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Generating Evacuation Route for Tsunami Evacuation Based on Megathrust Scenario Hazard Model in Palabuhanratu Village, Sukabumi, West Java

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Abstract

Palabuhanratu Village is one of the villages in Sukabumi, West Java, that is susceptible to earthquake and tsunami risks. This research intends to revise the tsunami hazard map, undertake a spatial analysis of the distribution of evacuation sites, and identify optimal tsunami evacuation routes. The tsunami hazard map was updated using tsunami modeling with COMCOT based on the worst-case scenario of potential magnitude moment 8.8 for the Megathrust segment in the south of West Java from PuSGeN. This modeling was used to predict the worst probable tsunami impact. On the basis of field survey data regarding the location of evacuation sites, evaluation of the distribution of evacuation sites was conducted. In addition, service area analysis is utilized to assess the service area of the present evacuation site in relation to each hamlet in Palabuhanratu village. Approximately 57.33 percent of the town could be affected by a tsunami, according to the findings of this study. The greatest tsunami height along the coast is expected to be between 18 and 22 meters, and the arrival time is 22 minutes. From a total of 35 hamlets, we determined that two hamlets in the Palabuhanratu village area were not harmed by the tsunami. Because not everyone can reach the evacuation location in time, the findings of this study show the need for an additional vertical evacuation site.

Keywords: tsunami evacuation route; tsunami modeling; Palabuhanratu

Introduction

Indonesia is an archipelagic country that has quite complex tectonic conditions. This condition is due to its location, which is at the confluence of three main plates, namely the Sunda, Pacific, and Australian Blocks, and several minor plates that interact with each other (Irsyam et al., 2020). These conditions make Indonesia a country prone to earthquakes and tsunamis. The South Coast of West Java is one of the areas that is vulnerable to earthquakes and tsunamis (Supendi et al., 2020), because of its position in the confluence of two earth plates (subduction zone), namely the Eurasian and Indo-Australian plates in the south which move to the northward with a plate movement speed of about 70 mm/year (Pusat Studi Gempa Nasional, 2017). In addition, active faults on land also pose a seismic threat in West Java, including the Cimandiri fault (Haryanto et al., 2017), Lembang fault (Haryanto, 2006) and others.

Based on the BMKG earthquake catalog for 1821-2018, the Palabuhanratu area has experienced several damaging earthquakes, including tectonic earthquakes on May 12, 1923, November 26, 1973 (M=4.9), August 8, 2007 (M=6.9), July 7, 2018 (M=4.4). In addition, a tectonic earthquake that caused a tsunami also hit Palabuhanratu on September 2, 2009 (M=7.3). This incident resulted in tsunami waves as high as 1 meter in Pameungpeuk and 20 cm in Palabuhanratu. Large-scale tsunamis are rare but can cause physical and economic damage to coastal communities (Triantafyllou et al., 2019).

Based on the 2017 Pusat Studi Gempa Nasional (PUSGEN), the maximum potential magnitude in Southwest Java reaches Mw 8.8, caused by the megathrust of the Sunda-Banten Strait segment. This scenario has been updated from the previous one in 2010 with a maximum potential magnitude of Mw 8.5. A big earthquake can cause a tsunami, such as the Pangandaran tsunami caused by an earthquake with a magnitude of 7.7 (Fujii & Satake, 2006). The tsunami hazard map for Palabuhanratu needs to be revised using the latest worst-case scenario. Making a tsunami hazard map requires modeling a tsunami source to determine the level of exposure to a tsunami disaster. Exposure in tourist areas will increase as the number of tourists increases over time (Marfai et al., 2021).

According to the Central Bureau of Statistics for Sukabumi Regency (2020), Palabuhanratu sub-district consists of ten villages. Because it is located in a coastal area and is a tourist destination (Juliandri et al., 2020), tourists and residents in the area should have more knowledge about the evacuation zones and safe routes for tsunami evacuation (Takabatake et al., 2017). A tsunami evacuation is an effective step to save yourself from a near-distant tsunami disaster (Z. Wang & Jia, 2021). Evacuation is the process of protecting human beings from a dangerous area to an evacuation site to reduce vulnerability in terms of life and health. In a disaster response, evacuation must be carried out quickly and adequately (Usman et al., 2017). Based on this background, this study aims to revise the Tsunami Hazard Map using the latest scenario from PUSGEN, identify the optimal tsunami evacuation route for the people in Palabuhanratu Village and evaluate the distribution of evacuation sites.

Methods

Study Site

Palabuhanratu is a village in the Palabuhanratu sub-district, Sukabumi Regency, West Java province. Palabuhanratu village has an area of approximately 821.62 hectares and is located in the Western part of the regency, precisely at coordinates 6° 58' 40.8" S - 7° 01' 01.2" S and 106° 32' 16.8" E - 106° 34' 40.8" E. The population in the Palabuhanratu village reaches 34,443 people. Palabuhanratu village consists of 133 Neighbourhoods and 35 hamlets, according to data from the Central Bureau of Statistics. Its location facing the Indian Ocean has made Palabuhanratu Village a potential tourism sector in West Java. However, this causes this area also to hold the potential threat of a tsunami hazard.

Data Collection

The first step taken is data collection. This study generally uses two kinds of data, namely primary and secondary data. To perform the tsunami modeling, we need input data such as bathymetry and topography. This study uses topographic data from DEMNAS and bathymetry data from BATNAS provided by the Geospatial Information Agency. In addition, earthquake source parameter data is also needed, which will be explained in point 2.3. Land cover data is also necessary to determine the friction coefficient used in tsunami modeling and obtained from the Ministry of Environment and Forestry. Then, to carry out the Network Analysis, road network data needed to be obtained from the University of Indonesia database. Then, we get the location of existing evacuation points/assembly points and evacuation signs from BPBD Sukabumi Regency and field survey data. Furthermore, the evacuation route's starting point is determined using hamlet administrative boundary data from the Central Bureau of Statistics.

Identification of Earthquake Source

Earthquake source parameters are obtained using scientific references and mathematical calculations, which will later be used as input in tsunami modeling. The detailed parameters used as modeling input are shown in Table 1 and Fig. 1. The earthquake source parameters used are as follows:

- The magnitude used is based on a study from PUSGEN (2017) where the Sunda Strait Megathrust is estimated to have a maximum potential magnitude of Mw 8.8;
- The rigidity used in the model is 30 GPa for a source depth of around 30 km (Bilek & Lay, 1999 ;Tanioka et al., 2017);

- Parameters of depth, strike, and source dip using the subduction model for the Sumatra-Java segment of the USGS (Hayes et al., 2018).

  The length and width parameters of the fracture are obtained by using the Wells & Coppersmith, Kevin (1994) equation which shows the relationship between the magnitude and the length and width of the fracture. The equation used is as follows:

$$Log_{10}L = -2.42 + (0.58 \times M_w) \quad (1)'$$

$$Log_{10}W = -1.61 + (0.41 \times M_w) \quad (2)'$$

where L is the length of the fault, W is the width of the fault, dan M_w is the moment magnitude of the earthquake.

Meanwhile, to get the value of vertical dislocations using the equation of the relationship between magnitude and seismic moment from Hanks & Kanamori (1979). Here is the equation used:

$$M_w = \frac{2}{3}\, log_{10}M_0 - 10.7 \quad (3)'$$

$$M_0 = \mu\, d\, LW \quad (4)'$$

where M_w is the moment magnitude of the earthquake, M_0 is the earthquake's seismic moment, μ is the rigidity, d is the vertical dislocation of the fault, L is the fault length, and W is fault width.

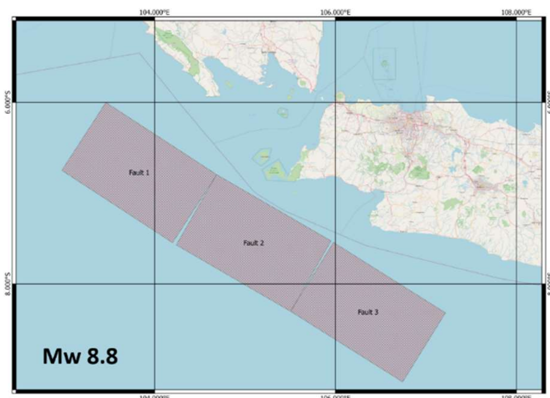

Figure 1. Map of the earthquake source area in the south of West Java used in tsunami modeling

Tsunami Modeling

The next step is to do tsunami modeling with numerical modeling using the COMCOT (Cornell Multigrid Couple Tsunami) software (X. Wang & Power, 2011), which can be used to reconstruct tsunami wave propagation from the source (Syamsidik et al., 2019). COMCOT is a numerical solver for Non-linear Shallow Water Equations. The equation in question is the Non-linear Shallow Water Equations using the spherical coordinate system as follows:

$$\frac{\partial \eta}{\partial t} + \frac{1}{Rcos\theta}\left[\frac{\partial M}{\partial \lambda} + \frac{\partial}{\partial \theta}(Ncos\theta)\right] = 0 \quad (5)'$$

$$\frac{\partial M}{\partial t} + \frac{gD}{Rcos\theta}\frac{\partial \eta}{\partial \lambda} + \frac{1}{Rcos\theta}\frac{\partial}{\partial \lambda}\left(\frac{M^2}{D}\right) + \frac{1}{Rcos\theta}\frac{\partial}{\partial \theta}\left(cos\theta\frac{MN}{D}\right) + \frac{gn^2}{D^{\frac{7}{3}}}M\sqrt{M^2+N^2} = 0 \quad (6)'$$

$$\frac{\partial N}{\partial t}+\frac{gD}{Rcos\theta}\frac{\partial \eta}{\partial \theta}(cos\theta\eta)+\frac{1}{Rcos\theta}\frac{\partial}{\partial \theta}\left(cos\theta\frac{N^2}{D}\right)+\frac{1}{Rcos\theta}\frac{\partial}{\partial \lambda}\left(\frac{MN}{D}\right)+\frac{gn^2}{D^{\frac{7}{3}}}N\sqrt{M^2+N^2}=0 \quad (7)'$$

where λ and θ are latitude and longitude, η is water level, M and N are discharge fluxes in λ and θ directions, t is time, g is gravitational acceleration, h is water depth, R is earth radius, n is coefficient manning, D is the total depth (= η + h).

Table 1. Earthquake source parameter

Subfault	Sunda Strait Megathrust										
	Epicenter (Deg)		Mag	Depth	Focal Mechanism			Dimension		Disloc.	Rigidity
	Lon	Lat	Mw	km	Strike	Dip	Rake	L (km)	W (km)	(m)	Gpa
Fault 1	103.8	- 6.7	8.5	19	302	9.7	90	161	99.5	12.4	30
Fault 2	105.1	-7.5	8.5	18	302	8.6	90	161	99.5	16.3	30
Fault 3	106.4	-8.3	8.5	22	307	10.6	90	161	99.5	12.4	30

Field Survey

The field survey was carried out to identify and geotag the location of the existing evacuation site/assembly point, find out the evacuation route, and take samples of the travel time for evacuating from the assembly point to the evacuation site will later be used as evaluation material. The survey was conducted five days from 29 October to 2 November 2022. The field data were collected using the Avenza application.

Network Analysis – Shortest Path

The shortest path is analyzed to determine the shortest distance to the evacuation site. We conduct the shortest path analysis using input data such as a starting point. This study uses a starting point or assembly point recommendations determined using the travel time criterion from the hamlet centroid point ≤ 5 minutes. The theoretical speed assumption used in this study is 0.751 m/s (the average walking speed of older people), which is intended to ensure that all people can evacuate on time. Then, the endpoint used is the existing evacuation/assembly point obtained from the field survey. To perform the analysis, we use Quantum GIS software that can be calculate the shortest path between two points on any line layer and plots this path over the road network (Ilayaraja, 2013) .

Assembly Point

An assembly point is a designated location where individuals or groups gather after they have evacuated a building or area in an emergency. It is typically a safe and easily accessible location (Sianturi et al., 2021), away from the building or area that was evacuated and identified by signs or markings. In the case of a tsunami disaster, there are two types of assembly points, namely assembly points located outside the house or building as a location for coordination and checking of family members or building occupants before evacuating to a safe point. Furthermore, an assembly point often refers to a temporary/final evacuation site. In the case study in Palabuhanratu, the local government uses the term assembly point as the location of the temporary/final evacuation site. As mentioned in the Data Collection section, we obtained the temporary/final evacuation site location from BPBD Sukabumi. However, we also need to recommend an assembly point as a meeting point location for residents before heading to a temporary or final evacuation site. So, in this study, the location of the gathering point is divided into two, namely, the assembly point as the final evacuation location and the recommended assembly point used as the initial evacuation location.

This research also uses assembly points as the starting point for evacuation. Some previous studies (Habibi & Khakim, 2016; Rumondor et al., 2019) determined the starting point of evacuation can use the location of the assembly point. This is because after a tsunami disaster, according to the evacuation procedure, everyone will first gather at the gathering point before evacuating to a safe temporary or final evacuation point/assembly point.

Network Analysis – Service Area

Service area analysis aims to determine the coverage of the area that can be reached from the existing evacuation site/assembly point using the evacuation time parameter (Evacuation Time/ET). Parameters of evacuation time (Evacuation Time/ET), or what we call response time for the community, can be calculated based on the empirical formula from Post et al., (2009) as follows:

$$RsT/ET = ETA - ToNW - RT \quad (8)'$$

$$ToNW = IDT + INT \quad (9)'$$

where *ET* or RsT is the time available for evacuation, ETA is estimated time of tsunami arrival, $ToNW$ is Technical natural warning time, RT is community reaction time, IDT is Institutional decision-making time, INT is Institutional notification time. We use Arc GIS software to conduct the analysis.

Validation

Validation was carried out by comparing the evacuation travel time based on mathematical calculations with the results of evacuation travel time sampling in the field.

Results

Updated Tsunami Hazard Maps using Worst Case from PUSGEN.

Based on the results of the tsunami modeling, we found that the area affected by tsunami hazards in the Palabuhanratu Village is around 57.33 percent of the Palabuhanratu Village area. Out of a total of 35 hamlets in the Palabuhanratu Village, only two hamlets were not affected by the tsunami, namely hamlet one and hamlet 35. Then, the estimated maximum tsunami inundation height reached between 18 and 22 m. The estimated time of the tsunami's arrival around Palabuhanratu beach is around 22 minutes. The farthest tsunami inundation or maximum inundation is 2 km. The results of the tsunami hazard modeling are shown in Fig. 2.

Almost the entire Palabuhanratu area was inundated by a tsunami with a reasonably extreme height because this study used the worst scenario, namely an earthquake with a moment magnitude of 8.8. The earthquake's magnitude significantly affects the size of the tsunami on land. In general, the greater value of moment magnitude and the width of the fault area of the earthquake influences the tsunami height caused by the earthquake (Nainitania & Darmawan, 2020). However, there are also rare earthquake events where the earthquake is not of very large magnitude but can generate high tsunami waves, such as tsunami earthquakes (Bilek & Lay, 2002). This potential big earthquake shows that a thorough evacuation is needed to save people.

Another factor that affected the tsunami height was bathymetry conditions. The height of the tsunami will increase in bathymetry conditions of shallow sea waters or located near bays. Besides, the speed of the tsunami decreases significantly as it approaches the coast, indicating that the bathymetry of the coastal area can influence the behavior of tsunami waves propagating toward the shore. Bathymetric conditions around the bay and Pelabuhanratu District have diverse morphologies. Starting from the shallow coastal morphology, although relatively few, then directly bordering the deep sea (Haryadi et al., 2022). These conditions will cause the rate or speed of propagation of tsunami waves around Pelabuhanratu Bay, especially those heading towards the coast in Pelabuhanratu Subdistrict, to be very fast.

The steepness and gentle morphology of the coast largely determine the inundation of the tsunami to land. The tsunami will not reach far inland on a steep coast because it is retained and reflected back by the coastal cliffs. Meanwhile, a tsunami could hit up to several kilometers inland on a sloping beach. Based on the results of the tsunami modeling in this study, where the distance of the tsunami reaches 2 km, we can see that the coast of

Palabuhanratu has a gentle slope. This condition is also consistent with the results of research from Oktariadi (2009), where the coastal area of Palabuhanratu has a less sensitive or low level of sensitivity to the coastal slopes.

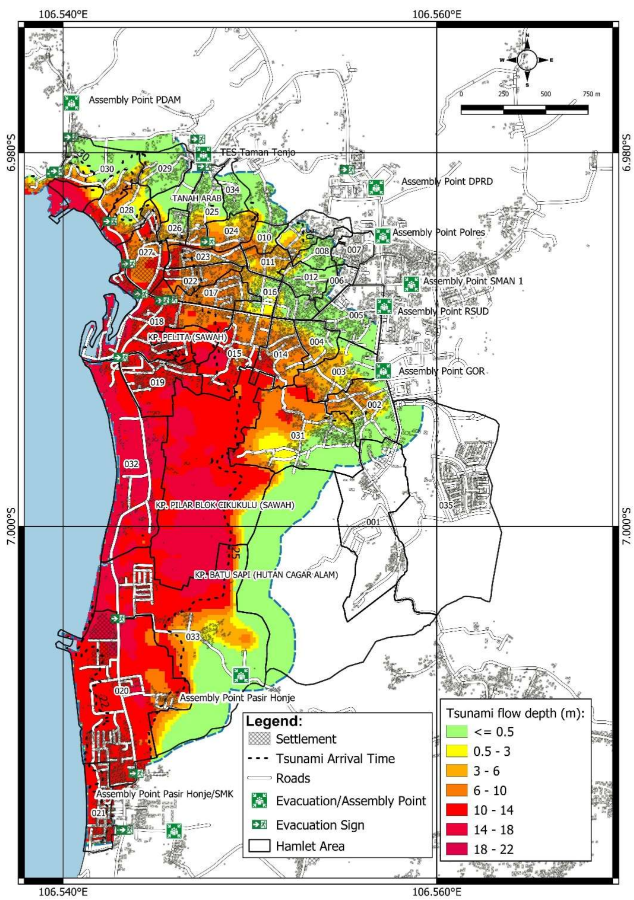

Figure 2. Result of tsunami hazard map in Palabuhanratu Village

Tsunami Evacuation Route for People in Palabuhanratu.

Evacuating people from tsunami-affected areas to safe places is a necessary and immediate action to save the population. Information on the shortest route and minimum travel time for evacuation play a critical role in the safety of the people to be evacuated (Sudarsana et al., 2013). Therefore, in this study, the determination of the optimal evacuation route was carried out using the Network Analysis - Shortest Path method at 34 points spread across 33 hamlets and 1 Pier in Palabuhanratu Village. Determination of 34 starting points or recommendation assembly points is carried out using the criterion of travel time ≤ 5 minutes from the hamlets centroid point. The location chosen must also be on the main road and crossroads. We select these criteria to represent the conditions where the community generally spends more time around their homes, and the general public meets at main roads and crossroads during evacuation. Each recommendation assembly point will generate the shortest evacuation route/path to one of the nine available evacuation locations/assembly points, along with an estimated time needed to get to the evacuation location. The estimated travel time required to reach an evacuation site assumes that the elderly people walking speed is 0.751 m/s (Purbani et al., 2022) choose the speed value because it is an assumed worst speed value, so it can be used as a reference to ensure the success of the whole community in evacuating.

Based on data processing using the Geographic Information System (GIS), the shortest evacuation route results are obtained as shown on the map, which is shown in Fig. 3. Details of the estimated distance and travel time required by each recommendation assembly point to the nearest evacuation location are shown in Table 2.

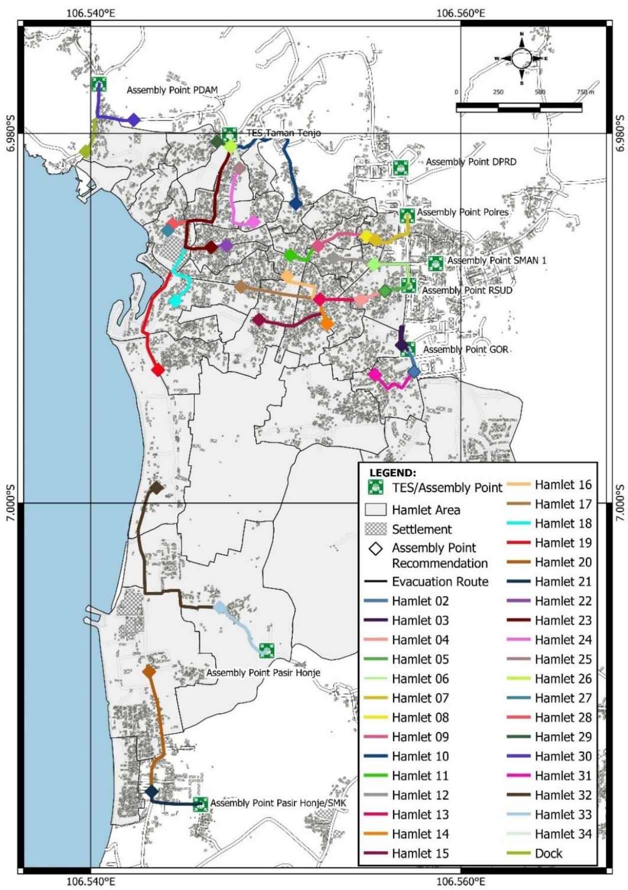

Figure 3. The optimal evacuation route is in Palabuhanratu Village. The location of the starting point or recommended assembly point is indicated by a dot in the shape of a rhombus, while the different colors represent each hamlet and Pier area. The colored line shows the evacuation route from each hamlet.

Table 2. Estimated distance and travel time needed to get to the nearest evacuation location.

Starting Location	Evacuation Location	Distance (m)	Travel time (minutes) (using avg. speed 0.751 m/s)
Hamlet 2	Assembly Point GOR	154	3
Hamlet 3	Assembly Point GOR	273	6

Hamlet 4	Assembly Point RSUD	310	7
Hamlet 5	Assembly Point RSUD	157	3
Hamlet 6	Assembly Point RSUD	339	8
Hamlet 7	Assembly Point Polres	323	7
Hamlet 8	Assembly Point Polres	381	8
Hamlet 9	Assembly Point Polres	693	15
Hamlet 10	Evacuation Site Taman Tenjo	876	19
Hamlet 11	Assembly Point Polres	912	20
Hamlet 12	Assembly Point RSUD	586	13
Hamlet 13	Assembly Point RSUD	555	12
Hamlet 14	Assembly Point RSUD	715	16
Hamlet 15	Assembly Point RSUD	1049	23
Hamlet 16	Assembly Point RSUD	862	19
Hamlet 17	Assembly Point RSUD	1032	23
Hamlet 18	Evacuation Site Taman Tenjo	1318	29
Hamlet 19	Evacuation Site Taman Tenjo	1710	38
Hamlet 20	Assembly Point Pasir Honje/SMK	1142	25
Hamlet 21	Assembly Point Pasir Honje/SMK	351	8
Hamlet 22	Evacuation Site Taman Tenjo	1118	25
Hamlet 23	Evacuation Site Taman Tenjo	1026	23
Hamlet 24	Evacuation Site Taman Tenjo	676	15
Hamlet 25	Evacuation Site Taman Tenjo	212	5
Hamlet 26	Evacuation Site Taman Tenjo	87	2
Hamlet 27	Evacuation Site Taman Tenjo	850	19
Hamlet 28	Evacuation Site Taman Tenjo	804	18
Hamlet 29	Evacuation Site Taman Tenjo	173	4
Hamlet 30	Assembly Point PDAM	414	9
Hamlet 31	Assembly Point GOR	497	11
Hamlet 32	Assembly Point Pasir Honje	1638	36
Hamlet 33	Assembly Point Pasir Honje	430	10
Hamlet 34	Evacuation Site Taman Tenjo	211	5
Pier	Assembly Point PDAM	424	9

Based on the shortest path network analysis results, the estimated distance from the recommended assembly point to the evacuation site/assembly point ranges between 87 and 1638 meters. Meanwhile, the time needed to reach the evacuation site with an average walking speed of parents varies from 2 minutes to 36 minutes. The hamlet that has the shortest distance to the existing evacuation site/assembly point is hamlet 26. Meanwhile, the hamlet farthest from the existing evacuation site/assembly point is hamlet 32, which has to cover a distance of up to 1.6 Km. There were 3 hamlets that evacuated to the GOR Assembly Point, 1 hamlet and Pier that evacuated to the PDAM Assembly Point, 2 hamlets evacuated to the Pasir Honje/SMK Assembly Point, 4 hamlets evacuated to the Polres Assembly Point, 2 hamlets evacuated to the Assembly Point Pasir Honje Point, 9 hamlets evacuated to RSUD Assembly Point, and 11 hamlets evacuated to Taman Tenjo Evacuation Site.

Based on the map and table, it can be seen that the evacuation locations from each hamlet are not evenly distributed among the nine existing evacuation sites/ assembly points. This condition could increase the number of people and cause congestion in evacuation sites such as the Taman Tenjo Evacuation Site and the RSUD Assembly Point. In addition, we found that two existing evacuation sites/assembly points were not selected as evacuation destinations, namely the DPRD Assembly Point and SMAN 1 Assembly Point, because their locations were too far from each hamlet.

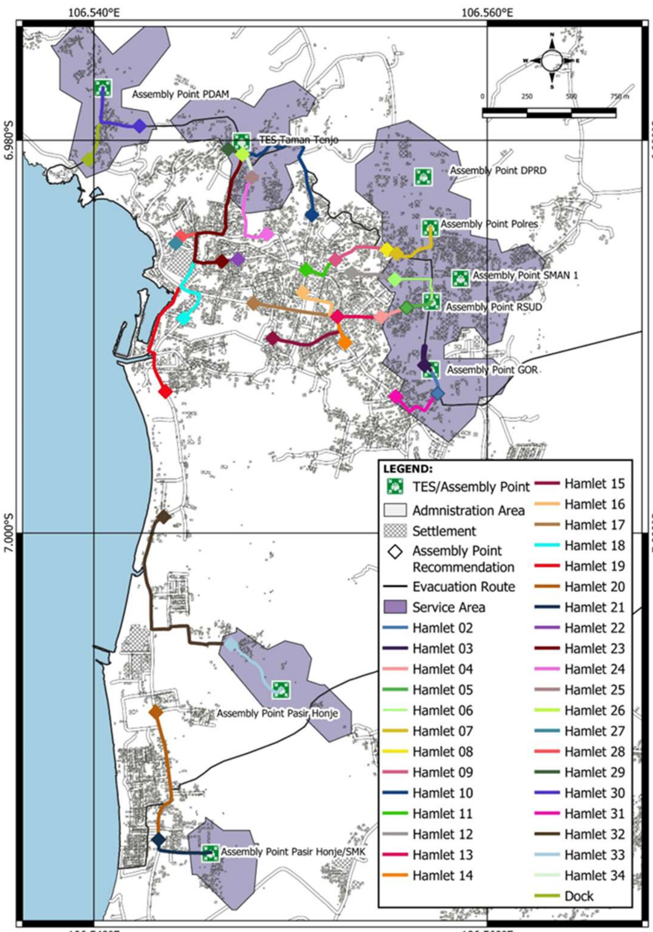

Figure 4. The Service Area Map in Palabuhanratu Village uses an 8-minute evacuation time. The purple area shows the extent of the service area.

Distribution of Evacuation Sites

Locations of evacuation sites/ assembly points were determined using field surveys and BPBD Sukabumi Regency data. Then the data is used to determine whether the evacuation location can be reached by the tsunami-affected community in Palabuhanratu Village using service area analysis. This service area analysis is one method for finding service areas around evacuation sites on the network or roads (ESRI, 2019). Service area analysis in this study was based on the evacuation time (ET) parameter using the empirical formula from Post et al. (2009). As for calculating the evacuation time (Evacuation Time / ET) using the empirical formula from Post et al. (2009), parameters such as the estimated time of arrival of the tsunami, the technical time of the natural warning, and the time the community reacts are needed. For the estimated time of arrival of the tsunami, 22 minutes was used, which was obtained from the results of tsunami modeling. The technical time for natural warnings was obtained from the sum of the decision-making time from the institution, namely the BMKG, which was 4 minutes, and the notification time from the institution, which was from the BPBD, was around 3 minutes. At the same time, the reaction time is determined by 7 minutes (Yunarto & Sari, 2018). So, the evacuation time parameter (Evacuation Time/ET) in this study is 8 minutes.

The service area analysis results show that some areas were affected by the tsunami but were not covered by the existing evacuation points/assembly points. When the government issues an evacuation order, people tend to evacuate to avoid the coastal area as far as possible (Imamura et al., 2012). This means that people will try to get to higher ground or away from the coastal area as quickly as possible, creating the potential for congestion on evacuation routes. Therefore, this study proposes using vertical evacuation sites so that all people can be safe from a tsunami threat. One solution is to use existing tall buildings in the area as vertical evacuation sites. This can reduce construction costs and land availability. The results of the service area analysis are shown on the map in Fig. 4.

Validation

Validation of travel time in this research was carried out by comparing the evacuation travel time based on mathematical calculations and the result of the field survey. The evacuation travel time was calculated following the optimal evacuation route obtained in this research. We selected three sample locations to collect the data: Pier, Hamlet 27, and Hamlet 33. Then, the result of the time difference between the calculation and field survey data was around 2 minutes in Pier, 7 minutes in Hamlet 27, and 2 minutes in Hamlet 33. The detail of travel time is shown in Table 3. The different conditions of each evacuation route may cause the travel time difference obtained from each location. On average, the travel time difference from the comparison of calculation data and field survey data is around 3 minutes and 40 seconds.

Table 3. Validation of travel time

Starting Location	Evacuation Location	Calculation Travel time (minute)	Field Survey Travel time (minute)
Pier	Assembly Point PDAM	9	7
Hamlet 27	Evacuation Site Taman Tenjo	19	12
Hamlet 33	Assembly Point Pasir Honje	10	8

Conclusions

The Palabuhanratu village can be affected by the tsunami, especially from the source of the Sunda Strait megathrust earthquake, which can reach at least a magnitude of 8.8. Based on the analysis of the level of tsunami hazard in Palabuhanratu Village, we found that around 57.33 percent of the village was affected by the tsunami. The maximum tsunami height reaches between 18 and 22 m, the tsunami arrival time is 22 minutes, and the maximum inundation is as far as 2 km.

Using the shortest path feature in network analysis, we successfully determined 34 optimal evacuation routes to the existing evacuation site/assembly point. The evacuation travel time ranges between 2 and 38 minutes, while the distance varies between 87 and 1638 meters.

We also estimate the evacuation time is around 8 minutes. Based on service area analysis we found that not everyone can reach the evacuation location in time, the finding of this study show the need for an additional vertical evacuation site.

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