TSUNAMI HAZARD MODELING IN THE COASTAL AREA OF KULON PROGO REGENCY

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Abstract. Kulon Progo Regency is prone to tsunamis because it faces a subduction zone in the Indian Ocean. Therefore, it is necessary to model tsunami inundation and map the tsunami hazard zone in the Kulon Progo coastal area. This study aims to model tsunami inundation and produce a tsunami hazard map with a tsunami height scenario of 5 meters and 10 meters. The method used in modeling tsunami inundation is using a mathematical calculation developed by Berryman-2006 using the parameters of the coefficient of surface roughness, slope, and the height of the tsunami at the coastline. The estimated tsunami inundation area is classified into a tsunami hazard index using the fuzzy logic method resulting in an index of 0 – 1, which is then divided into three hazard classes. The results of the tsunami hazard mapping with the 5 meters scenario are 15 villages in 4 sub-districts included in the hazard zone with a total area of 2067.234 Ha affected. The results of the tsunami hazard mapping with a 10 meters scenario are 26 villages in 4 sub-districts with a total area of 5304.266 Ha affected. The results of this research can be used as basic information for disaster mitigation.

Keywords: *tsunami, inundation, hazard, Kulon Progo, GIS*

1 INTRODUCTION

Indonesia is a country prone to natural disasters because Indonesia is located at the confluence of three tectonic plates, namely the Eurasian Plate, the Indo-Australian Plate, and the Pacific Plate. One of the natural disasters that are prone to occur in Indonesia is tsunamis. Tsunamis can be caused by various things, including earthquakes in subduction zones, volcanic eruptions, and landslides (Steinritz, V., et al., 2021). In the period 1600 to 1999, there were approximately 105 tsunamis, of which shallow tectonic earthquakes caused 90%, 9% were due to volcanic earthquakes, and only 1% were triggered by landslides (Hamzah, Puspito, & Imamura, 2000). Areas in Indonesia that are prone to tsunamis are areas directly opposite the subduction zone between plates, including western Sumatra, southern Java, Nusa Tenggara, northern Papua, Sulawesi, and Maluku (Badan Nasional Penanggulangan Bencana, 2012). The most at-risk area for tsunamis in Indonesia is the southern coast of Java because it has a high population density and its location is adjacent to the subduction zone of tectonic plates and is at risk of being hit by a tsunami due to the Megathrust earthquake (Hall et al., 2017; Surindar & Nurhadi, 2021). Based on paleo-tsunami studies in the southern area of Java, it is suspected that there were 16 locations as paleo-tsunami locations from 2011 to 2016 (Rizal, et al., 2017). In addition, based on historical tsunami events data in South Java, there have been two quite giant tsunamis, namely the Banyuwangi tsunami and the 2006 Pangandaran tsunami (Badan Meteorologi, Klimatologi, dan Geofisika, 2018).

Kulon Progo Regency is located in the southern part of Java Island and is one of the areas in Indonesia that is prone to tsunami disasters. Kulon Progo Regency is directly adjacent to the Indian Ocean and faces the subduction zone of the Eurasian Plate and the Indo-Australian Plate. The morphology of the coast in Kulon Progo Regency tends to be gentle so that when a tidal wave occurs, water can enter the land relatively far away, and the overflow area becomes very wide (Marwasta &

Priyono, 2007). Massive damage to buildings, infrastructure and even casualties can occur because of the tsunami (Marfai et al., 2019). The tsunami disaster can cause significant damage in Kulon Progo Regency because there are no barrier islands and the lack of dampening vegetation in the coastal area (Mukaryanti, 2005 in Tarigan, Subardjo, and Nugroho, 2015). In addition, the construction of the Yogyakarta International Airport can impact the rapid development of Kulon Progo Regency so that if a tsunami occurs, it can cause even more significant potential damage.

Until now, the tsunami disaster cannot be predicted. Therefore, it is necessary to mitigate the tsunami disaster. Remote sensing and Geographic Information System (GIS) can be used for disaster analysis. DEM data can be used for tsunami hazard mapping analysis because DEM can show the topographic characteristics of an area closely related to disasters (Marfai et al., 2021). One of the non-physical tsunami disaster mitigation strategies that can be done in Kulon Progo Regency is preparing a tsunami hazard map. A tsunami hazard map is essential in developing an evacuation strategy and disaster management (Kurowski, M. J., et. al., 2011; Fatchurohman, H., et. al., 2022). The fuzzy logic approach, which usually deals with uncertainties that are difficult to define, such as boundaries that are difficult to define decisively, can generate a tsunami hazard model (Malczewski, 2006). Furthermore, there is evidence that fuzzy logic has better accuracy than similar models (Qiu et al., 2014).

Previously, The German-Indonesian Cooperation carried out tsunami hazard modeling in Kulon Progo Regency for a Tsunami Early Warning System in 2012 using the TsunAWI inundation model provided by the Alfred Wegener Institute to produce a tsunami hazard map. Based on the tsunami hazard map, the hazard zone covers the area of Temon, Wates, Panjatan, and Galur Sub-districts. The hazard zone protrudes to the north in the area around the rivers. The sub-district that has the highest tsunami hazard potential is Galur Sub-district which is caused by the following factors: land use in the coastal area of Galur sub-district is dominated by settlements, rice fields, and ponds, flat relief, minimum vegetation, and there is the Progo River in the eastern part of Galur Sub-district (Surindar and Nurhadi, 2021). The tsunami hazard map produced by the German-Indonesian Cooperation for a Tsunami Early Warning System (2012) has not shown the tsunami height scenario used in the tsunami hazard modeling, it only shows areas that were included in the danger zone when the tsunami occurred with a height of >3 meters. Therefore, this study aims to model tsunami inundation and map the tsunami hazard zone on Kulon Progo Beach based on tsunami run-up modeling at variations in tsunami wave height (5 meters and 10 meters).

2 MATERIALS AND METHODOLOGY

2.1 Study Area

Kulon Progo Regency is one of the regencies in the Special Region of Yogyakarta Province. Purworejo Regency borders Kulon Progo Regency in the west, Magelang Regency in the north, Sleman Regency and Bantul Regency in the east, and the Indian Ocean in the south. This Sub-district faces the subduction zone of the Eurasian plate and the Indo-Australian plate. The movement of these plates can cause earthquakes. As is known, earthquakes are one of the causes of the tsunami hazard. Therefore, this research will focus on the tsunami hazard in the coastal area of Kulon Progo Regency. Figure 2-1. represents the location of the coastal area of Kulon Progo Regency as the area of interest in this study. This study's area of interest covers Temon, Wates, Panjatan, Galur, part of Kokap Sub-district and part of Pengasih, and part of Lendah Sub-district.

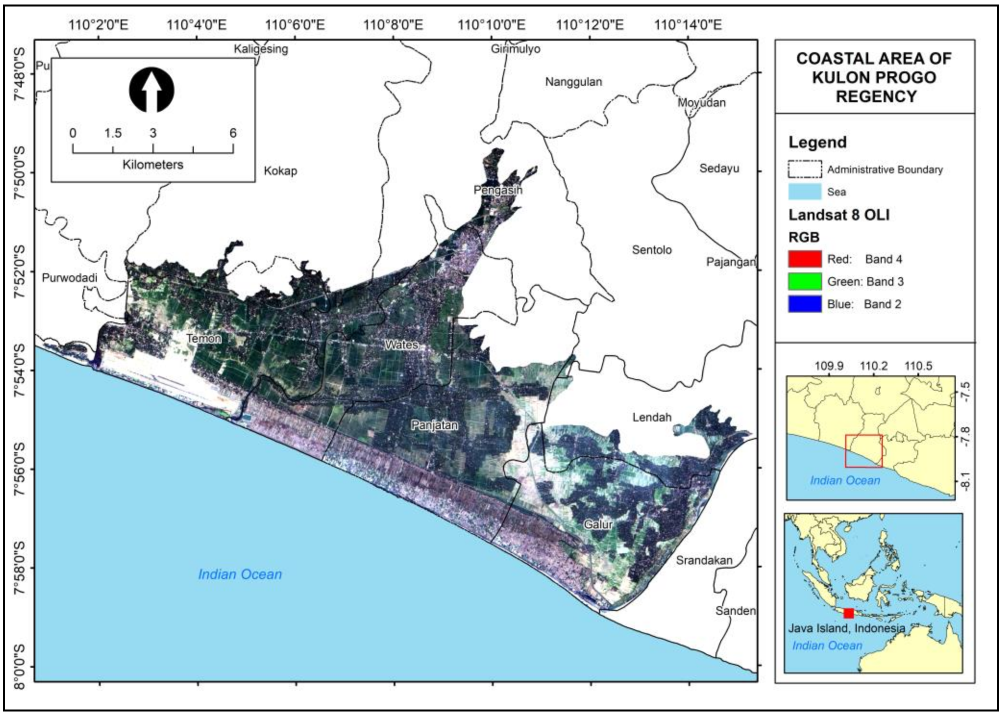

Figure 2-1: Study area location

2.2 Data Collection

The data used in this study are Landsat 8 OLI imagery, ALOS PALSAR DEM data with an altitude accuracy of 2.0×10^{-4} degree, river network data, road network data, and administrative boundaries data of the Kulon Progo Regency. Landsat 8 OLI imagery was obtained from the United States Geological Survey (USGS) on the website https://earthexplorer.usgs.gov/ and ALOS PALSAR DEM data can be obtained from the website //search.asf.alaska.edu/#/. River network data, road network data, and administrative boundary data can be obtained from the topographic map of the Kulon Progo Regency. The first step that needs to be done is image correction on the Landsat 8 imagery. The next step is to delineate the coastal area of Kulon Progo Regency. Then, clip all the data with the coastal area of Kulon Progo Regency. The study workflow is shown in Figure 2-2.

2.3 Data Processing

Each data has a different use. Landsat 8 OLI imagery is used as a basis for obtaining land use parameter which is derived into surface roughness coefficient data. The tsunami hazard parameters, slope, can be obtained from DEM ALOS PALSAR data. Coastline data is obtained from coastal delineation and administrative boundaries. The tsunami height scenario is based on the reference of the National Disaster Management Agency, namely 5 and 10 meters. The data sources for each parameter can be seen in Table 2-1.

Table 2-1: Data sources and tsunami hazard parameter.

Data Sources	Parameters
Landsat 8 OLI imagery	Coastline data Surface roughness coefficient data from land use
ALOS PALSAR DEM	Slope

The data needs to be processed first to make a tsunami hazard map. Landsat 8 OLI imagery is used to derive land use information by visual interpretation using an ecological approach. With this imagery, coastline delineation is also carried out according to the landform and administrative boundaries the of Kulon Progo Regency. ALOS PALSAR DEM data can be derived into slope data. The slope is processed using the slope 3D analyst tool. The field survey was conducted to validate land use and slope data.

2.4 Tsunami Hazard Modeling

Tsunami hazard modeling in Kulon Progo Regency was carried out based on the Technical Module for the Study of Tsunami Disaster Risk compiled by the National Disaster Management Agency. The method used in this tsunami hazard modeling is the mathematical calculation method developed by the Berryman (2006) method use coastline data, slopes, surface roughness coefficients, and scenarios for tsunami wave heights, namely 5 and 10 meters. These data are used to calculate *Hloss* or tsunami height loss per 1-meter inundation distance (inundation height). The calculation of the tsunami height loss per 1 meter according to the Berryman method is in Equation 1:

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

where H_{loss} is the tsunami height loss per 1 meter inundation distance, n is surface roughness coefficients, H_0 is maximum tsunami wave height (meters), and S is slope (degree).

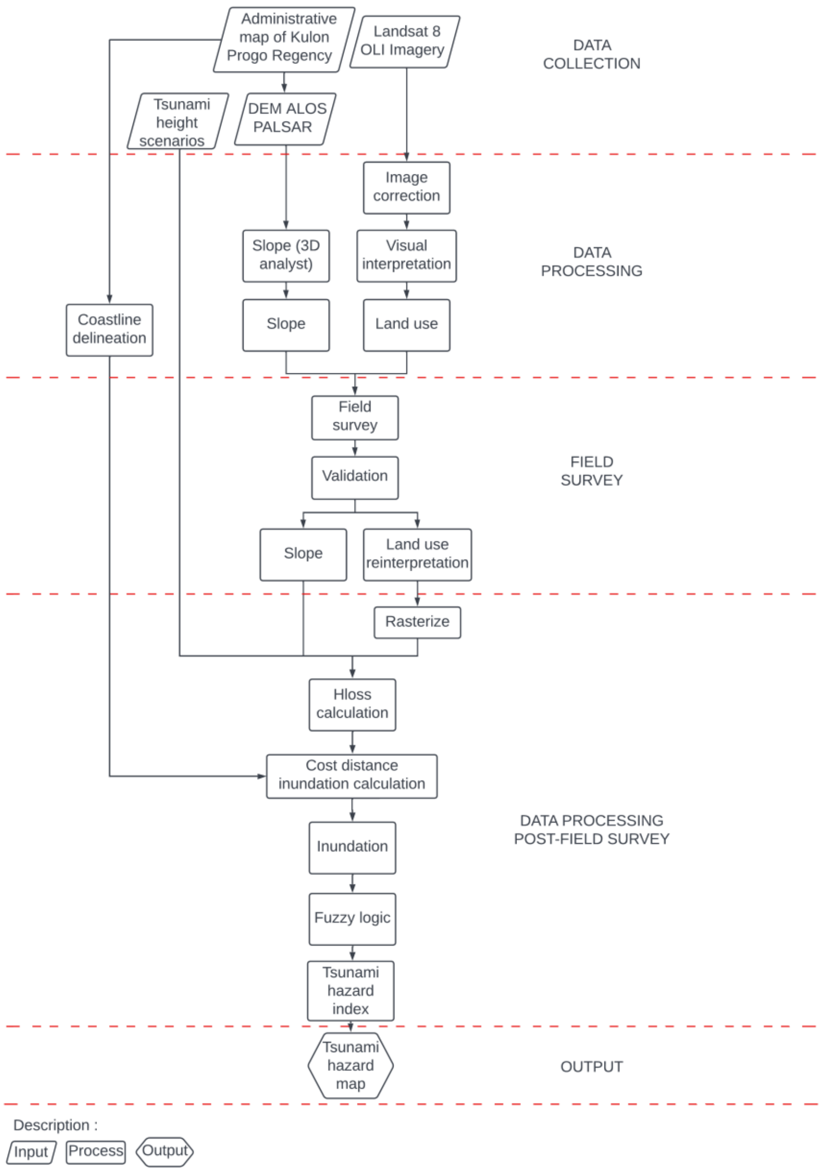

Figure 2-2: Study workflow

The surface roughness coefficient values is derived from land use data. Land use data used to derive surface roughness information has been reinterpreted based on the results of field surveys. The surface roughness coefficient for each type of land use is shown in the Table 2-2.

Table 2-2: Surface roughness coefficient.

Land use	Surface roughness coefficient
Water body	0.007
Swamp	0.015
Pond	0.010
Sand	0.018
Shrubs	0.040
Grassland	0.020
Forest	0.070
Plantation	0.035
Moor	0.030
Ricefield	0.020
Cropland	0.025
Settlement/build up area	0.050
Mangrove	0.060
Open land	0.015

Source: BNPB, 2012

Coastline data is used in calculating the cost distance inundation. Calculation of cost distance inundation and Hloss are used to estimate the tsunami inundation area. The estimated tsunami inundation area is classified into a tsunami hazard index using the fuzzy logic method resulting in an index of 0 – 1. The tsunami hazard index is classified into three tsunami hazard classifications according to the Head of National Disaster Management Agency No. 2 Year 2012, the low hazard class refers to an area with an inundation height of less than 1 meter (hazard index 0 – 0.333), the medium hazard class refers to an area with inundation height of 1 – 3 meters (hazard index 0.333 – 0.666), and high hazard class refers to areas experiencing inundation heights of more than 3 meters (hazard index 0.666 – 1). The classification of the tsunami hazard index produces a tsunami hazard map which is divided into low, medium, and high hazards.

3 RESULTS AND DISCUSSION

3.1 Parameters Used in Modeling

The modeling of the tsunami hazard in Kulon Progo Regency was carried out using several parameters, including the slope and the coefficient of surface roughness obtained from the reduction of information from land use data that has been reinterpreted based on the results of field surveys. The slope can affect the area potentially affected by a tsunami. The higher the slope of an area, the shorter the tsunami inundation. Based on the results of slope mapping from ALOS PALSAR DEM data, Kulon Progo Regency has a dominant flat/very flat to wavy morphology. The slope map of some parts of Kulon Progo Regency can be seen in Figure 3-1. The mapping results were tested in the field using Abney level at a predetermined sample point, and the results showed that the study area had a flat slope with a value of 2%.

In addition to using the slope, land use is used as data to derive surface roughness information. Land use information was obtained from the results of the visual interpretation of Landsat 8 OLI images according to the boundaries of the study area used. Land use in the coastal area is dominated by fields/moors with crops, horticultural fields/moors, and several fish/shrimp ponds. Settlements around the coastal area have an elongated pattern following a road parallel to the coastline. In Kulon Progo Regency, the Yogyakarta International Airport is also located in the coastal area. Figure 3-2 shows the land use interpretation map.

The interpretation results of the map are checked in the field using a sample consisting of the modeling sample (the reinterpretation preparation sample) and the sample that tests the accuracy of the interpretation result map. The reinterpretation samples used were two samples. This reinterpretation sample is used to build an interpretation key from the field. It is returned to the image so that it can be used to improve the results of pre-field image interpretation and produce the output reinterpretation map.

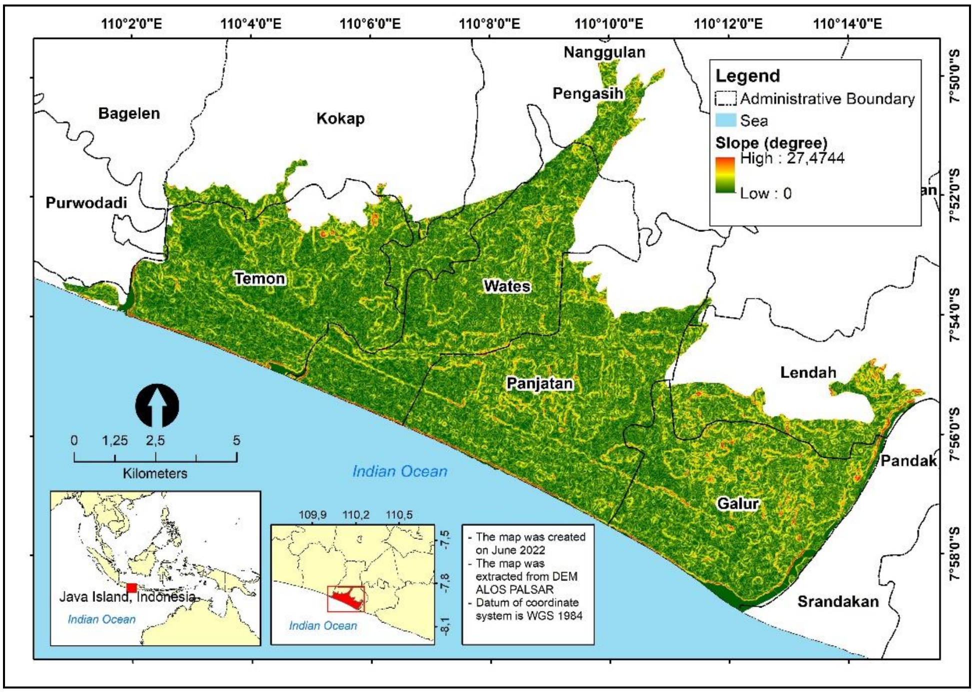

Figure 3-1: Slope map

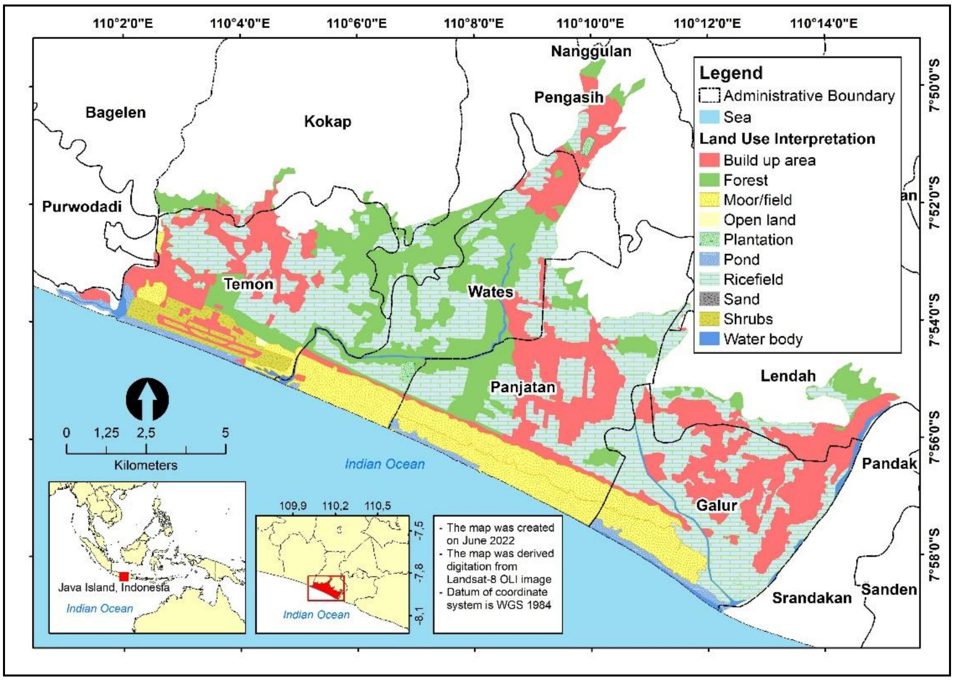

Figure 3-2: Land use interpretation map

Based on the results of the reinterpretation, it was found that the area of shrub's land use experienced a significant increase, with an area of 2014.2966 ha. In the interpretation results, some areas are classified as forest, but when validated in the field, it turns out to be shrubs. The accuracy test was carried out on 14 samples using the table confusion matrix method and the overall accuracy value obtained based on field results was 57.14% with a kappa index of 0.4717. The result indicates that 42.86% of the interpretation results have an error. The error can be caused by differences in interpreter understanding in interpreting. Changes in the type of land use cover in the field can also be a factor in the low accuracy value obtained. In addition, an insufficient number of samples and uneven distribution of samples can result in fairly low accuracy results.

The land use information that has been reinterpreted is then converted into the value of the surface roughness coefficient. The map resulting from the reinterpretation of land use in the study area can be seen in Figure 3-3. The results of land use classification have different surface roughness coefficient values. The surface roughness coefficient affects the tsunami run up value. The lower the value of the roughness coefficient, the wider the range of tsunami inundation. The results of the surface roughness coefficient classification are dominated by the coefficients of 0.02 and 0.05. This is because the study area is dominated by paddy fields with rice interspersed with other crops/ fallow (37.72%) and built-up land (25.42%). The distribution of surface roughness in the study area can be seen on the surface roughness map in Figure 3-4.

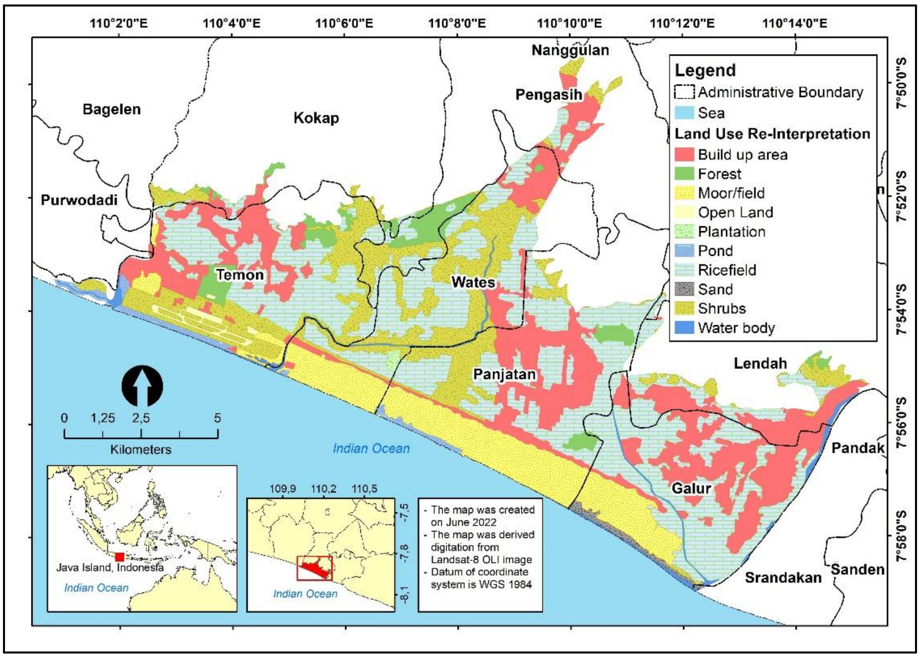

Figure 3-3: Land use re-interpretation map

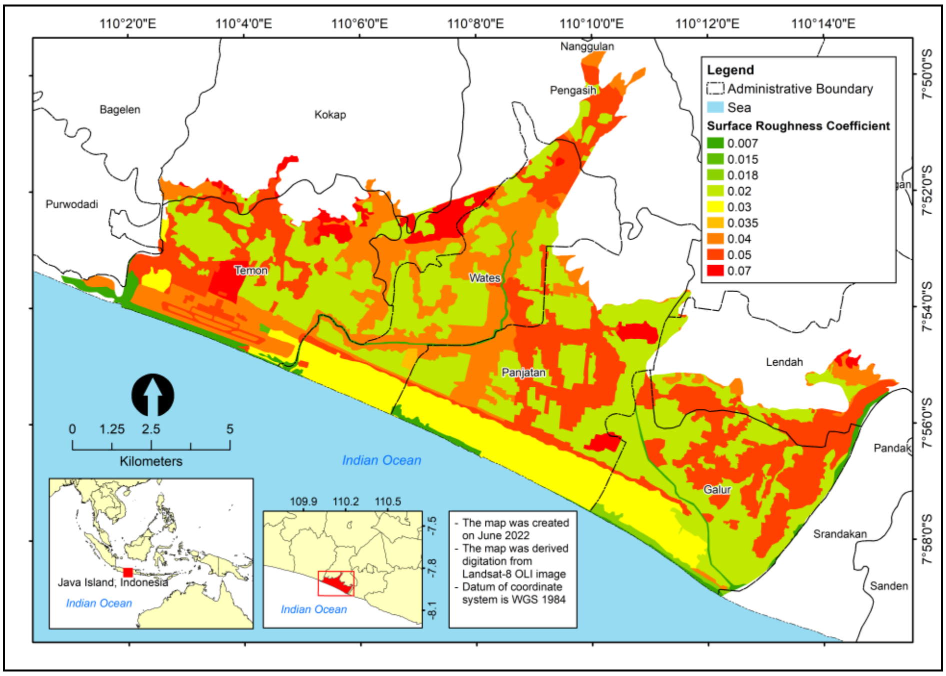

Figure 3-4: Surface roughness map

3.2 Tsunami Inundation Mapping

Tsunami inundation map with the 5 meters scenario can be seen in Figure 3-5. Based on the tsunami inundation map with the 5 meters tsunami height scenario, there are several inundation areas that protrude to the north at the border between the Temon and Bagelen Sub-district, the border between the Wates and Temon Sub-district, and the Galur Sub-district. This is due to the land use (rivers and shallow waters), which this class has the smallest surface roughness coefficient value. From the 5 meters scenario, the inundated area is 2076 Ha or 14% of the total coastal area of Kulon Progo Regency.

The tsunami, inundation map with a scenario of 10 meters tsunami height can be seen in the Figure 3-6. Based on this map, there are several inundation areas that protrude to the north at the Galur Sub-district and the border between Temon and Wates Sub-district. In the inundation area on the Temon and Wates Sub-district border, the inundation area widens on the land use of paddy field. The widening of the inundation is influenced by the low value of the paddy field's surface roughness coefficient.

3.3 Tsunami Hazard Modeling

The tsunami hazard in the coastal area of Kulon Progo Regency from low, medium, to high hazard levels. The tsunami hazard map with 5 meters height scenario can be seen in Figure 3-7. Area of tsunami hazard class in Kulon Progo Regency with 5 meters tsunami height scenario can be seen in Figure 3-8. Areas close to the coastline have a higher level of danger than areas far from the coastline. Based on the 5 meters tsunami height scenario, there are 15 villages in 4 sub-Sub-districts that are included in the danger zone, namely Galur Sub-district with a total area of 688.359 Ha, Panjatan Sub-district with a total area of 520.438 Ha, Temon Sub-district with an area of 566 Ha, and Wates Sub-district with total area 292.438 Ha. The village with the widest area of the high-hazard zone is Banaran Village, Galur Sub-district, and Jangkaran Village, Temon Sub-district. The area has a high level of hazard because the area is flat, and the coefficient of surface roughness tends to be low. Based on the scenario of a tsunami height of 5 meters, there is a total area of 829.234 ha of the low hazard zone, 249.953 ha of the medium hazard zone, and 988.047 ha of the high hazard zone.

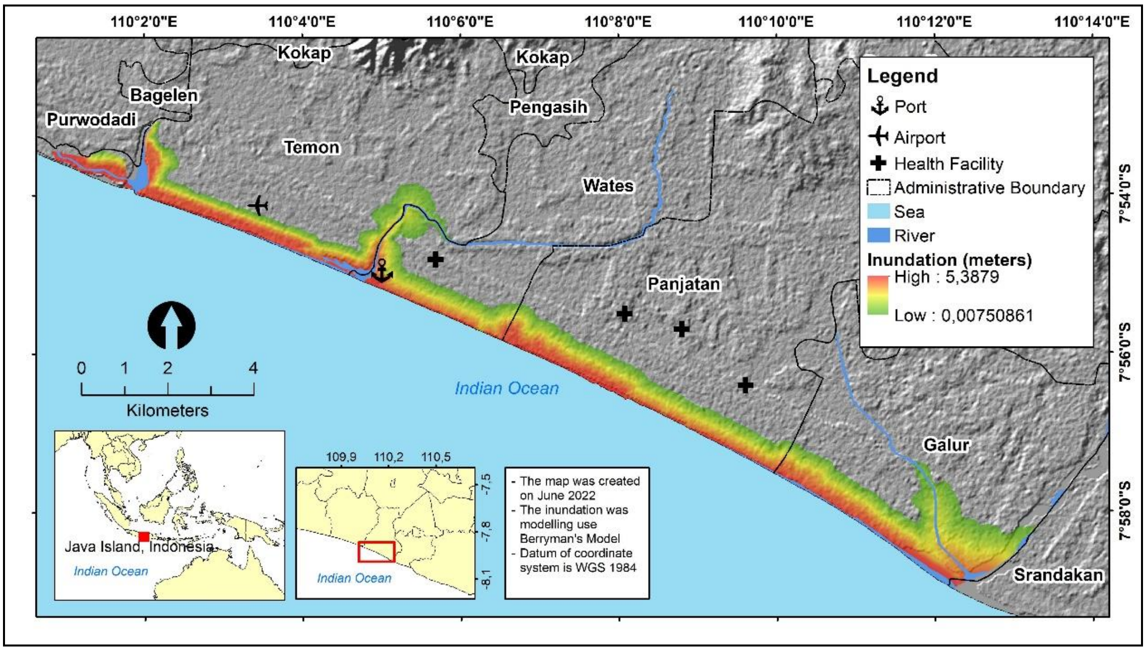

Figure 3-5: The tsunami inundation map with 5-meters scenario

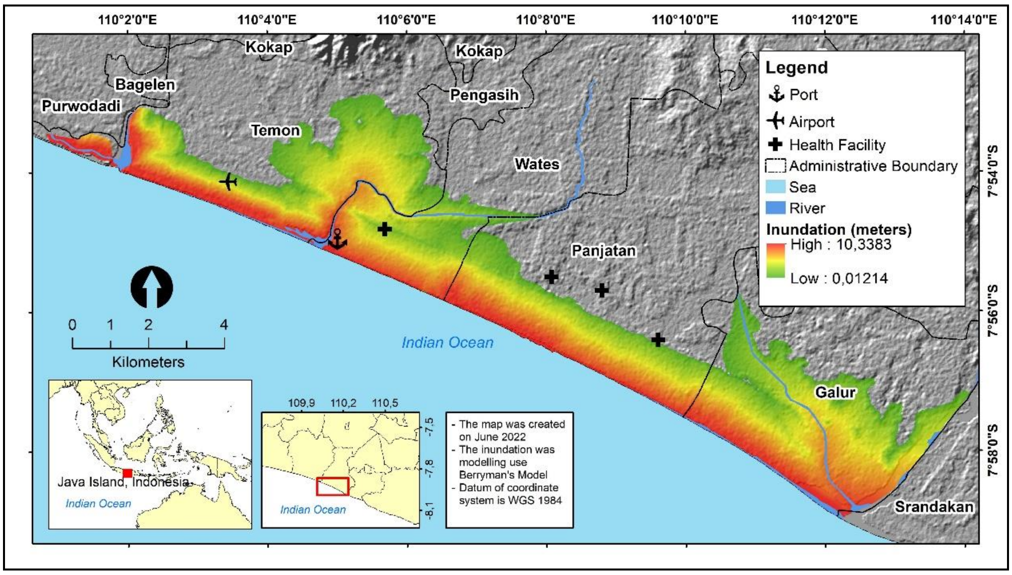

Figure 3-6: The tsunami inundation map with 10-meters scenario

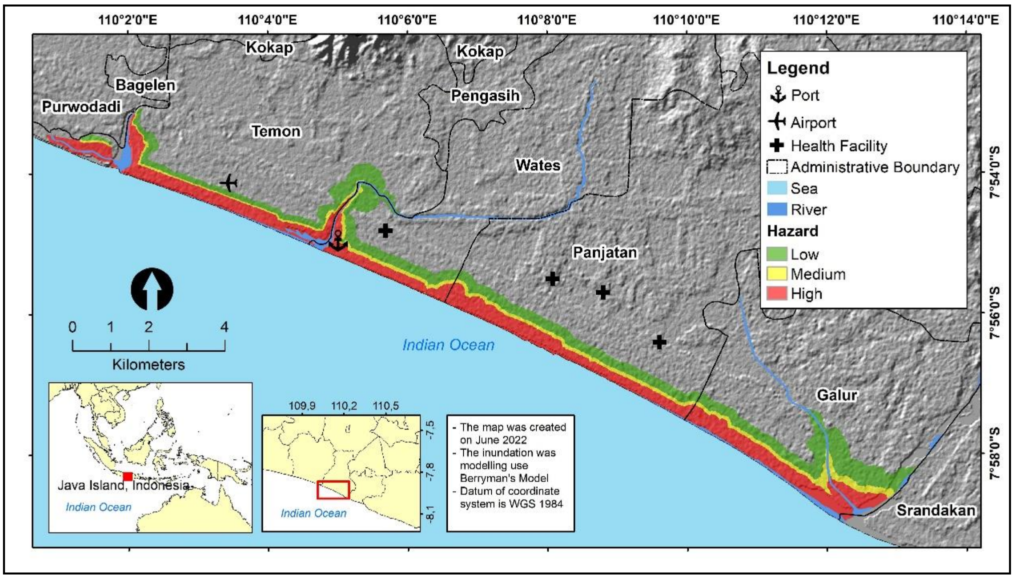

Figure 3-7: The tsunami hazard map with 5-meters scenario

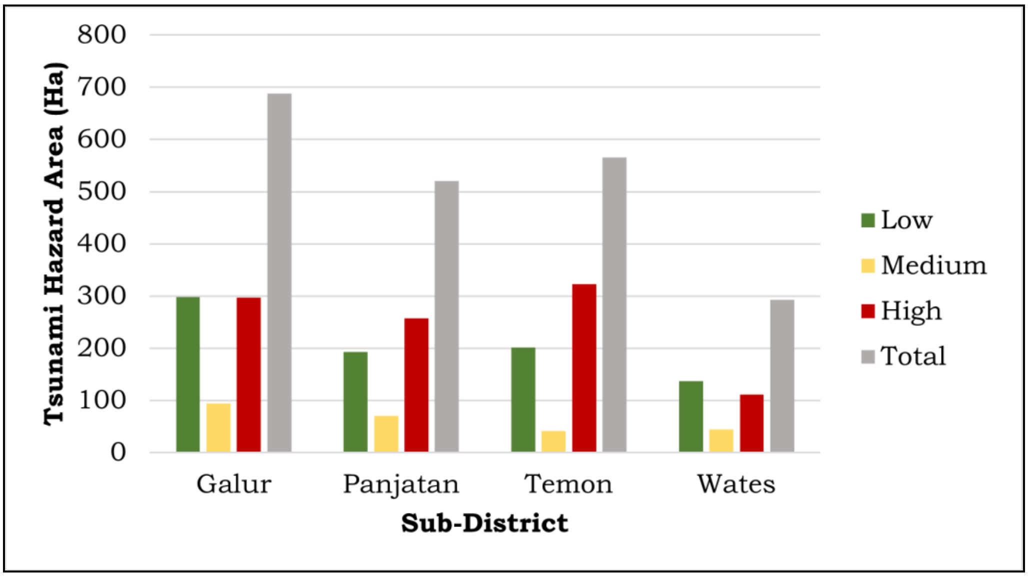

Figure 3-8: Tsunami hazard class area in Kulon Progo Regency with 5-meters scenario

The tsunami hazard map with 10 meters height scenario can be seen in Figure 3-9. The area of tsunami hazard class in Kulon Progo Regency with 10 meters tsunami height scenario can be seen in Figure 3-10. The hazard zone on the tsunami hazard map with 10 meters tsunami height scenario covers 4 sub-Sub-districts in Kulon Progo Regency, namely Galur, Panjatan, Temon, and Wates Sub-district. The hazard zone on the tsunami hazard map with 10 meters tsunami height scenario is getting wider. It is cover 26 villages. The wider area of potential tsunami hazard is caused by the low inundation resistance in the coastal area of Kulon Progo, where in the coastal area of Kulon Progo the slope is still flat and the coefficient of surface roughness tends to be low. Based on the scenario of a tsunami height of 10 meters, there is a low hazard zone of 466.641 Ha, a medium hazard zone of 1681.672 Ha, and a medium hazard zone of 3155.953 Ha. Several public facilities are included in the high-hazard zone, including Tanjung Adikarto Port and Yogyakarta International Airport.

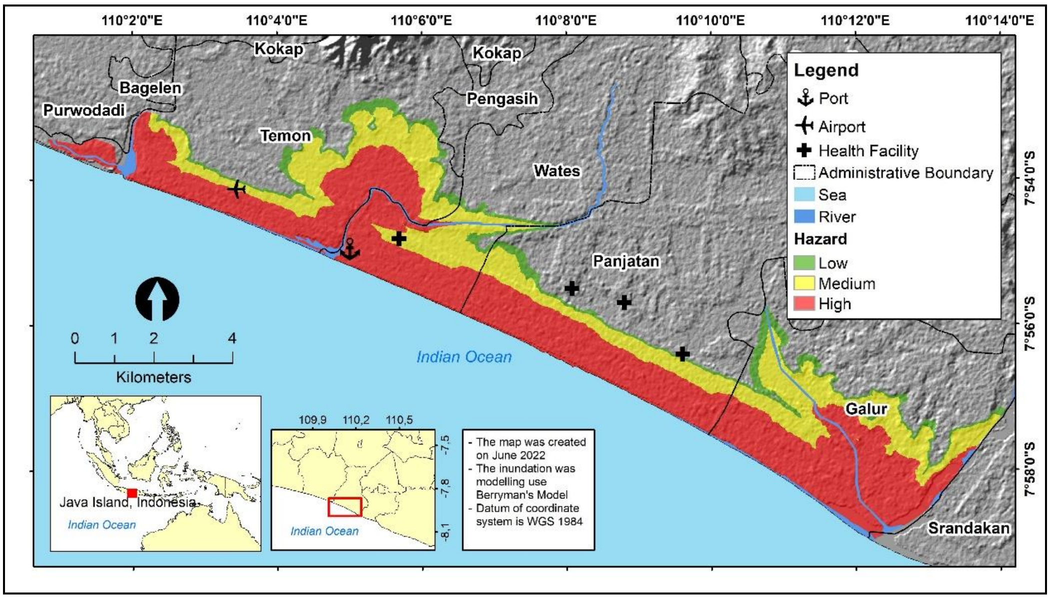

Figure 3-9: The tsunami hazard map with 10-meters scenario

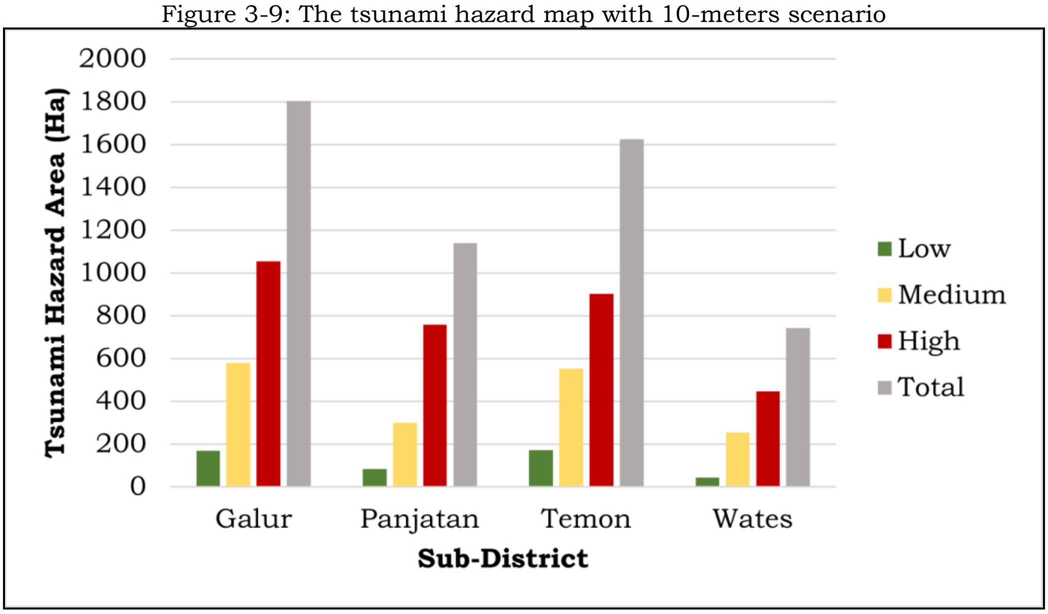

Figure 3-10: Tsunami hazard class area in Kulon Progo Regency with 10-meters scenario.

The results of the tsunami hazard modeling in this study has a pattern similar to the tsunami hazard map produced by German-Indonesian Cooperation for a Tsunami Early Warning System (2012) where the hazard zone covers Temon, Panjatan, Wates, and Galur sub-districts which there are areas that protrude to the north following the rivers. Rivers make it easier for water carried by tsunami waves to enter the land and cause further inundation so that the level of tsunami hazard becomes higher. The result of this study is similar to the research conducted by Surindar and Nurhadi (2021), which shows that the sub-district in Kulon Progo Regency that has the widest tsunami hazard zone is Galur Sub-district. Based on this research, the parameters used are more focused on community and government preparedness, while parameters related to terrain conditions, such as slope and surface roughness in disaster mitigation strategy also need further research.

4 CONCLUSIONS

Galur sub-district has the highest susceptibility among other sub-districts in the study area. Based on a tsunami height scenario of 5 meters, 21.8% of the Galur sub-district area is a hazard zone and based on a 10-meter scenario, 57% of the Galur sub-district area is a hazard zone. In this hazard zone, there are settlements in the villages of Karangsewu, Banaran, Tirtorahayu, Nomporejo, and Kranggan. Galur Sub-District also has tourist objects such as Trisik Beach, and other land uses include ponds, fields, paddy fields, shrubs, built-up areas, and sand.

Therefore, appropriate mitigation planning efforts must be designed both structurally and non-structurally to reduce the risks that can be caused. Mitigation efforts can be carried out by encouraging and educating people in the hazard zone area and planning appropriate evacuation routes. The results of this modeling can be used as a basis for planning evacuation routes, selecting evacuation route types (horizontal or vertical) and expanding the coverage area of the Early Warning System warning tower. However, this research still requires further improvement because the land use parameters still have low accuracy. In addition, this tsunami hazard modeling has not considered the time of the tsunami, the direction of the tsunami waves, and the strength of the tsunami waves in the modeling.

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