results at a run-up height of 20 meters show that 78% of the affected population can reach a TES. Similarly, at an inundation height of 15 meters, 70% of tsunami-affected residents are able to access a TES. However, the results for a 10-meter inundation height are significantly lower. Out of a total of 6,213 affected residents in the area, only 3,448 people, or 55%, can reach a Temporary

Evacuation Site (TES). This is due to the relatively distant locations of TES from tsunami hazard zones and their uneven distribution along the coastal areas.



(a) (b)

Figure 3 TES locations and coverage areas in the coastal area of Palabuhanratu District

3.9. Evacuation Routes to Temporary Evacuation Sites (TES) for Tsunami

Evacuation routes were created based on tsunami inundation modeling and TES accessibility areas. Several criteria must be met for an evacuation route to be considered viable, including route safety, shortest travel distance, and feasibility as an evacuation path[16]. The evacuation route analysis used the closest facility method in the Network Analyst feature in ArcGIS, with TES points as facilities and residential areas/buildings as incidents. The generated evacuation routes prioritize the shortest and fastest travel distances. The evacuation route modeling for TES in Palabuhanratu District resulted in 68 routes. The shortest and fastest evacuation route measures 5.4 meters with a travel time of 7.2 seconds (0.12 minutes) from a residential area in Citepus Village to the nearest TES, SMA 1 Palabuhanratu. In contrast, the longest route extends 2.75 km from a residential area to TES SMP 3 Palabuhanratu, passing through Palabuhanratu and Citepus Villages, with a travel time of 61.2 minutes.

Remaining Safe Time (RST) was calculated based on the 1994 Banyuwangi tsunami, which had an Estimated Time of Arrival (ETA) of 38 minutes, leaving 20 minutes as RST[10,11]. This aligns with the TES reachability classification, where the maximum time for the moderate category is 20 minutes. Of the 68 generated evacuation routes, 30 routes (categorized as very safe, safe, and moderate) have travel times between 0–20 minutes, while 38 routes exceed 20 minutes, falling into the distant and unsafe categories. The fastest evacuation routes are illustrated in **Figure 4**. Some TES locations, such as SMK 1 Palabuhanratu and Kebun Pasir Badak, were not covered by the generated routes. Therefore, additional TES are needed in coastal areas, particularly in Jayanti and Palabuhanratu Villages, to optimize evacuation routes for tsunami disaster mitigation. TES locations should be near residential areas with accessible roads to ensure safe and efficient evacuation within the recommended time frame.

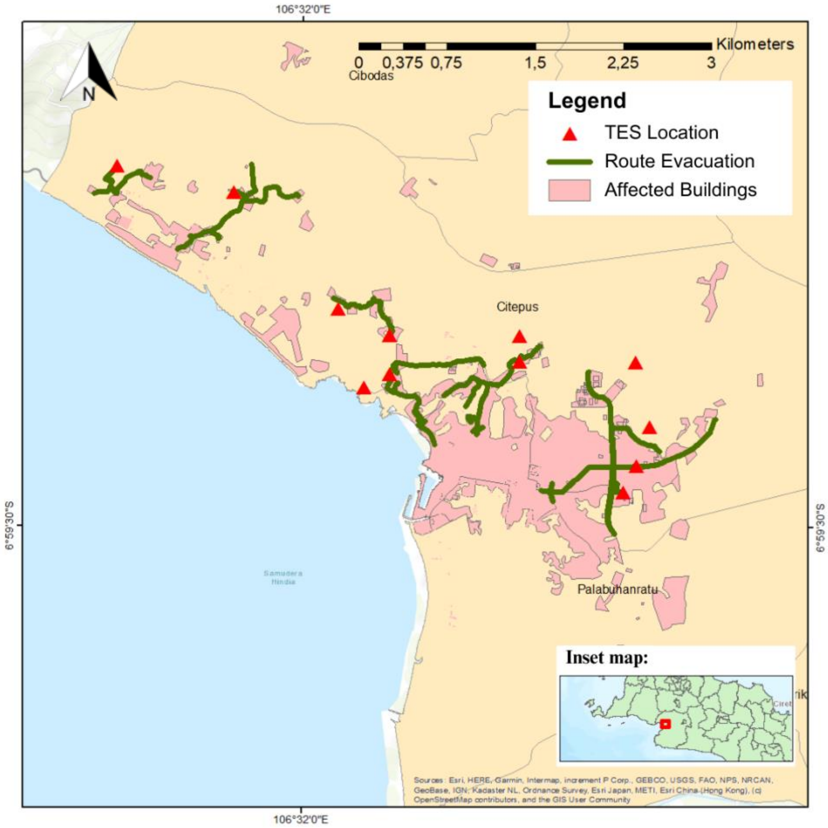


Figure 4 Fastest evacuation route in the coastal area of palabuhanratu district

4. Conclusions

The tsunami inundation modeling results indicate that the affected area for each run-up height is 3.32 km² for a 10 m run-up, 4.9 km² for a 15 m run-up, and 6.1 km² for a 20 m run-up. In the coastal area of Palabuhanratu District, 77.7% of the region falls into the "very safe" category from tsunami hazards. Additionally, 12.8% is classified as "safe," 5.1% as "at risk," and 4.4% as "highly at risk" of tsunami disasters. The number of tsunami-affected residents at inundation heights of 10 m, 15 m, and 20 m is 6,123, 9,348, and 12,849 people, respectively. A total of 78% of the affected population at a 20 m run-up height can reach a TES, with the farthest coverage extending beyond 1,350 meters from the TES location. A total of 68 evacuation routes were identified, with 30 routes classified as "very safe," "safe," or "moderate," having a travel time of 0–20 minutes. However, two TES locations do not have evacuation routes due to their remote locations far from residential areas. Therefore, new Temporary Evacuation Sites (TES) need to be established in a more evenly distributed manner in the coastal area of Palabuhanratu, particularly in Jayanti and Palabuhanratu sub-districts, to optimize evacuation routes for tsunami disaster mitigation in the region. TES locations should also be closer to residential areas to ensure more effective evacuation routes.

References

[1] Windupranata W, Hanifa NR, Nusantara CADS, Aristawati G, Arifianto MR. Analysis of tsunami hazard in the Southern Coast of West Java Province - Indonesia. IOP Conference Series: Earth and Environmental Science 2020; 618:012026. https://doi.org/10.1088/1755-1315/618/1/012026.

[2] BNPB. Indeks Risiko Bencana Indonesia Tahun 2023. vol. 02. 2024.

[3] BPS. Kecamatan Palabuhanratu Dalam Angka 2024 2024. https://sukabumikab.bps.go.id/id/publication/2024/09/26/a95c95d385a0825605e239d2/palabuhanratu-subdistrict-in-figures-2024.html (accessed March 25, 2025).

[4] Nugraha K, Somantri. Potential Tsunami Inundation Model Using UAV at Palangpang Beach, Ciletuh-Palabuhanratu Geopark, Sukabumi, Indonesia. International Journal of Geotourism Science and Development 2023;3:1–7. https://doi.org/10.58856/ijgsd.v3i1.24.

[5] Habibie MF. ANALISIS LOKASI SHELTER EVAKUASI TSUNAMI DI PELABUHAN RATU. 2022.

[6] Hamidah R, Mahlil T, Putriansyah C, Putri M, Prawiranegara M, Aufasani N, et al. Tsunami Evacuation Route Planning Research in Pelabuhan Ratu Village, Sukabumi Regency, EAI; 2023. https://doi.org/10.4108/eai.23-11-2022.2341572.

[7] BMKG. Pedoman Pelayanan Peringatan Dini Tsunami. Jakarta: 2013.

[8] Berryman K. Review of Tsunami Hazard and Risk in New Zealand. Lower Hutt: Institute of Geological & Nuclear Sciences; 2006.

[9] Ashar F, Amaratunga D, Haigh R. The Analysis of Tsunami Vertical Shelter in Padang City. Procedia Economics and Finance 2014;18:916–23. https://doi.org/10.1016/s2212-5671(14)01018-1.

[10] Hoppe MW, Spahn H. Panduan Pemetaan Bahaya Tsunami untuk Tingkat Kabupaten. Jakarta: GTZ International Service; 2009.

[11] Post J, Wegscheider S, Mück M, Zosseder K, Kiefl R, Steinmetz T, et al. Assessment of human immediate response capability related to tsunami threats in Indonesia at a sub-national scale. Natural Hazards and Earth System Sciences 2009;9:1075–86. https://doi.org/10.5194/nhess-9-1075-2009.

[12] Shabrina N, Ahmad D. Analisis Jalur Terdekat Menuju Bangunan Shelter Evakuasi Tsunami di Kota Padang Menggunakan Network Analyst. Jurnal Pendidikan Matematika 2023;1:13. https://doi.org/10.47134/ppm.v1i2.202.

[13] Isdianto A, Kurniasari D, Subagiyo A, Haykal MF, Supriyadi S. Pemetaan Kerentanan Tsunami untuk Mendukung Ketahanan Wilayah Pesisir. Jurnal Permukiman 2021;16:90. https://doi.org/10.31815/jp.2021.16.90-100.

[14] Zahro Q. KAJIAN SPASIAL RISIKO BENCANA TSUNAMI KABUPATEN SERANG, BANTEN. Jurnal Sains Dan Teknologi Mitigasi Bencana 2019;12:44–52. https://doi.org/10.29122/jstmb.v12i1.3699.

[15] Widiyantoro S, Gunawan E, Muhari A, Rawlinson N, Mori J, Hanifa NR, et al. Implications for megathrust earthquakes and tsunamis from seismic gaps south of Java Indonesia. Sci Rep 2020;10:15274–15274. https://doi.org/10.1038/s41598-020-72142-z.

[16] DISDUKCAPIL. Buku Profil Perkembangan Kependudukan Provinsi Jawa Barat. Jawa Barat: Dinas Kependudukan dan Pencatatan Sipil Provinsi Jawa Barat; 2023.