SPATIAL ANALYSIS OF THE TSUNAMI RISK IN PALABUHANRATU SUB-DISTRICT, SUKABUMI REGENCY, INDONESIA BASED ON THE DISASTER CRUNCH MODEL

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Abstract. Palabuhanratu Sub-District is one of the southern coastal areas of Java that has the potential to be exposed to tsunamis, with an estimated run-up of between 12-20 meters. Accordingly, it is necessary to conduct tsunami disaster mitigation by analysing the level of tsunami risk in the district to reduce potential losses if a tsunami occurs. This study aims to map the level of tsunami risk in Palabuhanratu Sub-District based on the disaster crunch model, which is a risk model that integrates vulnerability and tsunami hazard factors. The tsunami vulnerability analysis uses a weighted overlay quantitive approach, while the tsunami hazard analysis employs simulation of tsunami propagation by COMCOT V.1.7; the tsunami inundation reduction model; cost distance analysis; and fuzzy membership analysis. The results of the tsunami risk analysis show that villages included in the high-, medium-, and low-risk categories are Citepus, Palabuhanratu, and Jayanti. The percentage of high-risk areas in the three villages are 10% (139 hectares), 20.3% (114 hectares), and 0.01% (0.13 hectares) respectively. The higher the risk of a tsunami in an area, the higher the losses that will be incurred by the local population.

Keywords: *tsunami risk level, Disaster Crunch model, COMCOT V.1.7., Palabuhanratu Sub-District*

1 INTRODUCTION

A tsunami with an estimated run-up of between 12-20 meters has the potential to hit the southern coastal areas of Java in the future. The background for this is the discovery of a seismic gap located between the southern coast of Java and the Java Trench. The gap has weak seismicity but has a strong slip deficit, so has the potential to become a site for megathrust earthquakes in the future (Widiyantoro,S.,Gunawan,E.,Muhari,A.Rawlinson,N.,Mori,J.,et.al., 2020). One of the areas on the southern coast of Java which is tsunami-prone is Palabuhanratu Bay (Robiana & Afif, 2013). Palabuhanratu Sub-District is part of the Palabuhanratu Bay area.

Palabuhanratu Sub-District is the capital of Sukabumi Regency, West Java (Badan Pusat Statistik Kabupaten Sukabumi, 2020a). The area is dense with settlements and buildings that are used for supporting local population service activities. Palabuhanratu Sub-District is designated as a provincial National Activity Center (PKNp) and a Regional Activity Center (PKW) (Peraturan Daerah Kabupaten Sukabumi Nomor 22 Tahun 2012 Tentang Rencana Tata Ruang Wilayah Kabupaten Sukabumi Tahun 2012-2032, 2012).

The sub-district has the highest population density in Sukabumi Regency (Badan Pusat Statistik Kabupaten Sukabumi, 2020a). In addition to the local population, every

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day there are always people from outside the area who to stay temporarily or are on vacation because the Palabuhanratu coast is a popular tourist attraction (Awlia, 2016). Some of the characteristics of the Palabuhanratu Sub-District include a fairly complex local population and the regional assets accumulated from the numerous local population activities are high. When viewed from the point of view of regional development, this situation is very beneficial because it can accelerate regional development. However, when viewed from a disaster perspective, the situation is very problematic because it can increase the potential for vulnerability to the hazards of a tsunami.

The potential tsunami hazards and vulnerability that currently threaten the Palabuhanratu Sub-District need to be countered by mitigation efforts (Nahak et al., 2017). One of these is by conducting a tsunami risk level study so that areas that have the potential to suffer losses can be recognised, so that if a tsunami does occur in the future, the local population will know which areas to avoid (Santius, 2015). Material losses may be difficult to minimise, but a large number of casualties can be avoided.

Therefore, this study aims to map the level of tsunami risk in the Palabuhanratu Sub-District based on the disaster crunch model, a risk model that integrates vulnerability and tsunami hazard factors; it analyses the vulnerability, hazard, and risk level of a tsunami using the integration of remote sensing technology and a geographic information system (GIS).

Remote sensing can make extensive observations and record objects in real-time, so is vital for the analysis of tsunami disasters, which generally occur in a short time with little warning and affect a large area (Roopa, 2014). A GIS can also perform modeling, which is the process of simplifying the reality of the earth's surface to make it simpler and easier to understand (Huisman & De, 2010).

2 MATERIALS AND METHODOLOGY

2.1 Location and Data

Palabuhanratu Sub-District is located at coordinates 6°58'37" South and 106°34'23" East. The sub-district is part of Palabuhanratu Bay, with an area of around 8,260 hectares. Figure 2-1 shows that it comprises ten villages, Citarik, Palabuhanratu, Citepus, Cibodas, Buniwangi, Cikadu, Pasirsuren, Tonjong, Jayanti, and Cimanggu village.

Its border to the north is Cikakak Sub-District, to the east Bantargadung Sub-District, to the south the Simpenan Sub-District, and to the west the Indian Ocean (Badan Pusat Statistik Kabupaten Sukabumi, 2020b). The research materials and sources are listed in Table 2-1.

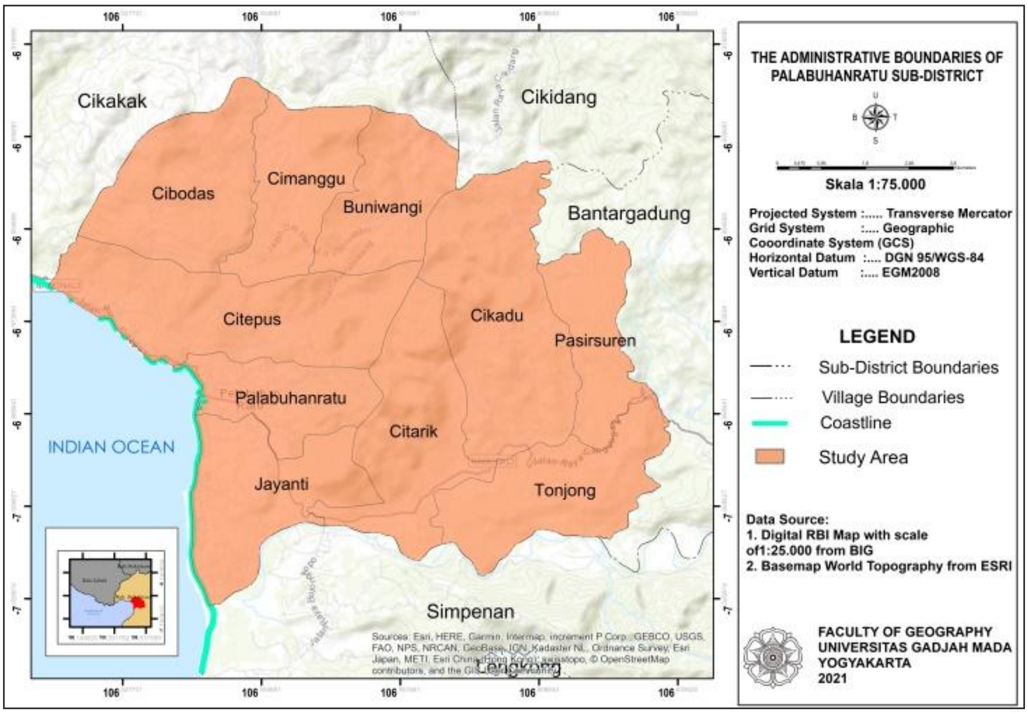

Figure 2-1: Administrative boundaries of Palabuhanratu Sub-District

Table 2-1: Research materials and sources.

Materials	Sources
SRTM imagery with 1 arc-second spatial resolution	United States Geological Survey (USGS)
GEBCO imagery with 30 grid spatial resolution	The British Oceanographic Data Centre (BODC)
Google Earth imagery	Badan Informasi Geospasial (BIG)
RBI digital 1:25,000 scale map sheet number 1208-111	Badan Informasi Geospasial (BIG)
Sunda Strait earthquake parameters	Global Centroid Moment Tensor (GCMT)
Social census data (density, sex ratio, and number of people with disabilities); economic census data (productive land area and GDP); and infrastructure census data (number of houses, public facilities, and critical facilities) of Palabuhanratu Sub-District in 2019	Badan Pusat Statistik (BPS) of Sukabumi Regency
Sukabumi Regency spatial plan map for 2012-2032	Local Government of Sukabumi Regency

2.2 Methods

The research phase was divided into three stages, namely the pre-field survey, field survey, and data processing and analysis.

2.2.1 Pre-Field Survey

This stage began with the collection of research materials from various sources and preparation of the research tools. The process of the visual interpretation of land cover objects was then conducted using Google Earth images covering the area of Palabuhanratu Sub-District. Land cover classes were determined according to the Land Cover Mapping Standard 1:50,000 scale document from BIG. The results of the land cover interpretation were used to create a distribution digital map of the land cover sample points to be validated at the field survey stage. Land cover sample points included accuracy tests and interpretation sample points. The number of accuracy test sample points was four times that of the land cover classes. In addition, the number of interpretation samples was determined according to the Slovin formula in Equation 1 below (Danoedoro et al., 2017):

$$n = \frac{N}{1+Ne^2} \tag{2-1}$$

where

n	=	number of interpretation samples
N	=	number of interpreted land cover polygons
e	=	desired level of fault tolerance

2.2.2 Field Survey

Activities undertaken during the land cover validation survey included determination of the size of the observation area at each land cover sample point; and observing the existing land cover in the field and field units around the land cover sample point. Equation 2 was used to determine the side length of the observation area (Danoedoro et al., 2017).

$$A = Rs \times (1 + 2 \times RMSe) \tag{2-2}$$

where

A	=	length of the side of the observation area (meters)
Rs	=	spatial resolution of the land cover interpretation reference image (meters)
Rmse	=	root mean square error from the results of the geometric correction of the land cover interpretation reference image in pixels.

The actual land cover classes observed at each sample point location were plotted and digitised in the form of polygons on the distribution digital map of the sample points that had been produced in the pre-field survey stage. In addition, field unit observations were made visually.

2.2.3 Data Processing and Analysis

The data processing performed after the land cover validation field survey was intended to test the accuracy and test the reinterpretation of the land cover. The accuracy test was performed by superimposing the accuracy-test sample polygons on the interpreted land cover class polygons. The total accuracy value was calculated using a confusion matrix. Equation 3 was the formula used to determine the total accuracy value of the land cover interpretation results (Danoedoro et al., 2017).

$$\text{Total accuracy} = \frac{1}{N}\sum_{k=1}^{r} ni \times 100\% \tag{2-3}$$

where

N	=	total number of pixels
ni	=	total number of correct land cover interpretations
r	=	representation of the number of interpretation classes

The accuracy test was followed by reinterpretation, which is a process of correcting land cover polygons that were misinterpreted at the pre-field survey stage, based on the data from the land cover validation field survey. The land cover re-interpretation map will be included in the tsunami hazard analysis.

Three data analysis activities were conducted in the study, namely vulnerability, hazard, and tsunami risk analysis. Tsunami vulnerability analysis was performed using a weighted overlay quantitative approach, namely giving a value to each item in a theme according to its contribution to the results (Suharyadi et al., 2018). Furthermore, in this study the notion of value is the weight of vulnerability; the items are vulnerability variables; and the themes are vulnerability parameters. Four parameters of tsunami vulnerability are employed, namely social, economic, physical, and environmental ones.

The values of the variables in each parameter were divided into three levels, namely low, medium, and high. Each level was given a score: the low level 1, the medium-level 2, and the high-level 3. After assigning a score, this was then multiplied by the respective weights and added together, resulting in a value for each vulnerability parameter. The samesteps were then taken at the level of the vulnerability parameters, so that the final value for the tsunami vulnerability of Palabuhanratu Sub-District was visualised into three levels: low, medium, and high. The parameters and variables of tsunami vulnerability and their respective weights are listed in Table 2-2.

The next analysis was tsunami hazard analysis. The hazard of a tsunami disaster was represented by inundation, which was divided into three levels, namely low, medium, and high. The tsunami inundation raster was generated from the tsunami inundation reduction modeling based on the tsunami inundation reduction equation (*Hloss*), as shown by Equation 4 (Santius, 2015).

Table 2-2: Parameters and variables of tsunami vulnerability.

Parameters and Variables	**Level**			**Weight**
	Low	**Medium**	**High**	
Social vulnerabilities				**0.4**
Density population	<500 people/km^2	500-100 people/km^2	>1000 people/km2	0.8
Sex ratio		<20-40%	>40%	0.1
Disability ratio	<20%			0.1
Economic vulnerabilities				**0.25**
Productive land area	Automatic classification in ArcMap			0.6
GDP				0.4
Physical vulnerabilities				**0.25**
Residential buildings	Automatic classification in ArcMap			0.4
Public facility buildings				0.3
Critical facility buildings				0.3
Environmental Vulnerabilities				**0.1**
Area of Water Catchment	Automatic classification in ArcMap			0.4
River Border Area				0.3
Area of Nature Reserve				0.3

Source: (Regulation of the Head of the National Disaster Management Agency Number 02 of 2012 concerning General Guidelines for Disaster Risk Assessment (2012)

$$H_{loss} = \left(\frac{167\,n^2}{Ho^{1/3}}\right) + 5 \sin S \qquad (2\text{-}4)$$

where

Hloss	=	tsunami inundation reduction value
n	=	surface roughness coefficient
H_o	=	run-up on the coastline
S		slope

The surface roughness raster was converted from the reinterpreted land cover raster. The reinterpreted land cover classes were reclassified into more general land cover classes, then linked to their respective roughness coefficient values, as shown in Table 2-3. The slope raster was extracted from the SRTM image of the Palabuhanratu Sub-District and expressed in units of degrees radians. The tsunami run-up value used the maximum run-up from the numerical simulation of tsunami propagation using the COMCOT V.1.7 program.

The steps involved in the tsunami numerical propagation simulation were as follows. First, a nested grid was created in Global Mapper; second, the coordinates of the simulated area boundaries were determined in surfer software; third, the simulation data were initialised to the comcot.ctl file in Notepad++; fourth, the process was simulated in the command prompt; and fifth, the simulation results were visualised using MatLab. The simulation data entered into the comcot.ctl file were the parameter data for the Sunda Strait earthquake on April 9 2018 at 11.46 WIB with a magnitude of Mw 8.

The surface roughness raster,slope gradient raster, and run-up maximum values, which were input data for the tsunami inundation reduction modeling, will produce a tsunami inundation reduction (*Hloss*) raster. The raster was then processed in a cost-distance analysis to the coastline, so that an inundation raster would be generated.

In order to to be able to represent the level of tsunami disaster hazard in Palabuhanratu Sub-District, the inundation raster was then divided into three levels, namely low, medium, and high, using fuzzy membership analysis. The tsunami hazard and vulnerability level rasters were integrated to produce a tsunami risk level raster for the Palabuhanratu Sub-District as a result of the final analysis in the study, namely that of the tsunami risk level. The integration used principles of the disaster crunch model. Tsunami risk was also divided into three levels, low, medium, and high. The determination of the level was based on the results of the overlapping between the levels of vulnerability and tsunami hazard, as shown in Table 2-4.

Table 2-3: Surface roughness coefficients.

Land Cover Class	**Surface Roughness Coefficient**
Functional buildings	0.055
Forest	0.07
Plantation	0.035
Field	0.015
Rice field	0.025
Bush	0.04
River	0.007
Empty land	0.015
Residential buildings	0.045

Source: Qossam et al. (2020)

Table 2-4: Determination matrix of the tsunami risk level.

Loss Level	Tsunami Vulnerability Level		
	Low	Medium	High
Tsunami Hazard Level			

Source: (Regulation of the Head of the National Disaster Management Agency Number 02 of 2012 concerning General Guidelines for Disaster Risk Assessment (2012)

3 RESULTS AND DISCUSSION

3.1 Tsunami Vulnerability Analysis

Tsunami vulnerability is the condition of a population, system or asset that makes it vulnerable to the damaging effects of tsunami waves (Anwar et al., 2011). Assessment of such vulnerability in the Palabuhanratu Sub-District depends on the results of the analysis of the social, economic, physical, and environmental parameters.

The results of the social vulnerability analysis show that Jayanti, Cibodas, and Buniwangi villages have low vulnerability levels. Cikadu, Citepus, and Cimanggu villages have medium levels, while Citarik, Pasirsuren, and Tonjong villages are areas with high social vulnerability levels.

Those with high social vulnerability have a high population density and sex ratio of the female to the male population. The sex ratio is an important parameter to use because the female population is considered more vulnerable to being tsunami victims compared to the male population. However, the ratio of those with disabilities does not affect loss of life due to the tsunami too much, because the results are low for all the villages in Palabuhanratu Sub-District. Areas with a high population density and a dominant female population have the potential to suffer the highest number of fatalities resulting from a tsunami disaster. The female population has a slower evacuation movement than the male population..

The results of the economic vulnerability analysis show that Jayanti village is an area with low vulnerability levels; Citepus, Buniwangi, Citarik, Tonjong, and Pasirsuren villages have medium levels; and Palabuhanratu, Cibodas, Cimanggu, and Cikadu villages have high economic vulnerability levels.

Those with a high economic vulnerability level have highly productive land areas ranging from 2.6-4.6 billion rupiahs in a year and Gross Domestic Product (GDP) at varying levels, ranging from 3 billion rupiahs to over 5 billion rupiahs in a year. The weight of productive land area which is greater than Gross Domestic Product (GDP) makes this variable more influential on the results of the economic vulnerability analysis. Villages with a high economic vulnerability are estimated to have more assets in the form of economic income and more diverse economic activities. Therefore, if there is a tsunami, they may experience the worst economic paralysis compared to other villages.

The results of the physical vulnerability analysis show that Jayanti, Cimanggu, and Pasirsuren villages are areas with low vulnerability levels; Cibodas, Citarik, Cikadu, and Tonjong villages have medium levels; and Citepus and Palabuhanratu villages have high physical vulnerability levels.

Those with a high level of physical vulnerability have extensive public facility and critical facility buildings , with the value of building houses at various levels. The value of public facility buidlings is around 3.5 billion rupiahs in a year, while that of critical facility buildings is around 120 million rupiahs a year. In addition, the value of houses ranges from 6.7 billion to over 10 billion rupiahs in a year.

These characteristics mean that the villages with a high level of physical vulnerability have the potential to experience the greatest material losses in relation to the high number of residents who lose their homes, the number of damaged public facility buildings, and the number of critical (health) facilities that become unavailable to deal with local residents who are injured.

The results of the environmental vulnerability analysis show that Cibodas, Cimanggu, and Palabuhanratu village are areas with low vulnerability levels. Citepus, Buniwangi, Tonjong, Cikadu, Jayanti, and Pasirsuren villages have medium levels, while Citarik village has a high environmental vulnerability level.

This high level is influenced by the existence of a very large water catchment area of around 671,781 hectares (Peraturan Daerah Kabupaten Sukabumi Nomor 22 Tahun 2012 Tentang Rencana Tata Ruang Wilayah Kabupaten Sukabumi Tahun 2012-2032, 2012). Most of the area is within the range of a volcanic field with massive igneous rock that has been further eroded. This means the area has a large water catchment zone. In addition, the main river that passes through the southern part of Citarik village, namely the Cimandiri River, means the village has a fairly wide river border area. These characteristics result in the village having have the potential to experience the greatest damage within the water catchment areas and river borders.

The presence of the river will increase the tsunami inundation and damage water catchment areas. making it difficult for the local population to obtain clean water. This potential is based on the function of water catchment areas and river borders described in the spatial and regional planning regulation of Sukabumi Regency in 2012-2023 (Peraturan Daerah Kabupaten Sukabumi Nomor 22 Tahun 2012 Tentang Rencana Tata Ruang Wilayah Kabupaten Sukabumi Tahun 2012-2032, 2012). Based on the integration of the results of the tsunami vulnerability parameters, a map of tsunami vulnerability levels in Palabuhanratu Sub-District was produced, as shown in Figure 3-1.

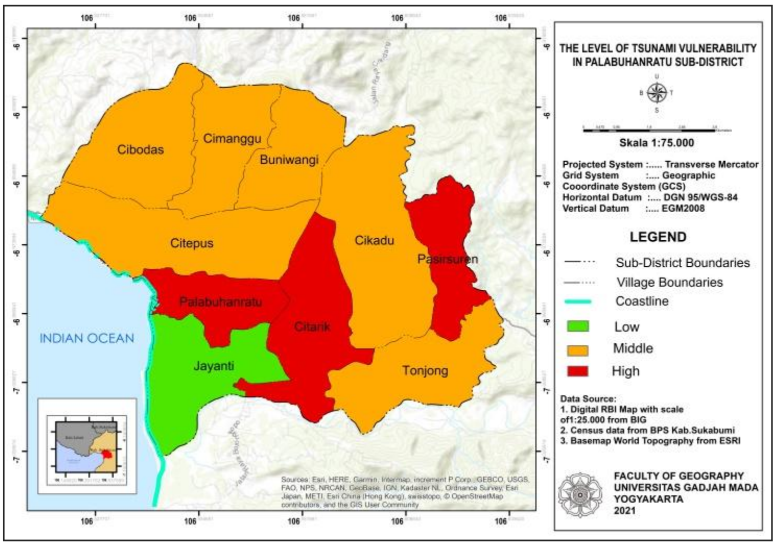

Figure 3-1: Level of tsunami vulnerability in the Palabuhanratu Sub-District.

It can be seen in Figure 3-1 that the village included in the area with a low tsunami vulnerability level is Jayanti. The villages included in areas with medium tsunami vulnerability levels are Cibodas, Cimanggu, Citepus, Buniwangi, Cikadu, and Tonjong, while those in areas with high vulnerability levels are Citarik, Palabuhanratu, and Pasirsuren.

The higher the level of vulnerability to a tsunami disaster, which represents the condition of the population (social) and the assets (economic, physical, and environmental) owned, the more capable the population should be to prepare itself for the impacts caused by the tsunami hazard (Qossam et al., 2020)

3.2 Tsunami Hazard Analysis

The tsunami disaster hazard refers to the height of a tsunami wave that reaches the coastline and spreads inland, causing inundations (Amri et al., 2016). The parameters that are substituted into the model builder in ArcGIS for the tsunami inundation reduction model are surface roughness, slope, and tsunami run-up value.

The surface roughness raster, which was successfully converted from the land cover map of Palabuhanratu Sub-District, has values ranging from 0.007 to 0.07, meaning that the surface or land in the district has a roughness level that varies from smooth to rough. Surface roughness affects the inundation height. The rougher the surface through which the tsunami inundation passes, the more easily the inundation height will be reduced (Qossam et al., 2020).

General land cover classes converted into surface roughness coefficient values include functional buildings, forests, gardens, fields, rice fields, rivers, open land, and residential buildings. The eight general land cover classes are generalisations of the 20 land cover classes resulting from the interpretation of Google Earth imagery in the Palabuhanratu Sub-District, which was validated at the field survey stage with a total interpretation sample of 44/88.

The result of the total accuracy test of the twenty land cover classes was 85.96%, a percentage which exceeds the specified threshold of 85%. This means that 85% land cover polygons were interpreted relatively accurately and were suitable with land cover objects in the field (Danoedoro et al., 2017).

The slope gradient raster from the DEM image extraction shows that the value of the slope degree in the Palabuhanratu Sub-District ranges from 0-1.21^{o}. The greater the value of the slope of an area, the more quickly the tsunami inundation height will be reduced (Qossam et al., 2020).

The estimated maximum run-up value from the simulation of tsunami propagation at the observation points located on the coastal coastline of Palabuhanratu Sub-District was 7.4096 meters, or around 7.5 meters. The tsunami propagation simulation was performed for 20 minutes and took place in four chronological stages. First, the seawater receded significantly in the first 4 minutes, or shortly after the earthquake occurred (Figure 3-2); second, the tsunami waves reached the peak of the first run-up at around the 10th minute; third, the run-up decreased in the 11th minute until reaching its maximum value when combined with a follow-up run-up in the 13th minute; and fourth, the run-up again dropped notably between the 14th and 20th minutes. Figure 3-3 shows the relationship between the arrival time and tsunami run-up in the first minute.

The tsunami inundation reduction raster resulting from the modeling, which was then processed in the cost distance and fuzzy membership analysis, produced the tsunami inundation level as a representation of the tsunami hazard level, which was mapped according to Figure 3-4. The figure shows that the villages that have the potential to be hit by all three levels of tsunami hazard are Citepus, Palabuhanratu, and Jayanti. The higher the tsunami hazard level, the greater the impact of the damage (Qossam et al., 2020). The total area of tsunami inundation in Citepus is 27.86 hectares, in Palabuhanratu it is 178 hectares, and in Jayanti 370.78 hectares.

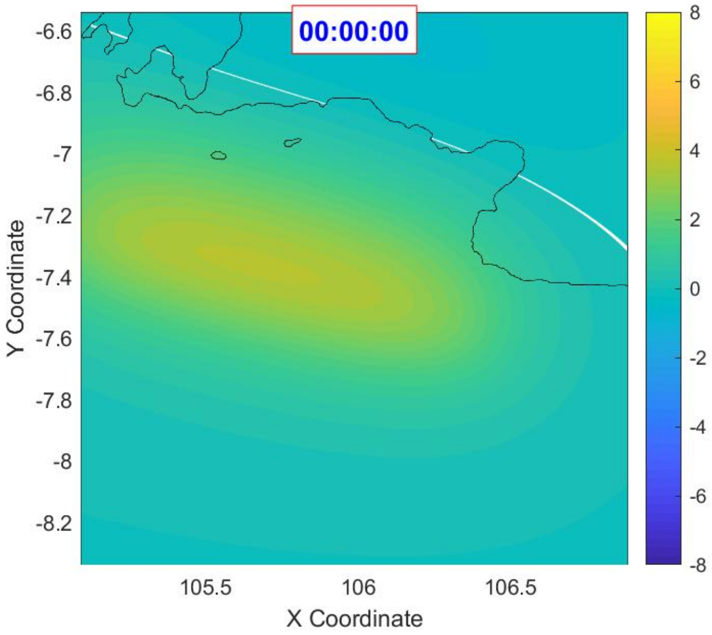

Figure 3-2: Initial condition of the tsunami shortly after the earthquake occurred.

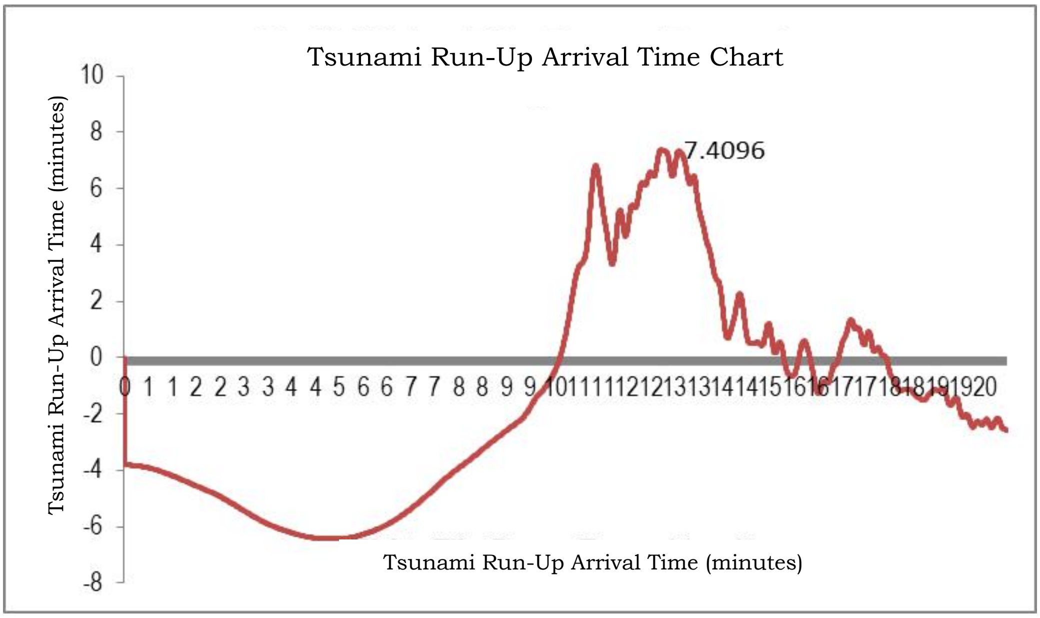

Figure 3-3: Tsunami run-up arrival time chart.

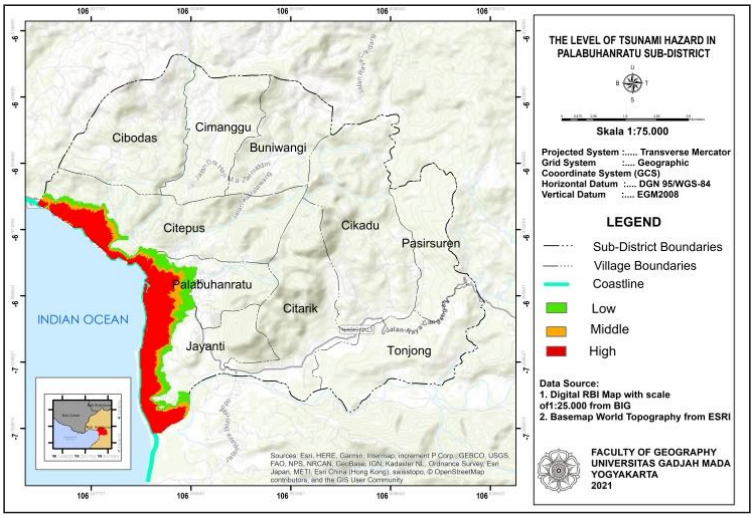

Figure 3-4: Level of tsunami hazard in the Palabuhanratu Sub-District.

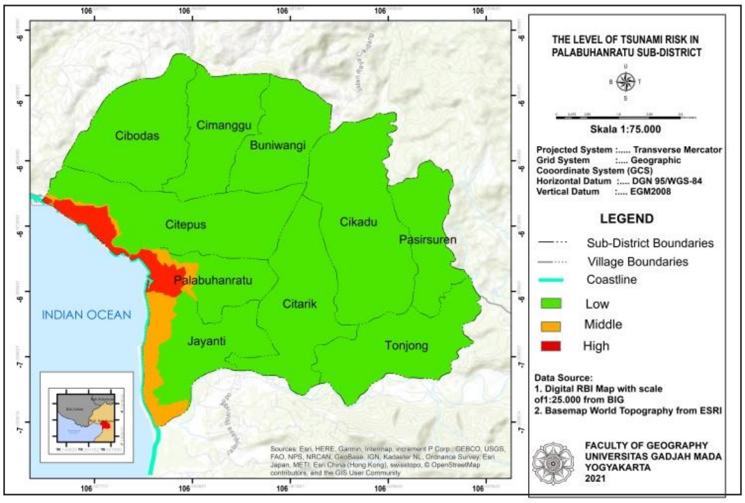

Figure 3-5: Level of tsunami risk in the Palabuhanratu Sub-District.

3.3 Tsunami Disaster Risk Analysis

Tsunami disaster risk is defined by the level of losses that will be faced depending on the level of hazard and an area's vulnerability to disaster (Hai & Smyth, 2012). Based on the tsunami risk level map of Palabuhanratu Sub-District shown in Figure 3-5, the villages that face the three level of tsunami risk are Citepus, Palabuhanratu, and Jayanti.

The percentage of the Citepus village area that is included in the high level of tsunami risk is around 10% (139 hectares); in the medium level it is around 2% (28 hectares); and the remainder is included in the low level. The percentage of the area of Palabuhanratu Sub-District which is included in the high level of tsunami disaster risk is around 20.3% (114 hectares) of the village area, with the medium level at around 11.1% (67 hectares), and the remainder in the low level. The percentage of the Jayanti village area that is included in the high level of tsunami disaster risk is around 0.01% (0.13 hectares) of the village area, at the medium level it is around 23.3% (257 hectares), and the remainder is included in the low level. The higher the risk of a tsunami in an area, the higher the losses that will be faced by the population (Santius, 2015).

4 CONCLUSION

The results of the tsunami risk analysis show that all villages are not potentially at risk of tsunami except for three villages namely Palabuhanratu, Citepus, and Jayanti. The percentage of the high-risk areas in the three villages are respectively 10% (139 hectares), 20.3% (114 hectares), and 0.01% (0.13 hectares). Tsunami risk shows the magnitude of the potential loss that will be experienced by an area.

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AUTHOR CONTRIBUTIONS

Inti Raidah Hidayat; conceptualization, methodology, writing, preparation of original draft, and data processing; Dr. Sudaryatno, M.Si.; validation and formal analysis.

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