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Spatial Analysis on Tsunami Predictions in Pandeglang Regency

Della Ayu Lestari *, Novi Sofia Fitriasari, Taufiq Ejaz Ahmad, Amien Rais, Dhea Rahma Azhari
Marine Information System, Universitas Pendidikan Indonesia
Jl. Dr. Setiabudi No.229, Bandung, West Java, Indonesia
*) Corresponding autho: della.ayu@upi.edu

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Abstract. Pandeglang Regency is an area that has the potentiel to be hit by tsunamis. The plate subduction paths of Indo-Australia and Anak Krakatau Volcano make Pandeglang Regency a region with a high tsunami potential. One step that can be taken to overcome and minimize losses is to do spatial planning to protect it against potential tsunami damage. This research aimed to evaluate the spatial area of Pandeglang Regency based on the identification of potential tsunami hazards. The concept of modelling the tsunami inundation height developed by Berryman and based on Head Regulation No.4 of 2012 of the Indonesian National Board for Disaster Management has been used to identify potential tsunami hazards. The modelling was carried out by calculating the potential distribution of tsunami wave heights in coastal areas. Three scenarios were used to estimate the distribution. The results showed that the first scenario predicted a maximum tsunami height of 7.5 meters above sea level with the furthest tsunami inundation reaching 1,700.12 meters. Second scenario predicted maximum height of 15 meters, with the furthest tsunami inundation reaching 3,384.62 meters. Meanwhile, the last scenario was able to predict a height of 20 meters and showed the furthest tsunami inundation reaching 5.155,11 meters. These results proved that in all scenarios, the widest inundation would occur in Panimbang Regency. This is due to the relatively small variations in roughness and slope of the surface. The same condition also occurs in the last two scenarios, in which Sumur District was the area most ffected. Therefore, the spatial plan of Pandeglang Regency needs to be evaluated and the function of residential area changed to reduce and prevent large losses.

Keywords: Geography Information System; residential area; spatial analysis; tsunami; tsunami inundation

1. Introduction

A tsunami is the most dangerous natural disaster other than an earthquake (Ji Y, 2018). The word 'tsunami' comes from the Japanese "tsu", which means ''port'', and "nami", which means ''big wave'' (Domroes, 2006). Viewed in terms of its cause and shape, a tsunami wave is an extraordinary movement of water that brings about massive energy and momentum. This movement is caused by earthquakes at sea, volcanic eruptions, underwater landslides, and other natural environment activities (Latief *et al.*, 2000). Water can function as a medium for energy propagation caused by sufficient momentum as can be proven by observing the volume or mass of water when the propagation of water waves occurs. In this energy propagation, the mass of seawater is not transmitted because the mass of water moves in the vertical plane up and down, not in the horizontal plane. However, a large amount of water is spreads over over the shore when a tsunami occurs. The transmission of a volume of water is caused by refraction in water waves during the tsunami. Refraction in seawater waves is an event in which the direction of the wave vector changes from perpendicular to the wavefront (Huda, 2015). This is due to the silting of the wave's lower boundary so that the velocity of propagation changes (Aziz, 2006).

This refraction of ocean waves causes a tsunami to become something dangerous and is called a hazard. The magnitude of the initial momentum causes the waves to vary in height so that they have the power to propagate at certain points on the earth's surface and destroy various man-made structures standing in the tsunami wave propagation path. Scientifically, tsunamis are described as long waves that arise due to changes in the seabed or changes in water bodies that occur suddenly and impulsively. Tsunamis are disasters of a destructive nature. Therefore, early action to address any problems they may cause is required.

Pandeglang Regency is an area that runs the risk of being hit by tsunamis. This is because geographically, Pandeglang Regency is found in an area prone to tsunami disasters (Sari, 2019). Pandeglang Regency is in the subduction zone of the Indo-Australian Plate and the Eurasian plate in the Sunda Strait (Alhamidi *et al.*, 2018). The latest research has suggested that Banten Province could generate a giant earthquake of 9.1 Mw and a huge tsunami with a maximum height of 20.2 m, probably near the small islands lying to the south of Banten (Widiyantoro, 2020). The proximity of the Anak Krakatau volcano is another factor that causes the area to be prone to tsunami disasters. Tsunamis, which are caused by volcanic eruptions, do not happen often. However, their impact would probably be much more devastating than that caused by an earthquake (TW Yan, 2016). For example, history recorded that Mt. Krakatau has erupted twice, once in 1883 and once in 1928. Some of the Pandeglang area has been affected by the Mt. Krakatau Tsunami, including Anyer, Merak, Carita, Labuan, and Panimbang (W L Farahdita, 2019).

The coastal areas of Sumatra and Java, especially the southern parts, are categorized as vulnerable to tsunamis' impact. This is because they are located directly adjacent to the Indo-Australian Plate. The movement of the plates in this area may trigger the occurrence of a large earthquake that may cause tsunamis. The Australian Plate dips to a depth of 100-120 km below the island of Java and stretches 600 km north of Java. Plate puncture results in high levels of seismicity with more than 20 active volcanoes in this zone. Banten Province is quite close to the earthquake source which causes tsunamis in deep-sea waters in the southern part of the Indo-Australian plate.

Banten Province, especially Pendeglang Regency, has been hit by several tsunamis, which is hardly surprising considering that Banten Province has an active subduction zone in the Sundra Strait area. The large tsunami that occurred in the Sunda Strait in 1883 was triggered by the eruption of Mount Krakatau, which resulted in infrastructure damage and claimed more than 35,000 lives (Gouhier, 2019). A similar incident occurred in 1928 on a scale that was almost the same as the event that occurred in 1883. This event led to the formation of a new mountain, Anak Krakatau Volcano. The last tsunami caused by the eruption of Anak Krakatau Volcano occurred on December 22, 2019. This tsunami was probably caused by the collapse of the Anak Krakatau Volcano material that appeared above sea level in the Sunda Strait. These findings are in accordance with the visual interpretation and analysis of seismic activity of the eruption of Anak Krakatau Volcano on December 22, 2018, by Walter *et al.* (2019). In the tsunami caused by the eruption of Mount Anak Krakatau in Sumur Sub District in 2018, especially in Kertamukti and Kertajaya villages, Panimbang Regency, especially in the Tanjung Lesung area, and Labuan Regency especially in Teluk village close to Carita were the areas most affected because of their geographic position close to the Anak Krakatau Volcano. Therefore, tsunami disaster management is needed to reduce the losses that could occur when the volcano erupts again.

The importance of tsunami disaster management in Indonesia has been reflected in the laws of the Republic of Indonesia, especially Law (UU) Number 24 of 2007 regarding disaster relief, including tsunami disaster management. One of the stages important to implementing disaster management is disaster management planning (Berryman *et al.*, 2006). The implementation of disaster management planning starts from estimates of the magnitude of the hazard associated with the disaster. Mathematical approaches are commonly used in determining the magnitude of the danger of a disaster, especially in the context of a tsunami disaster (Giachetti *et al.*, 2012)

All the disasters that have occurred in Pandeglang Regency have made us aware of the vulnerability of this area, and we have realized that spatial planning as initial mitigation is necessary to prevent much greater losses that may occur in the Pandeglang Regency area (Lestari *et al.*, 2020). Tsunami modeling using several different scenarios was carried out to assess the high potential of a tsunami in Pandeglang Regency. The next step after modeling was calculating the probability of the inundation of areas in Pandeglang Regency. One of the steps that can be taken in this case is implementing spatial planning for areas considered to be at great risk of being affected by a tsunami. This study aims to evaluate the spatial layout of Pandeglang Regency by identifying potential tsunami hazards. We use the tsunami inundation height modeling concept developed by Berryman and based on the Head of the Indonesian National Disaster Management Agency Regulation No. 4 of 2012 to identify potential tsunami hazards by calculating the distribution of the potential height of tsunami waves in coastal areas. The determination of tsunami prone areas is carried out by identifying tsunami inundation areas along with the maximum tsunami height in the coastal area of Pandeglang Regency. In this case, the slope is obtained from DEM data processing and the surface roughness index is obtained from the 2015 SPOT land cover digitization results.

2. Research Method

Tsunami hazard maps were created by using the concept of tsunami inundation height modelling developed by Berryman (2006). The tsunami height modelling done for this study started with the factor of slope, the surface roughness, and the tsunami wave height scenario (Figure 1). The selection of a tsunami wave height scenario has been selected to represent the tsunami wave heights which are classified as ranging from likely to cause minor damage to likely to cause major damage. This approach starts with the calculation of the loss of tsunami height per 1 m inundation distance (inundation height) by considering slope distance and surface roughness.

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

H_{loss} = Loss of height every 1 meter to the unity of distance's slope
n = Surface roughness index
H_0 = Tsunami wave height
S = Slope elevation

This study's model construction has used the tsunami coastline assumption (H0) cited in the Head of the National Disaster Management Agency Regulation Number 4 of 2012 (Majid, 2020). The information used for data processing has come from the Digital Elevation Model (DEM) map provided by DEMNAS with a resolution of 5 meters for each grid. The calculations have been performed to obtain the H-loss value for each raster grid. The expected output from this model is the classification of areas at elevated risk of being affected by a tsunami and areas that are not spatially affected.

We have determined which areas are tsunami-prone by modelling the tsunami inundation areas. We have used three tsunami inundation area scenarios based on the findings published in the journal article "A National Tsunami Hazard Assessment for Indonesia" by Horspool *et al.*, 2013. This journal article divides the time over which tsunami heights have been predicted into three periods for Pandeglang Regency, and these periods last 100 years, 500 years, and 2500 years. For Pandeglang Regency, the estimated maximum height possible for a tsunami over a period of 100 years is 7.5 meters, over a period of 500 years is 15 meters, and over a period of 2500 years is 20 meters.

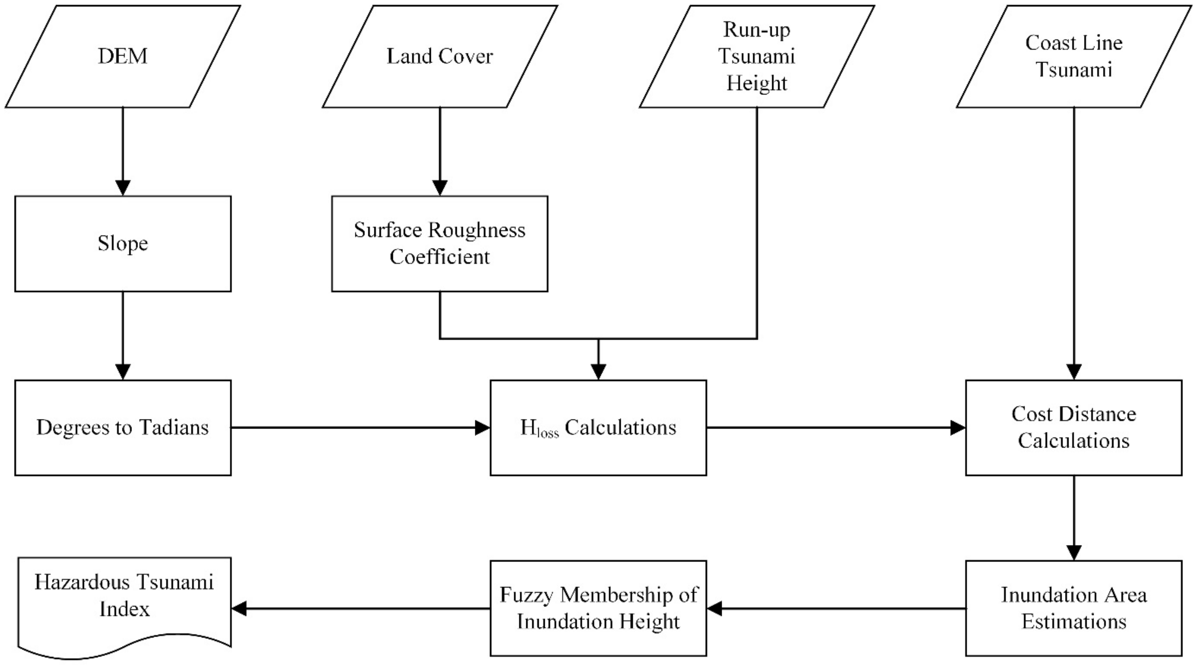

Figure 1. Workflow of methodology of the tsunami inundation model (BNPB, 2011)**.**

3. Results and Discussion

3.1. Land Cover and Slope in Pandeglang Regency

The highest coefficient in the surface roughness index (Table 1) is 0.07. Rivers and other bodies of water constitute land cover that has the lowest surface roughness coefficient, 0.007. Sand, roads, and open land have a roughness coefficient of 0.015. Meanwhile, the surface roughness coefficient for agricultural land is 0.025. Plants and shrubs have surface roughness coefficients of 0.035 and 0.04. The surface roughness coefficient for settlements and other built-upland is 0.045. The surface roughness coefficient is used as an input to calculate the loss of tsunami height per 1 m inundation distance to produce a model of the tsunami-exposed area of the Pandeglang land cover type. The results of this modeling are shown in Figure 2.

Based on the procedures for implementing built-in environmental planning, it is known that the slope of 0 - 8% is the slope most suitable for built-up areas (housing areas). This is because the 0-8% slope does not require technical engineering of the soil. On the other hand, slopes with weight and with a slope percentage of 9-15% require technical techniques related to soil. The least weight on slopes with a percentage of> 15% requires further technical engineering. This percentage is shown in Figure 4. Figure 3 shows that 13 sub-districts affected by the tsunami, as a whole, have wave heights of up to 20 meters where slopes of 0-8% account for the largest proportion, with a total of 78.84%, or 143,438.23 Ha out of 181,935.86 Ha. For slopes of 9-15%, the percentage of distribution reaches 15.11%, or 27,490.51 Ha. The smallest proportion of land is steepest, with a slope of more than 15%, and accounts for 6.04% of land, or 10,988.92 Ha.

Table 1. Roughness Efficiency by Land Cover Type

Type of Land Cover	Surface Roughness Index
Water Bodies	0.007
Bush	0.040
Forrest	0.070
Plants	0.035
Open Field/Sand/Road	0.015
Rice Fields	0.025
Settlement/Land Use	0.045

Source: on Head Regulation of Indonesian National Board for Disaster Management, No.4 (2012).

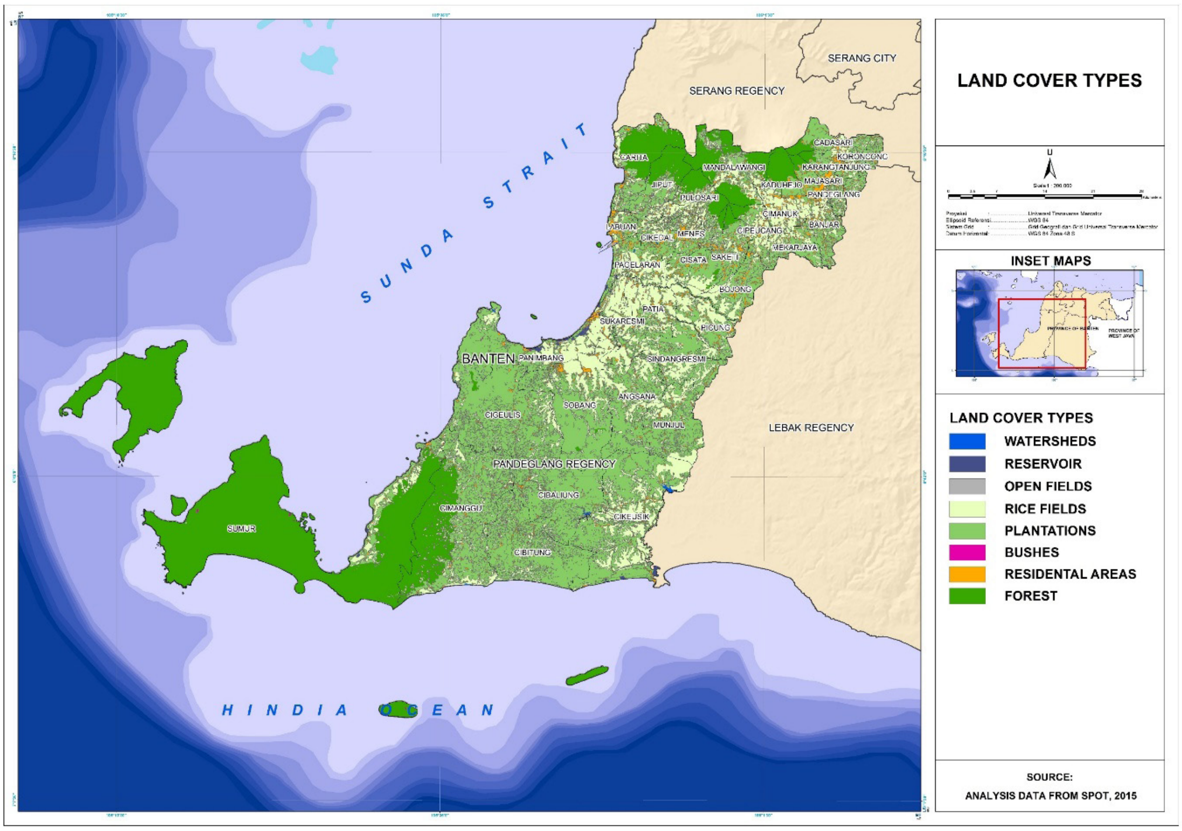

Figure 2. Land Cover Diversity in Pandeglang Regency (Landsat ETM 8).

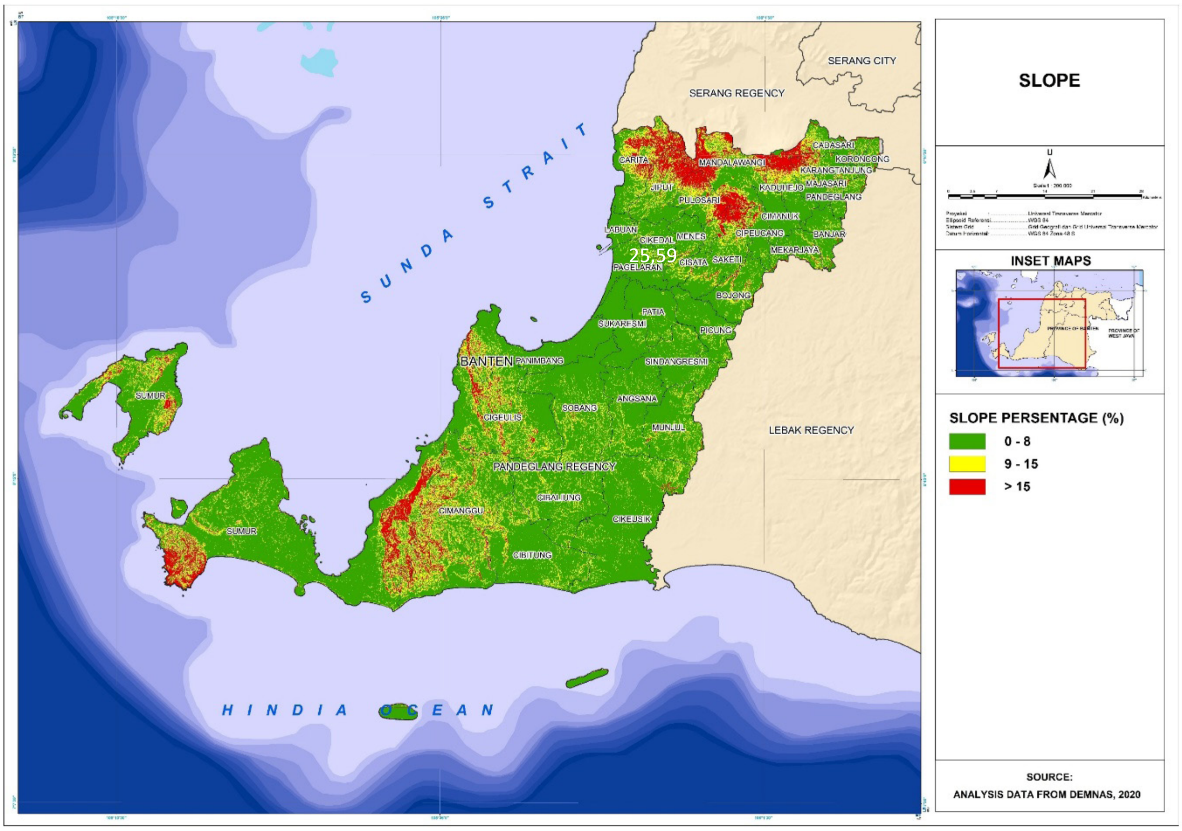

Figure 3. Slope of Pandeglang Regency.

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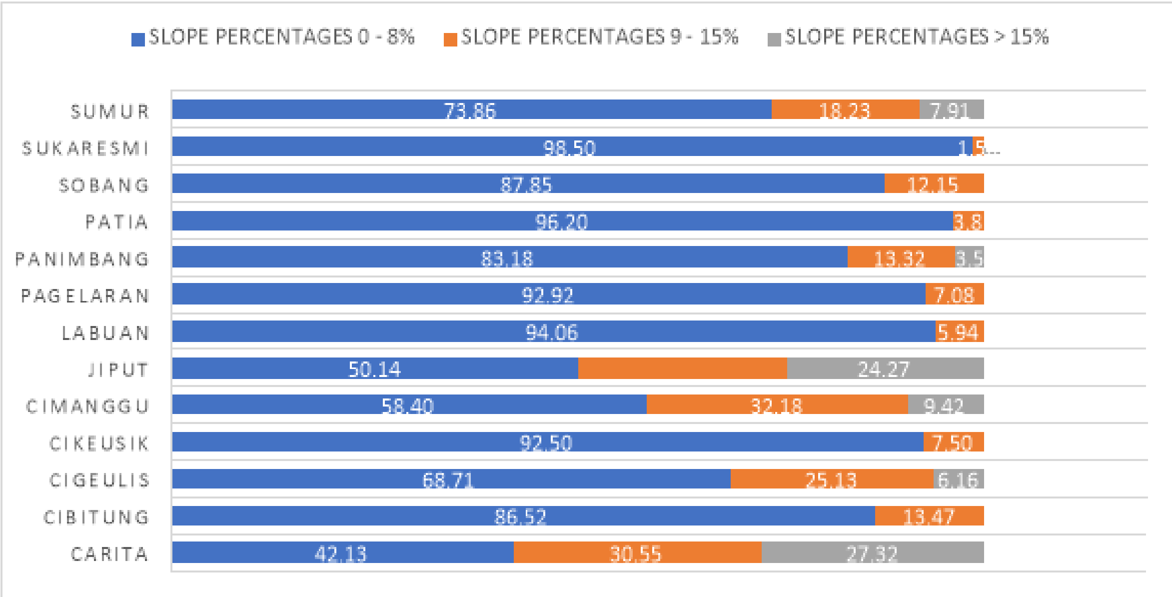

Figure 4. Percentage of Slope in Each Affected Sub-district.

3.2. Inundation Area Predictions of Tsunami 7.5 Meter Height

The Prediction modeling was carried out for all sub-districts in Pandeglang Regency, especially in the sub-districts which faces the Sunda Strait and Anak Krakatau. These areas stretch from Carita to Sumur and Cikeusik areas. The first height modeling carried out was for a 7.5-metre tsunami, as shown in Figure 5.

Modeling of the scenario of tsunami propagation height of 7.5 meters has produced an inundation area of 5,467.37 hectares, or about 1.97% of the area of Pandeglang, Labuan and Panimbang districts. Labuan sub-district has a fairly high inundation ratio, with a percentage of 22.66%. This is due to the small administrative area of the Labuan District. Besides, it has a large amount of land cover with a high roughness index, and many slopes are only very gentle, allowing the propagation of tsunami waves to reach a point quite far in from the coastline. Some of the areas of Panimbang which are close to the coastline feature reservoirs and rice fields. Regulation Number 4 of 2012 of the Head of the National Disaster Management Agency, it mentioned that this is an indication of a low surface roughness value. The Panimbang area is an area which faces the sea for the most part. In the western part of this sub-district features a fairly steep section so that the inundation distribution of tsunami waves is worse on the Panimbang coastline which stretches eastward.

3.3. Inundation Area Predictions for a Tsunami of 7.5 Meter Height

In the modeling of the propagation of a tsunami with a height of 15 meters (Figure 6), the inundation area reached 23,729.71 Ha, or about 8.56% of the total area of Pandeglang Regency (Table 3). In the 15 Meter Modeling Scenario (Figure 6), both Panimbang and Labuan Districts still had a large percentage of inundation risk, with the greatest value being 55.26%. This is because the two areas have low measurement variable values. Besides, in the 15-meter scenario, there was a significant increase in the percentage of inundation in several areas, especially in Sukaresmi and Pagelaran Sub-districts, which have very steeply sloping shorelines.

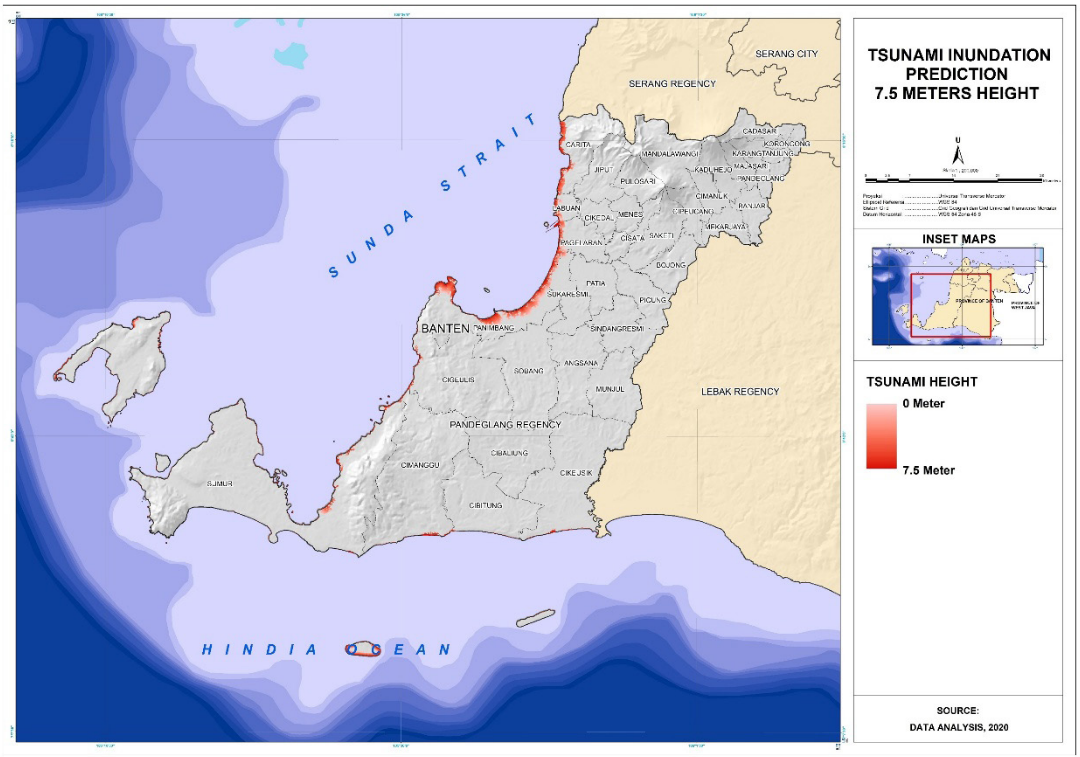

Figure 5. Inundation Area Predictions for a Tsunami of 7.5 Metre Height.

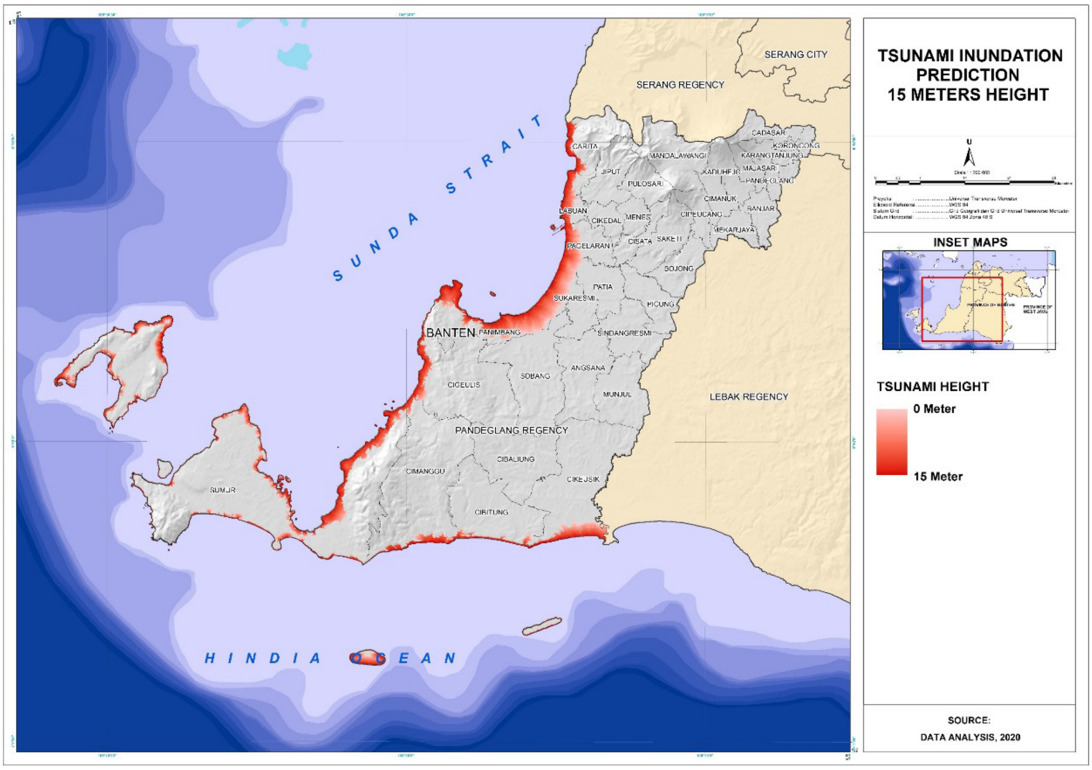

Figure 6. Inundation Area Predictions for a Tsunami of 15 Meter Height.

Table 2. Index of Estimated Inundation Area with a Tsunami Height of 7.5 Meters

SUB-DISTRICT	Inundation Area (Ha)	Sub-District Area (Ha)	Percentage (%)
CARITA	583.01	7091.66	8.22
CIBITUNG	26.65	12369.46	0.22
CIGEULIS	127.72	17447.24	0.73
CIKEUSIK	84.28	19703.13	0.43
CIMANGGU	148.815	23588.71	0.63
LABUAN	367.55	1621.49	22.70
PAGELARAN	557.96	4225.29	13.20
PANIMBANG	2007.34	9994.48	20.09
SUKARESMI	301.66	5059.92	5.96
SUMUR	9561.04	56758.34	2.23

Table 3. Index of Estimated Inundation Area for a Tsunami with a Height of 15 Meters.

SUB-DISTRICT	Inundation Area (Ha)	Sub-District Area (Ha)	Percentage (%)
CARITA	583.01	1232.94	17.39
CIBITUNG	26.65	468.73	3.79
CIGEULIS	127.72	1099.17	6.30
CIKEUSIK	84.28	1844.41	9.36
CIMANGGU	148.815	1118.58	4.74
LABUAN	367.55	839.16	51.75
PAGELARAN	557.96	1283.99	30.39
PANIMBANG	2007.34	5523.70	55.27
PATIA	67.07	67.07	1.40
SOBANG	101.40	101.40	0.74
SUKARESMI	301.66	1568.53	31.00
SUMUR	8586.46	8597.23	15.15

3.3. Inundation Area Predictions for a Tsunami of 20 Meter Height

In the modeling of the propagation of a tsunami with a height of 20 meters, the inundation area reached 28917.35 Ha or 10.43% of the total area of Pandeglang District. In the 20 Meter Modeling Scenario, the highest percentage is almost the same as the 7.5- and 15-meters tsunami heights. The greatest percentage was found in Panimbang and Labuan Sub Districts with percentages of 61.08% and 55.75% respectively. However, in the modeling scenario of a 20-meter inundation area, three sub-districts, namely Jiput, Patia, and Sobang, had a low percentage of inundation areas, with a value of < 11%. This is due to the geographic location of these three sub-districts which do not directly face the open sea and have a relatively good land cover where the shorelines' slopes are not so flat.

From the combined scenarios of the tsunamis with wave heights of 7.5 meters, 15 meters, and 20 meters, it is found that Labuan is the area with the highest percentage of inundation. Meanwhile, the area with the widest inundation is Panimbang district. This difference in the percentage and the area of inundated districts is due to factors of slope, land cover, length of areas' coastlines, and the size of administrative areas. This should be a consideration in sustainable planning or even in disaster mitigation. A low ratio of inundation area to total area for a given district results in it having a low percentage of inundation. On the other hand, a district has a small inundation area but a high percentage of inundation when the ratio of area to area is high. This is influenced by the ability of tsunami wave propagation which is calculated using the formula developed by Berryman (2006).

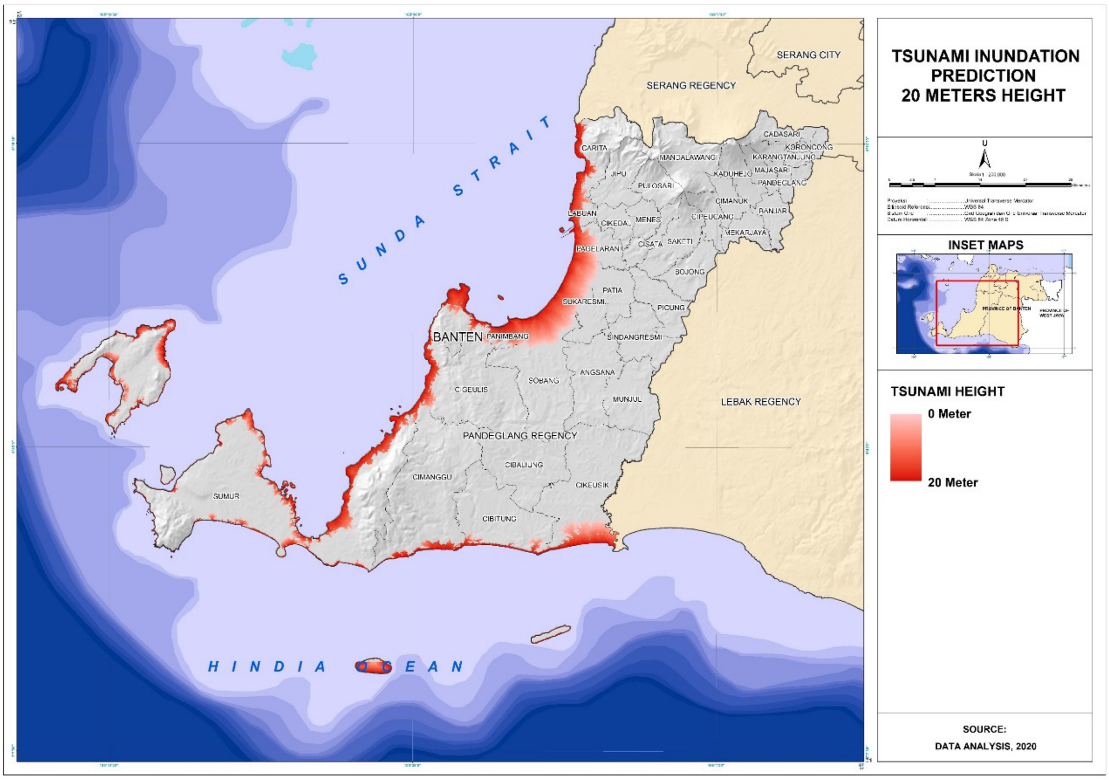

Figure 7. Inundation Area Predictions for a Tsunami of 20 Meter Height.

Table 4. Index of Estimated Inundation Area for a Tsunami with a Height of 20 Meters.

SUB-DISTRICT	Inundation Area (Ha)	Sub-District Area (Ha)	Percentage (%)
CARITA	1285.56	7091.66	18.13
CIBITUNG	581.57	12369.46	4.70
CIGEULIS	1216.01	17447.24	6.97
CIKEUSIK	2720.00	19703.13	13.80
CIMANGGU	1139.35	23588.71	4.83
JIPUT	0.90	5652.64	0.02
LABUAN	904.01	1621.49	55.75
PAGELARAN	1705.60	4225.29	40.37
PANIMBANG	6104.19	9994.48	61.08
PATIA	514.83	4803.34	10.72
SOBANG	1118.59	13620.15	8.21
SUKARESMI	2082.41	5059.92	41.15
SUMUR	9561.04	56758.34	16.85

The maximum tsunami wave propagation point calculated from the shoreline, or the maximum tsunami wave penetration, is affected by the roughness of the earth's surface, and rougher conditions reflected in the coefficient index can create a larger barrier to the penetration of tsunami wave propagation. If the shoreline's slope is flatter and approaches 0°, the waves will more easily propagate on land. The slope coefficient and surface roughness are barriers reducing the propagation force of the penetrating tsunami waves (Fauzi, 2014).

Panimbang (Figure 8) has the highest probability percentage and the largest inundation area. This area has a low coefficient of roughness with a fairly large area coverage.

The area of Panimbang District is 9994.48104 hectares and its reservoir area is around 276.28 hectares (Table 5). In other words, the reservoir area is 2.67% of the total area. Some of these reservoirs are located on the shoreline and some on the river. This is one of the causes of the wide inundation area in the Panimbang sub-district because its coefficient of roughness is low.

From Figure 9 it can be seen clearly how relatively flat the slopes are along the Panimbang coastline where almost the entire shore is sloping. The earth's shape makes it easier for the waves to propagate on land.

After knowing that Panimbang is an area that has a gentle slope and low surface roughness index, we know that the residential area affected by the tsunami is very large. Of the total of 9,994.48 Ha of Residential Areas, 6104.19 Ha were affected by the tsunami waves, the equivalent of 61.08% of all residential areas in Panimbang Regency. Figure 10 illustrates that the effect of a tsunami wave 20 meters high is very large in areas that have a low slope and roughness coefficient. The situation described by Figure 10 requires follow-up to anticipate and mitigate disasters, given the predicted immersion rate in the wave-swept area is very wide. With appropriate measures tailored to the affected communities' circumstances and sensitivities, disaster mitigation in this area can be implemented.

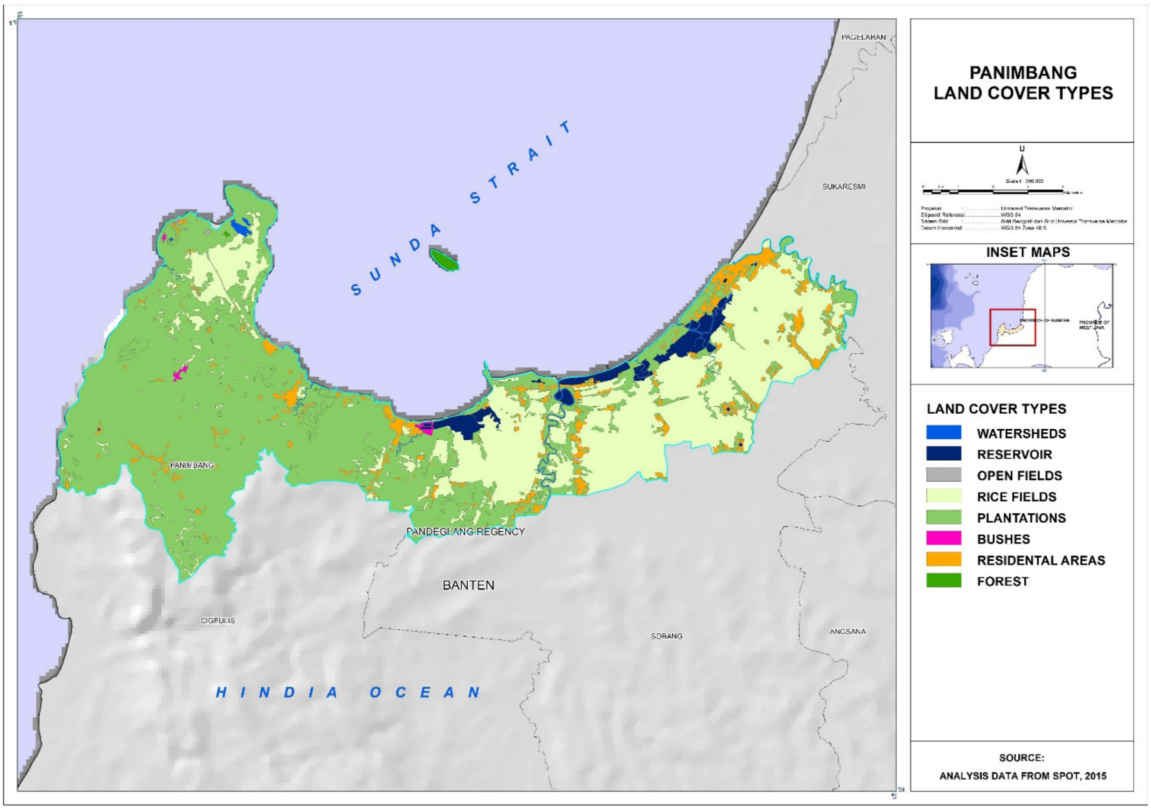

Figure 8. Land Cover Types in Panimbang District.

Table 5. Panimbang Land Cover Clasifications.

Land cover types	Area (Ha)
Watersheds	83,46
Reservoirs	276,28
Open fields	20,29
Rice fields	3198,48

Land cover types	Area (Ha)
Plants	5861,03
Bushes	17,09
Residential areas	512,90
Forests	24,96

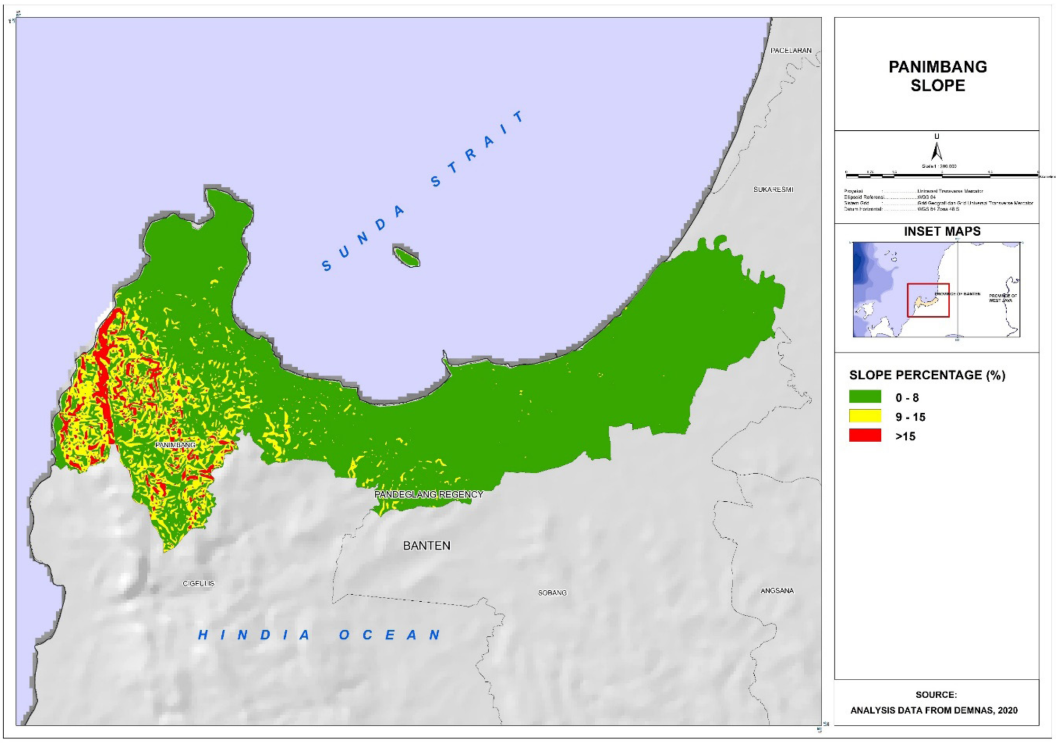

Figure 9. Slope Percentages of Panimbang Sub-district.

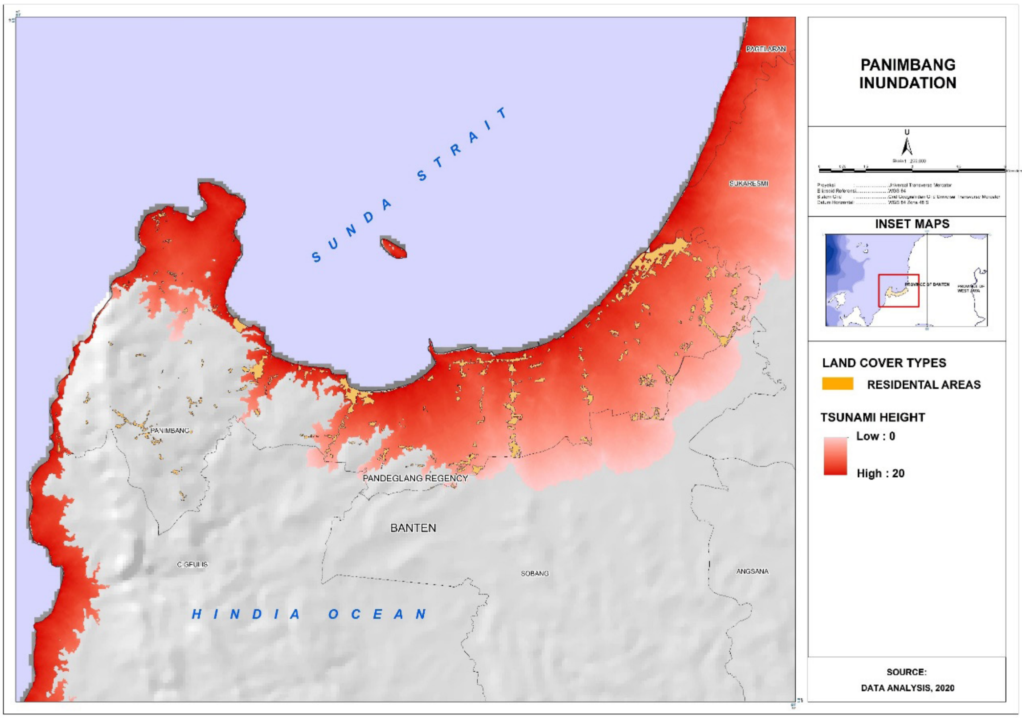

Figure 10. Residential Areas that would be Affected by a Hypothetical 20-metre-tall Tsunami (Horspool et al., 2013).

The method adopted for this study has been used and validated by Majid (2020). Majid's paper compares the modelling informed by Berryman's calculation method for estimating the inundation area and wave propagation against data for the tsunami that occurred on December 22, 2018, as obtained from the RBI map for the area affected by the disaster. Majid's paper includes only an inundation area model based on the height of the tsunami on 22 December 2018. Therefore, in this study, by contrast, we predict the area and propagation of the waves based on geographical conditions and predicted wave heights (Horspool *et al.*, 2013). Thus, an estimate of geographical influence on the tsunami wave prediction will be obtained.

4. Conclusion

Based on the results of the data analysis that has been carried out, it was found that higher the tsunami waves would result in wider inundations along the coastline of Pandeglang Regency. This is largely due to the influence of the geographical conditions of the area, consisting of flat slopes and the presence of land cover. Waves encounter obstacles to their propagation, and even when these waves do not actually deliver water, but instead deliver energy, water will still be pushed onto the land. This is due to the nature of the wave which releases energy itself so that when the wave moves through shallower and shallower water towards the land, its speed will decrease while its height increases (Aziz, 2006). This is the refraction of the wave itself where the wave front is parallel to the coastline so that the resistance value of the ground surface (surface roughness and slope) obstructing the propagation of the tsunami water wave becomes a form of energy release. Even surface water on land, such as rivers and other inundations, has a small resistance value. This shows that the energy released by tsunami waves is affected by the propagation medium and is inversely proportional to the distance calculated from the coastline. In the event of a disaster, the maximum inundation area for each period can be used as a reference for public scale development oriented towards disaster mitigation, such as increasing property security and reliability. Sumur and Panimbang sub-districts are areas with a high percentage of inundated areas. These two sub-districts need special attention because the ratio of inundation area to total area is still high. The Sumur sub-district with the largest inundation area also requires the same treatment. In general, it is important to use the potential of spatial analysis to inform decisions about disaster prevention and it may be necessary to implement a system of regularly updating analysis to reflect changes in vegetation, forestation, ground cover, etc. and to ensure that policies, budgets, and the infrastructure projects they support are updated and maintained.

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