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Inundation Risk Level Tsunami in Trenggalek District, Indonesia

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Abstract - The southern coast of Trenggalek District is prone to tsunami disasters, because it is located north of the megathrust zone. This study aims to map the level of tsunami inundation risk in The Trenggalek District, especially on the coast of Watulimo Subdistrict. This mapping was done with the help of Model Builder in ArcGIS software, using scenarios of tsunami wave heights on the shore of 1 m, 2 m, 5 m, 15 m, 27 m, and 30 m. The risk map of tsunami inundation was obtained by combining the tsunami hazard map with the vulnerability map. The study results show that the area of tsunami inundation at a high-altitude scenario with wave heights of 1 m has low, medium, and high-risk levels covering 0.254 km², 0.240 km², and 0.032 km², respectively. In the 27 m scenario, which is the worst-case scenario according to Meteorology, Climatology, and Geophysics Agency (BMKG), the areas of inundation at low, medium, and high-risk levels reach 23.032 km², 16.471 km², and 7.904 km², respectively. In this 27 m scenario, four villages in Watulimo Subdistrict are almost entirely inundated by the tsunami. The results of this study are expected to be used as the material for tsunami disaster mitigation in the Trenggalek District.

Keywords: inundation, mapping, risk level, tsunami, Trenggalek

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Introduction

The southern coast of Java Island, Indonesia, is highly prone to earthquakes and tsunamis due to its proximity to the subduction zone between the Indo-Australian and Eurasian Plates. The Indian-Australian Plate is moving relatively north, while the Eurasian Plate is moving south (Caraka *et al.*, 2021; Felix *et al.*, 2022). Apart from these two plates, Indonesia is also influenced by other active plates, namely the Pacific Plate moving west and northwest, and the Philippine Sea Microplate moving northwestward. The complex geodynamics resulting from the interactions among these plates significantly increase the seismic instability, leading to earthquakes capable of generating tsunamis. The geodynamics of these three plates also cause downstream disasters such as landslides, liquefaction, and floods (Hutchings and Mooney, 2021; Suryani *et al.*, 2020). As a result of the geodynamics of these three plates, four regions in Indonesia have formed with sufficiently high seismicity. Due to this tectonic activity, four regions in Indonesia exhibit particularly high seismicity: the Sunda Arc (megathrust/ subduction zone), Banda Arc, Maluku Sea Collision Zone, and Papua Collision Zone (Housing, 2023). The southern coast of Java Island, including the southern beaches of Trenggalek District, lies within this vulnerable zone. Historically, three major tsunamis have occurred here, namely The Banyuwangi Tsunami in 1994, the Pangandaran Tsunami in 2006, and The Sunda Strait Tsunami in 2018 (Yusup *et al.*, 2023).

Tsunami disasters, though unforeseen, can be predicted to some extent, particularly in terms of their potential inundation areas, arrival times, and wave heights, when triggered by seismic activities such as large earthquakes. Therefore, emergency response and mitigation efforts based on these predictions are essential to effectively confront tsunami disasters (Jumadi *et al.*, 2025). Nonstructural mitigation that can be undertaken includes creating hazard maps, tsunami risk maps, and evacuation route maps. Education on tsunami mitigation is also vitally important for the population in these disaster-prone areas. Disaster mitigation efforts through the mapping of tsunami-prone areas have been extensively carried out, including creating a tsunami scenario in Pelabuhan Ratu in case of an M 8.8 earthquake along The Sunda Arc (Ar-Rouf *et al.*, 2022). If a megathrust earthquake occurs simultaneously throughout the south of Java, then the tsunami wave height at the shoreline could reach approximately 20 m on the south coast of West Java and 12 m on the south coast of East Java (Widiyantoro *et al.*, 2020). The average maximum heights along the southern coast of Java are about 4.5 m (Widiyantoro *et al.*, 2020).

Three subdistricts in Pandeglang District were the worst affected by the 2018 tsunami: Sumur, Panimbang, and Labuan Subdistricts. The tsunami waves reached heights of 1 to 6 m, with flood ranges extending up to 200 m from the beach edge (Daulat *et al.*, 2021). The 2018 tsunami also caused significant abrasion at Tanjung Lesung Beach in Banten Province, with abrasion reaching 18.89 m inland from the shoreline (Fuad *et al.*, 2022). The vulnerability level of the tsunami disaster on the southwest coast of Banten Province is also at a very high-risk level, reaching 19.94 km² (Anastasya *et al.*, 2023). In this province, tsunami-prone areas have also been mapped, especially in Ciwadan Subdistrict, Cilegon City, where 0.11 km² of its area is exposed to the tsunami at a low level, 3.05 km² at medium level, and 1.13 km² at high level (Khansa *et al.*, 2022). Mapping of tsunami-affected areas on the south coast of Yogyakarta has also been done using the ANN algorithm to map areas at risk of damage due to tsunamis on built-up land in Kulonprogo Subdistrict based on Building Indices Analysis. This study concludes that eighteen villages in this subdistrict are at high risk (Permatasari and Prasetyo, 2022). From Vegetation Index data in Landsat OLI.8 imagery, potential classification of areas likely to suffer land damage due to tsunamis in Bantul District has been conducted. The results show that seven villages in this district are at high risk (Isnaeni and Prasetyo, 2022). Tsunami vulnerability mapping has also been carried out in East Java Province, including through tsunami simulation on the coast of Banyuwangi in the event of an earthquake with a magnitude of Mw 7.0−8.5 (Putu *et al.*, n.d.). Tsunami modeling in Pacitan Subdistrict for a hypothetical megathrust earthquake in the East Java segment measuring Mw 8.7 showed the furthest inundation in Pacitan as far as 4.19 km north of Ranuharjo Beach. The maximum run-up height was 21.82 m at Soge Beach, Ngadirojo Subdistrict. The most extensive inundation occurred in Pacitan Subdistrict, covering an area of 21.63 km², and the smallest inundation occurred in Tulakan Subdistrict, covering an area of 0.33 km² (Putu *et al.*, n.d.). Modeling of estimated tsunami heights in Tanjung Benoa, Bali, has also been conducted. The estimated tsunami heights on the east side are around 10−14 m and on the west side around 3 −6 m, with an estimated tsunami arrival time of about 20‒25 minutes (Hanifa *et al.*, n.d.). Based on the information above, there is an identified knowledge gap regarding tsunami risk research in East Java. Previously published studies on tsunami risks have predominantly focused on the western regions such as Banten, West Java, and parts of Yogyakarta. In contrast, research on tsunami risk in East Java remains limited, primarily concentrated in certain areas such as Banyuwangi and Pacitan. Existing publications have not comprehensively addressed other coastal regions in East Java that also possess a high potential tsunami risk. Therefore, further studies are required to fill this research gap. This study aims to map the tsunami inundation risk levels in Watulimo Subdistrict, Trenggalek District, East Java Province, as an effort to complement and enrich the existing knowledge concerning tsunami disaster risks in this region.

Method

Tsunami inundation mapping along the southern coast of Watulimo Subdistrict, Trenggalek District, was created based on inputs from a tsunami hazard map and its corresponding vulnerability map. Hazard maps were generated using ArcGIS 10.8 software, with input parameters including slope, surface roughness coefficient, coastline, and various tsunami wave height scenarios that reach the shore. The slope map was derived from the DEM SRTM 1 Arc-Second global and was processed to calculate slope on the raster surface via the 3D Analyst Tools in the Arctoolbox menu. The surface roughness coefficient map was obtained by entering roughness values in the land cover map attributes, which were then rasterized using the conversion tools in the ArcToolbox within the ArcGIS application. The roughness coefficient used refers to the table of coefficients from Berryman (Berryman, 2005). Shoreline parameters were obtained from topographic maps, specifically the land cover map of Trenggalek District at a 1:25,000 scale. The tsunami wave height scenarios used at the shoreline are based on the Imamura-Iida intensity scale, including heights of 1 m, 2 m, 5 m, 15 m, 30 m, and the worst-case wave height estimate from BMKG at 27 m.

Based on these parameters, the next step involves modelling the tsunami inundation danger as developed by McSaveney and Rattenbury. This tsunami inundation modeling was done using the distance function in ArcGIS software. This function estimates the reduction in tsunami inundation height from the run-up source, starting from the coastline and extending inland. To model this tsunami inundation, the following equation was used (Berryman, K., 2005):

$$H_{loss} = \frac{167\, n^2}{\left(H_o^{1/3}\right)} + 5 \sin S \quad \text{.............................(1)}$$

where:

H loss = Loss of tsunami height per 1 m inundation distance (m)

n = Coefficient of roughness

H o = Tsunami height at the coastline (m)

S = Slope (°)

A tsunami vulnerability map was created from a land cover map. This land cover map represents the physical appearance of the earth's surface, including vegetation, rocks, soil, flooded areas, rivers, natural objects, and cultural features. From this land cover map, an assessment of the map attributes was performed and then classified.

In creating the tsunami flood risk level map, two main variables were used. Vulnerability variables are derived from land cover data, while hazard variables come from tsunami inundation modeling. The inundation modeling is based on tsunami wave height scenarios at the shoreline. To determine the level of tsunami flood risk, the Crunch Model equation is employed (Calderón *et al.*, 1996):

$$R = H \times V \quad \text{..(2)}$$

where:

R = risk index

H = hazard index

V = vulnerability index

Result and Discussion

Tsunami Vulnerability

Watulimo Subdistrict in Trenggalek District is predominantly covered by forests, spanning an area of 129.419 km², followed by settlements covering 16.259 km², agricultural land of 3.694 km², shrubs of 2.874 km², water bodies of 1.781 km², plantations of 1.549 km², vacant land/open land of 0.107 km², and mangrove forests of 0.001 km². Figure 1 displays the land cover map of Watulimo Subdistrict.

To create a map of tsunami vulnerability, scores of 1, 2, 3, and 4 were assigned to each type of land cover. This scoring is based on the influence of each land cover type on the economic activities of the community (Wood and Good, 2004). Land cover classes that have a high influence on economic activities are given a higher score, indicating greater vulnerability, and vice-versa. Figure 2 displays the vulnerability map where the highest score (value 4) is assigned to residential areas and built-up land. A score of 3 is assigned to plantation and agricultural lands, which are the livelihoods of most people in Watulimo Subdistrict. Forest areas, mangrove forests, and bushes/shrubs receive the score of 2. The lowest score, 1, is assigned to water bodies, rivers, and open or vacant lands.

Tsunami Risk

To map the risk level of tsunami inundation, inputs from hazard and vulnerability maps were used. Based on Equation 2, the values from the danger and vulnerability variables were multiplied using the raster calculator feature in ArcGIS software. The determination of tsunami inundation risk levels uses three classes: low, medium, and high risk. Research results show that the extent of tsunami inundation in The Watulimo Subdistrict, under the tsunami wave height scenario of 1 m on the coast, reaches 0.254 km² at a low risk level. At a moderate risk level, the area reaches 0.240 km², and at a high risk level, it is

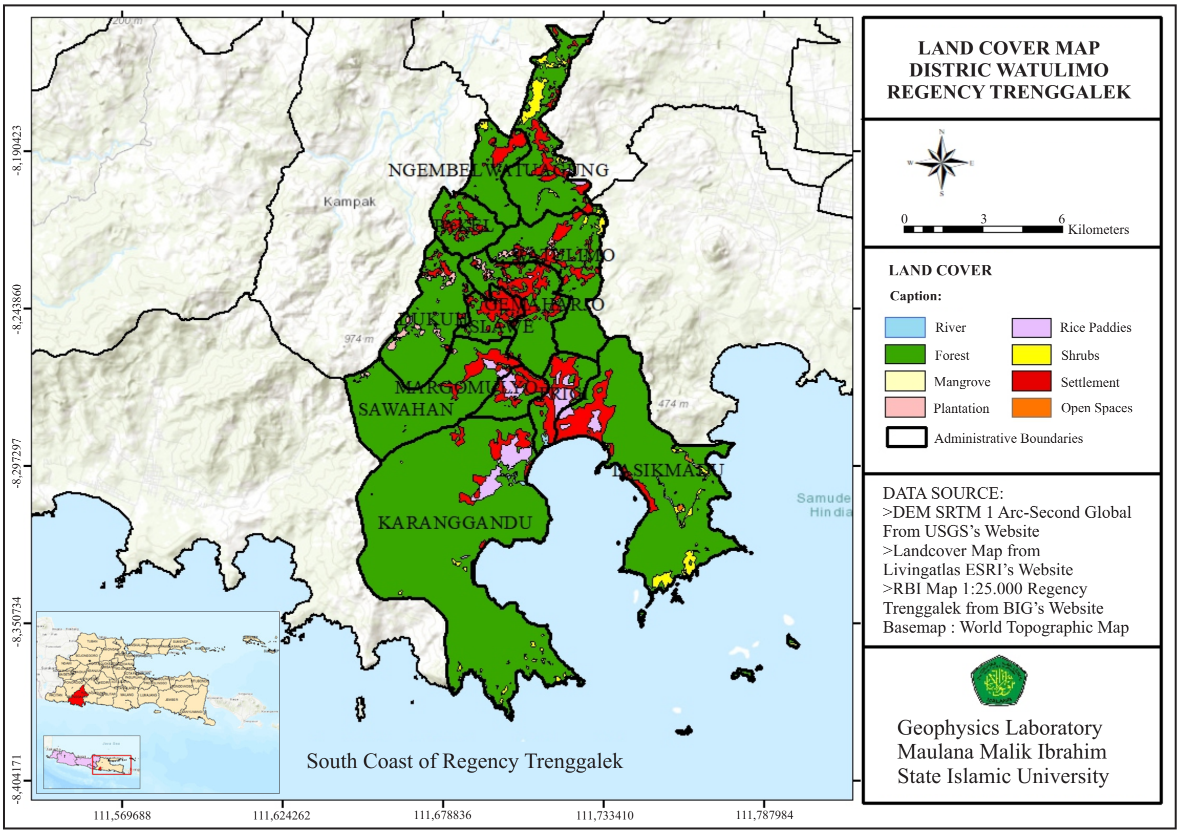

Figure 1. Land cover map.

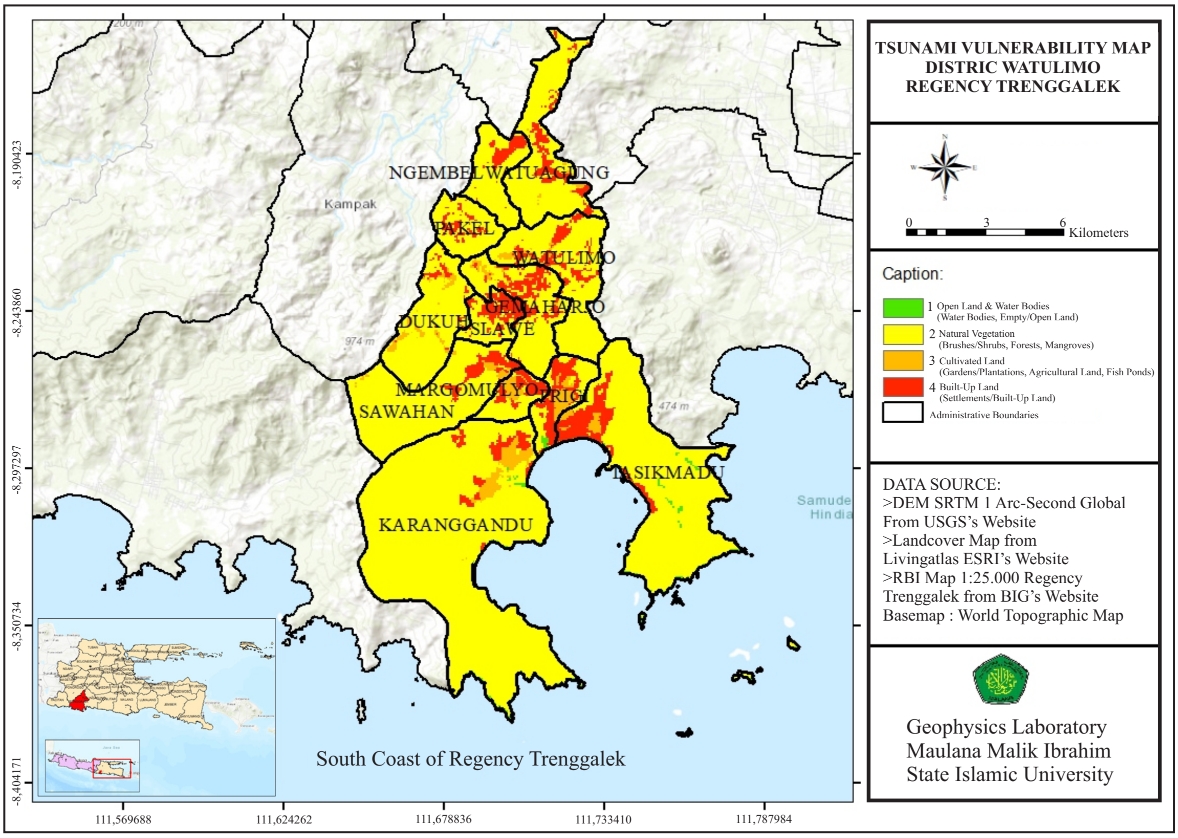

Figure 2. Tsunami vulnerability map.

0.032 km². In this scenario, the area affected by the tsunami is still located around the coast in Karanggandu, Prigi, and Tasikmadu Villages. Only a few residential areas and built-up land in these three villages are affected by the tsunami. Figure 3 displays a tsunami inundation risk map for The Watulimo Subdistrict with wave heights of 1 m.

Figure 4 displays the tsunami inundation risk map for a tsunami wave height scenario of 2 m along the coastline. The area affected at a low risk level reaches 0.279 km², at a medium risk level it is 0.265 km², and at a high risk level, it is 0.069 km². In this scenario, the area affected by the tsunami inundation impacts three villages, similar to the scenario with a wave height of 1 m. The areas affected by tsunami inundation in residential areas and built-up land in these three villages have begun to expand.

The flood risk map for a tsunami with a wave height scenario of 5 m is shown in Figure 5. At low risk levels, the inundated area covers 3.769 km². At medium and high-risk levels, the respective inundated areas cover 1.325 km² and 0.467 km². In this scenario, three villages are affected at a high-risk level, namely Karanggandu, Prigi, and Tasikmadu Villages. In Karanggandu Village, the affected areas include forests, agricultural land, plantations, bushes, and mangrove forests. The area of residential zones affected by the tsunami inundation in this village reached 0.179 km² or 13 % of the total residential area. In Prigi and Tasikmadu Villages, the sizes of each inundation area are around 11 % and 28 % of the settlement areas, respectively. In Tasikmadu Village, high risk levels also impact forest areas, agricultural land, and plantations.

The number of villages affected by tsunami inundation in Watulimo Subdistrict increases by one when the tsunami wave height scenario reaches 15 m, specifically in Margomulyo Village. Figure 6 shows the map of tsunami inundation where the area affected at a low risk level reaches 12.072 km², at a medium risk level it is 9.290 km², and at a high risk level, it is 3.104 km². Three villages

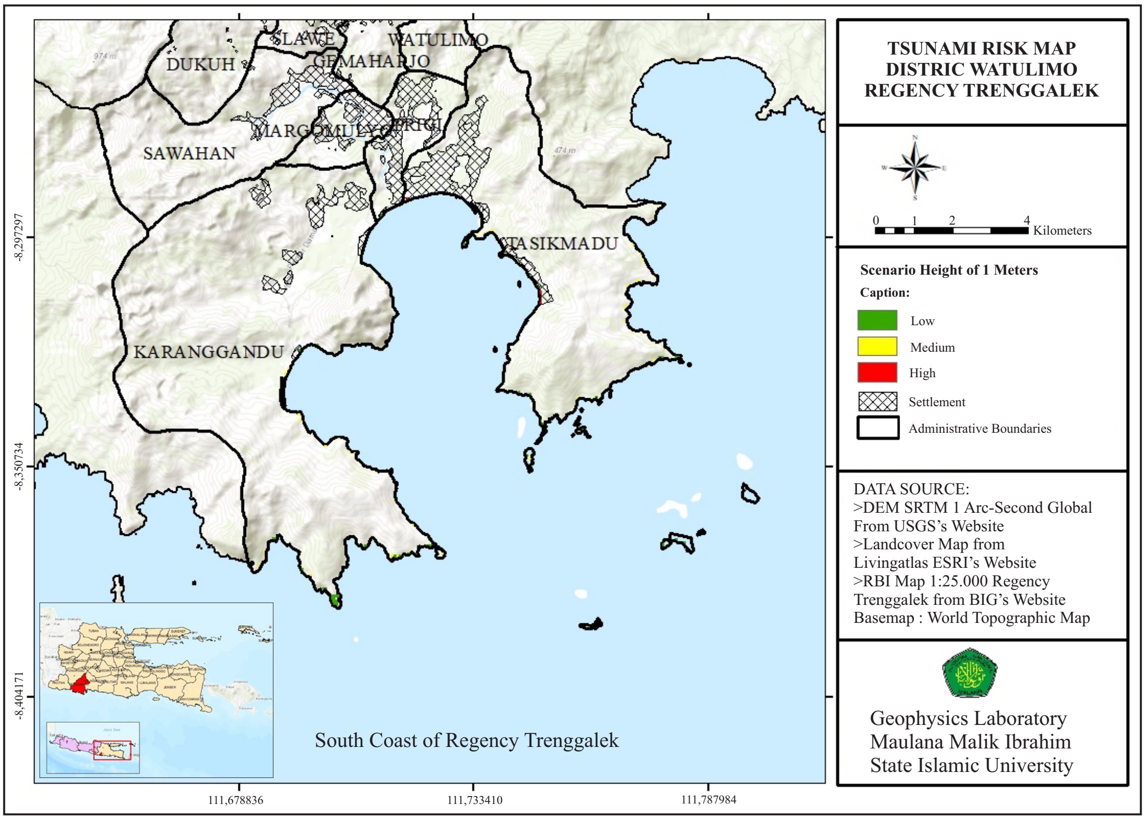

Figure 3. Tsunami inundation map in 1m height scenario.

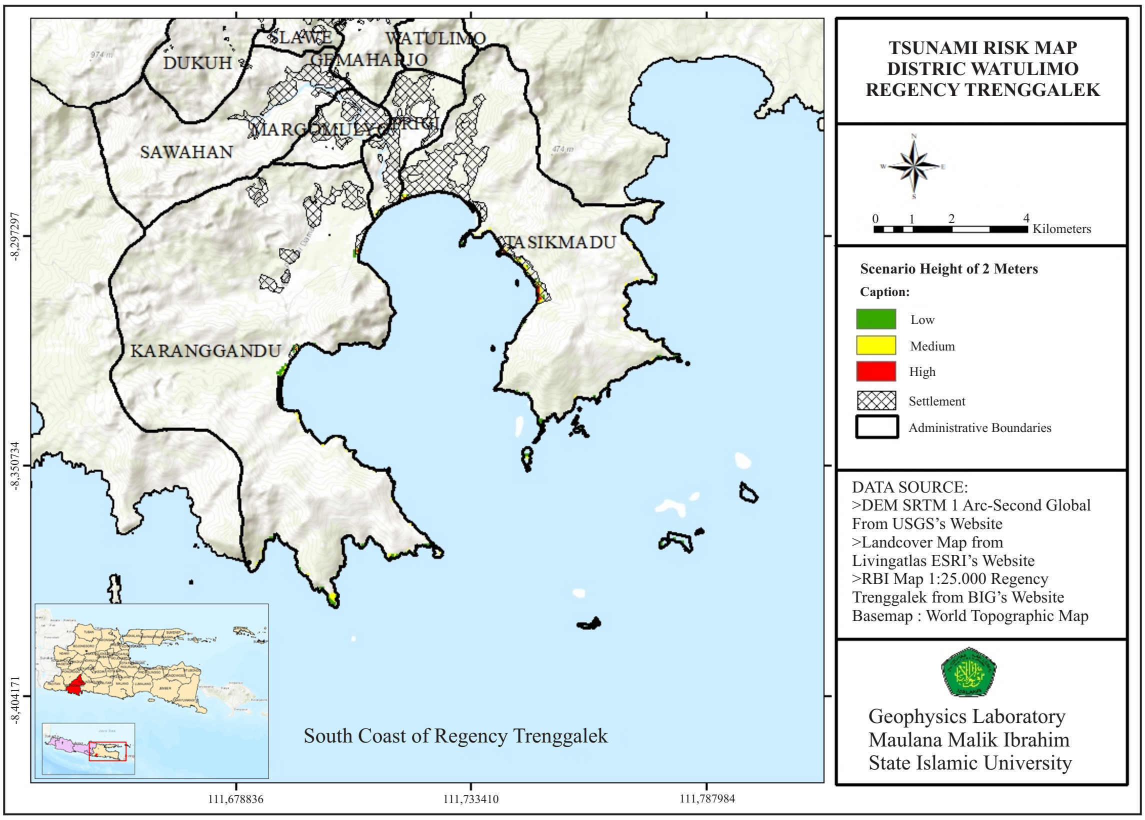

Figure 4. Tsunami inundation map in 2 m height scenario.

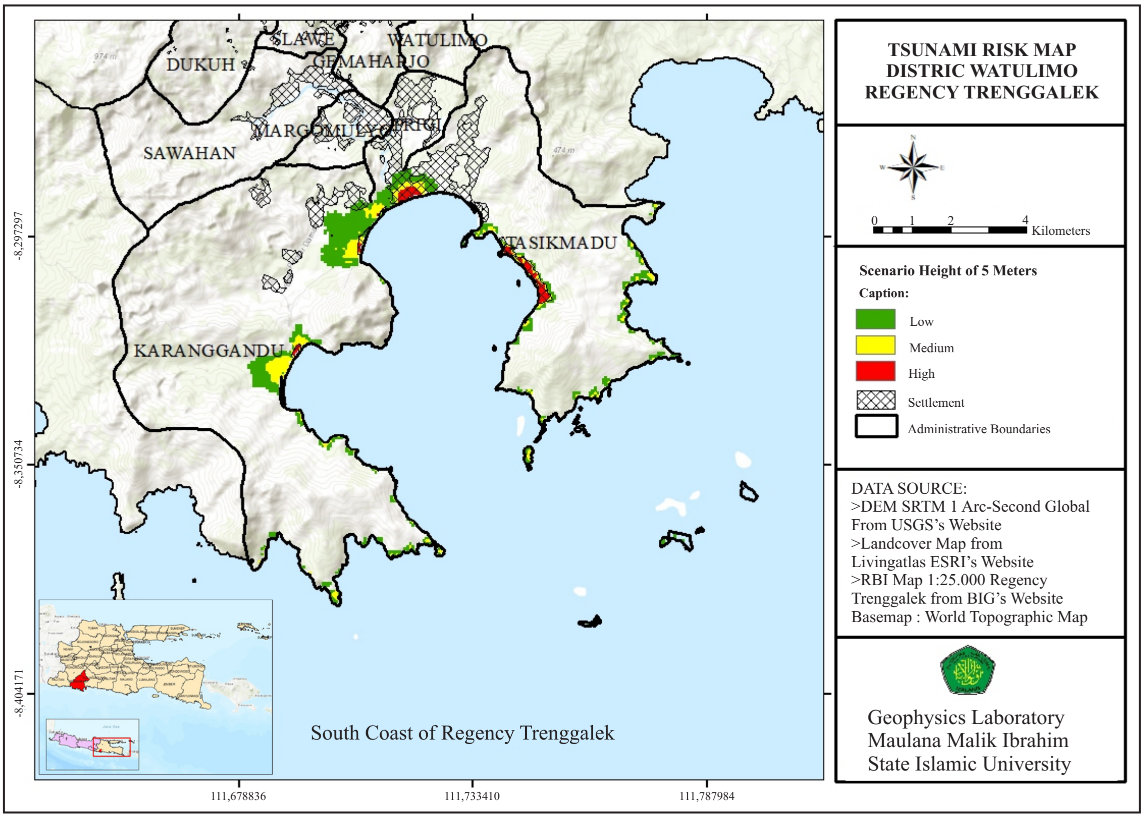

Figure 5. Tsunami inundation map in 5 m height scenario.

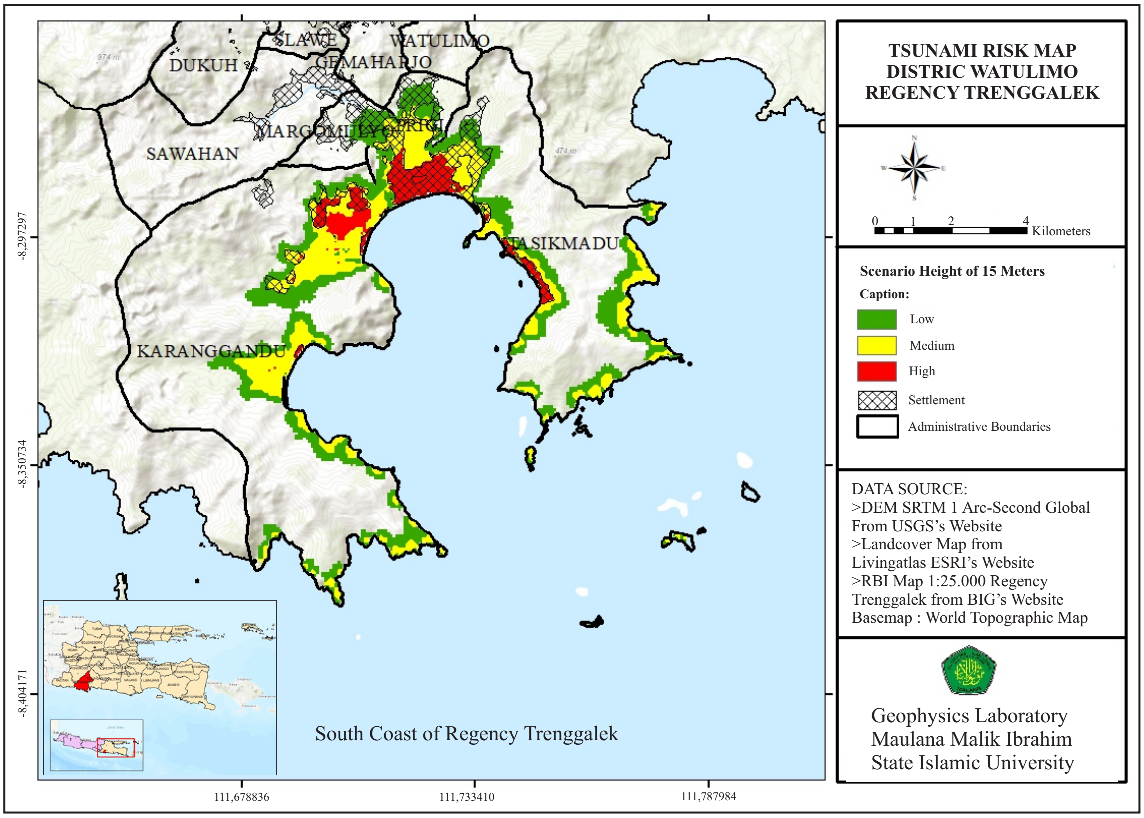

Figure 6. Tsunami inundation map in 15 m height scenario.

are affected at a high risk level in this scenario: Karanggandu, Prigi, and Tasikmadu Villages. In Margomulyo Village, the risk level ranges from low to currently unknown.

The area of residential zones affected by tsunami inundation at a high risk level in Karanggandu Village reaches 0.559 km², which is more than 40 % of its residential area. The tsunami also inundated forests, agricultural land, plantations, shrubs, and mangrove forests. In Prigi Village, the areas affected by tsunami inundation are almost the same as in Karanggandu Village, except that the area of residential zones affected is slightly more, around 0.431 km² or 24 % of the settlement area. Tsunami inundation in the residential area of Tasikmadu Village has expanded to cover 50 % of the settlement, approximately 1.329 km². Although Margomulyo Village was indeed affected by the tsunami in this scenario, the risk level remains low to date due to the village considerable distance from the beach.

The tsunami inundation map for the 27 m height scenario, which is the worst-case scenario from BMKG, is shown in Figure 7. This figure indicates an area with a low risk of flooding covering 23.032 km², medium risk covering 16.471 km², and high risk covering 7.904 km². In this scenario, 1.051 km² or about 78 % of the settlement area in Karangandu Village is inundated by the tsunami. In Prigi Village, the tsunami inundation in residential areas is almost the same as in Karanganyar, namely 79 % or approximately 1.352 km². The area of tsunami inundation in Tasikmadu Village is wider than the previous two villages, reaching 88 % or around 2.326 km². In these three villages, the tsunami also inundated forests, agricultural lands, plantations, and bushes. From the percentage size of residential areas affected by tsunami inundation in these three villages, it can be said that almost all settlements are at a high risk level in this scenario. In Margomulyo Village, the tsunami

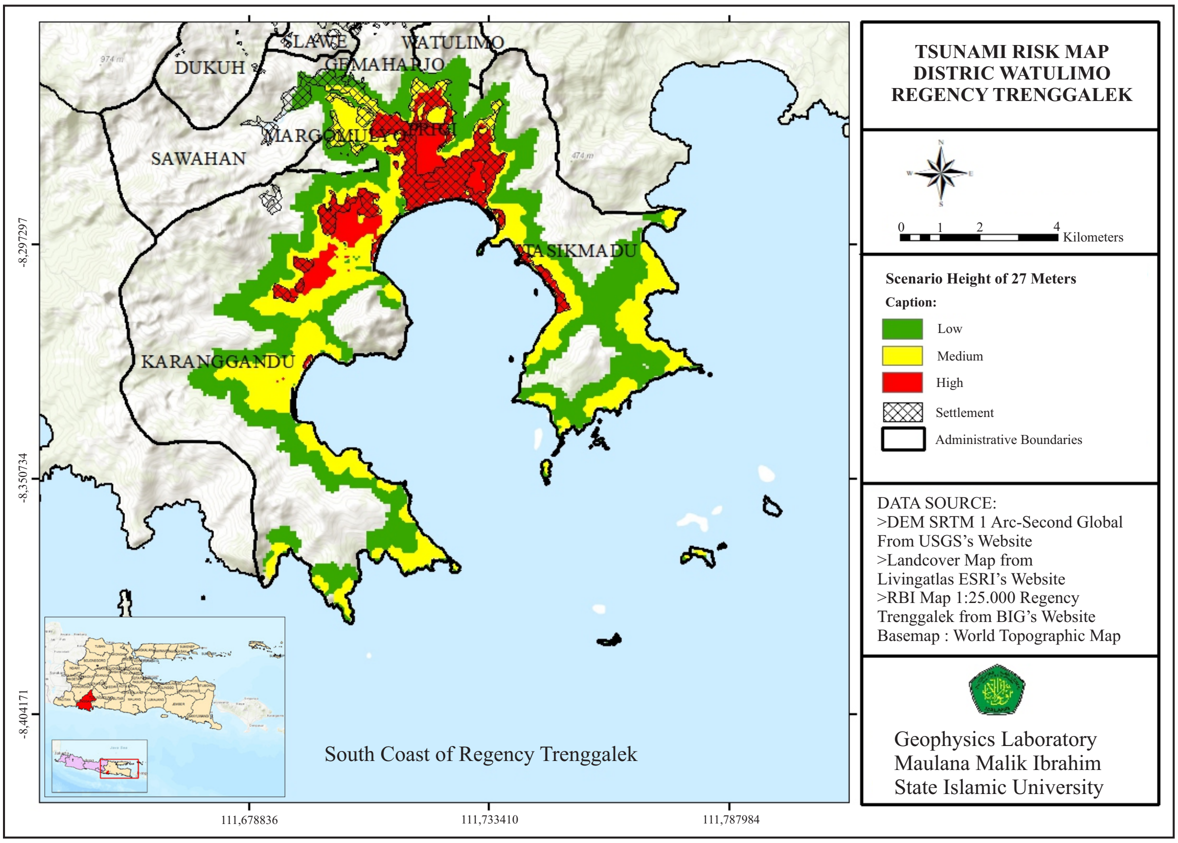

Figure 7. Tsunami inundation map in 27 m height scenario.

only flooded one-third of the residential area, or approximately 0.394 km².

The high risk level of flooding in the three villages mentioned above is due to the lack of tsunami barriers and their low slopes. Three other villages in the subdistrict of Watulimo, namely Gemaharjo, Sawahan, and Watulimo, were not affected by tsunami inundation due to their high slope levels and their land cover of forests, which are capable of withstanding tsunami waves. Residential areas and built-up land in these three villages were also unaffected due to their relatively far distance from the beach.

The tsunami inundation map with a wave height of 30 m is shown in Figure 8. The affected areas at a low risk level cover 24.957 km², while medium risk covers 18.761 km², and high risk covers 8.454 km². In Karanggandu Village, the residential area covering 1.137 km² or 84 % was inundated by the tsunami. The village with the most severe tsunami impact in this scenario is Margomulyo Village. Besides forests, agricultural land, scrubs, plantations, and the entire residential area of 1.056 km² was inundated by the tsunami.

The worst impact of the tsunami in the villages of Karanggandu, Prigi, Margomulyo, and Tasikmadu is attributed to the absence of a tsunami barrier and the low slope level in the area. Gemaharjo, Sawahan, and Watulimo Villages are not at high risk due to their high slopes and the forest cover that can withstand the waves. Settlements and built-up land in these three villages were not affected by tsunami inundation, because they are sufficiently far from the beach.

From all the tsunami inundation risk level maps shown above, it can be said that vulnerability significantly affects the level of risk. For example, for a scenario with a wave height of 5 m on the coast, the hazard map in Figure 9 shows no areas of tsunami inundation at a high level , but the risk map shows an area affected by inunda-

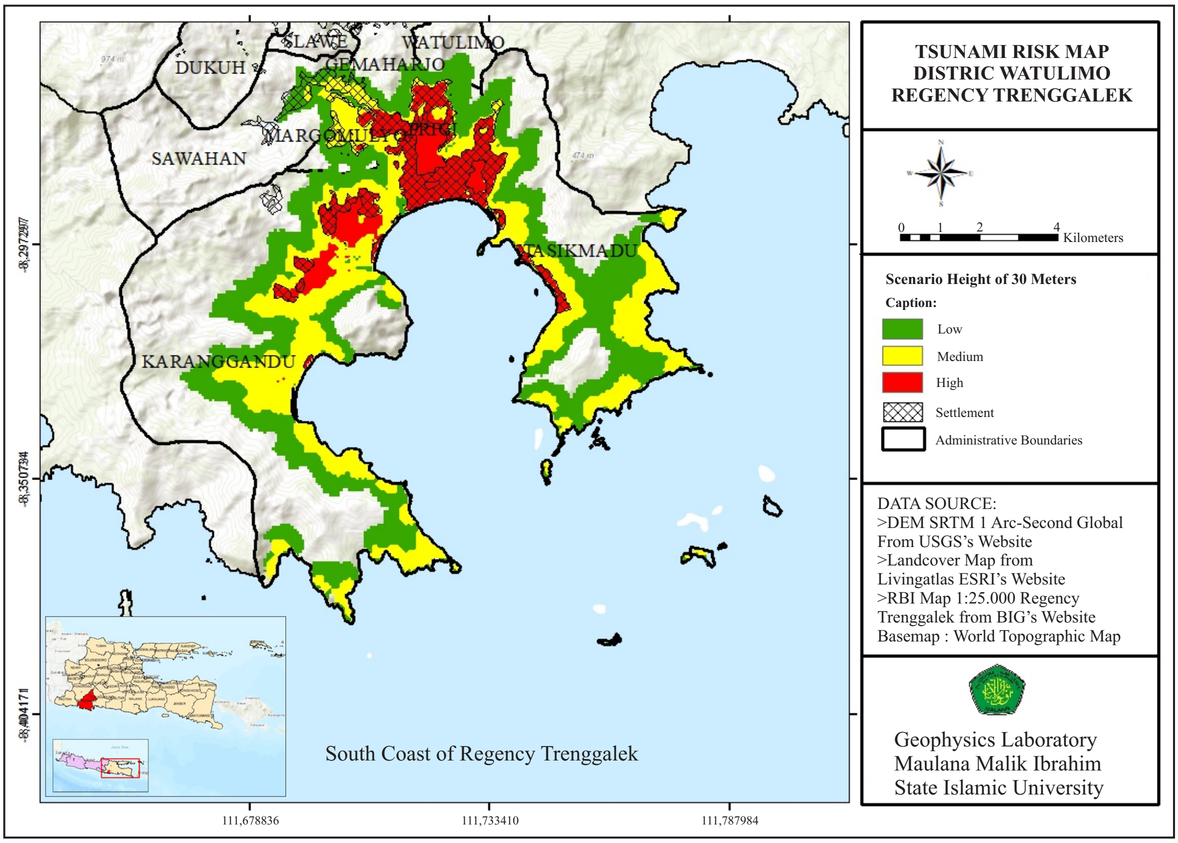

Figure 8. Tsunami inundation map in 30 m height scenario.

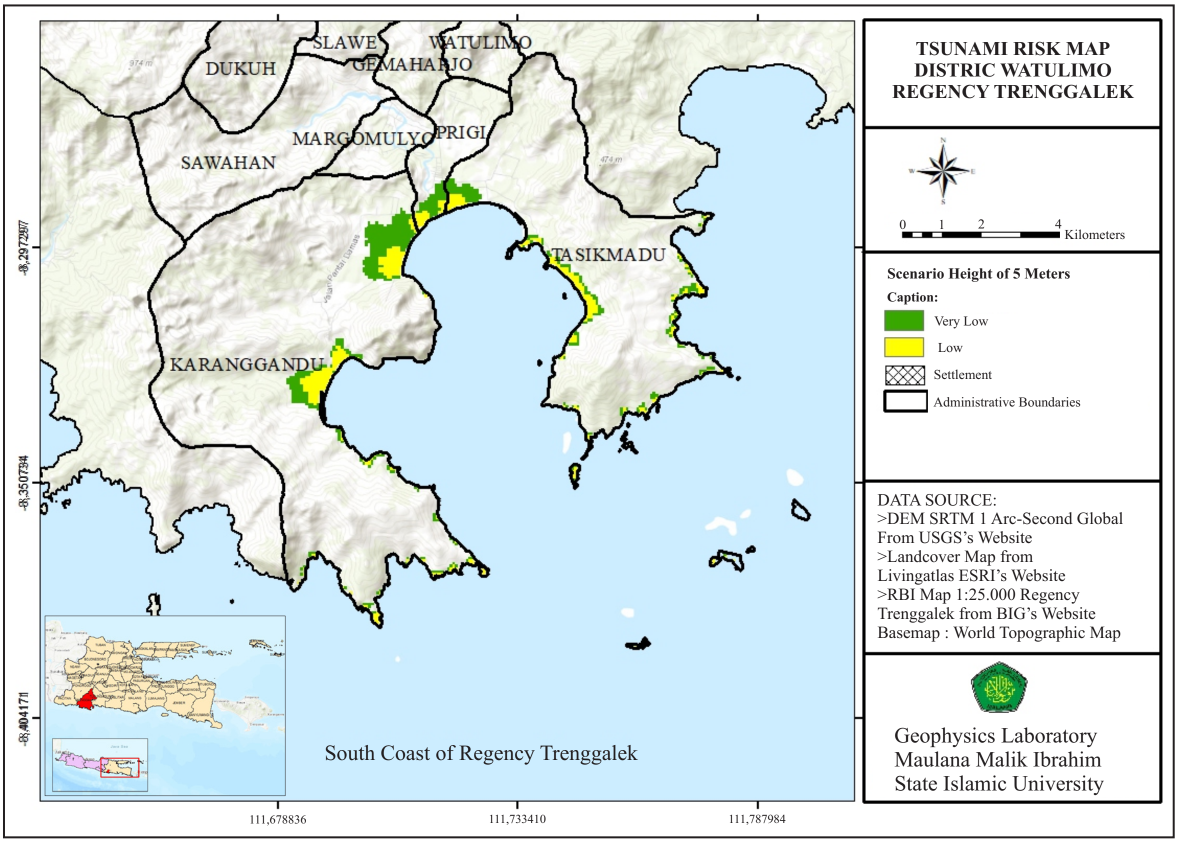

Figure 9. Tsunami Hazard Map for 5 m Height Scenario.

tion with a high risk of 0.467 km². Conversely, in the 15 m scenario, while the area affected by inundation on the hazard map is at a high level, it decreases on the risk map. In this scenario, the area affected by the tsunami at a high level is 15.330 km² on the hazard map, decreasing to 3.104 km² on the risk map. Similarly, for the 27 m and 30 m wave height scenarios, the area affected by the tsunami at a high level experiences a decrease in its inundation area from the hazard map to the risk map.

Where there is a low level of danger or risk, the affected area actually increases from the hazard map to the risk map. For example, in the 15 m wave height scenario, the area of the affected zone increases from 3.583 km² on the hazard map to 12.072 km² on the risk map. Similarly, for the 27 m and 30 m wave height scenarios, the area of the tsunami-affected zone increases at a low level from the hazard map to the risk map. However, the total area affected by tsunami inundation shows almost no change. For instance, in the 15 m wave height scenario, the area of tsunami inundation on the hazard map reaches 24.439 km², and on the risk map the area of flooding is almost the same, namely 24.466 km². Likewise, for the other scenarios, there is almost no change in the total area affected by the tsunami.

Conclusions

In conclusion, Watulimo Subdistrict, Trenggalek District, if the tsunami wave height at the shoreline is 1 m, the areas at low, medium, and high-risk reach 0.254 km², 0.240 km², and 0.032 km², respectively. In this scenario, tsunami inundation has not yet reached on residential areas. In the scenario with a 2 m wave height, areas affected by tsunami inundation at low, medium, and high-risk levels respectively reach 0.279 km², 0.265 km², and 0.069 km². In this scenario, tsunami inundation begins to encroach on residential areas. In the 5 m and 15 m scenarios, the residential areas affected by the tsunami inundation expand, affecting four villages instead of three. In the worst-case scenario from BMKG, with a 27 m wave, the flooded areas at low, medium, and high-risk levels reach 23.032 km², 16.471 km², and 7.904 km², respectively. In this scenario, four villages in Watulimo Subdistrict are almost entirely inundated by the tsunami, namely Karanggandu, Prigi, Tasikmadu, and Margomulyo. In Watulimo Subdistrict, there are three villages not affected by tsunami flooding, namely Gemaharjo, Sawahan, and Watulimo.

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