Coastal Hazard Modeling in Indonesia Small Island: Case Study of Ternate Island

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Abstract. Indonesia's small islands have a high potential for multi coastal hazards, including tsunami and coastal floods due to sea-level rise and tidal waves. Meanwhile, most small island populations live in coastal areas, which increases the potential for disaster risk. Hazard assessment is one of the essential stages and bases in disaster management. This study focuses on tsunami and coastal flood hazards modeling in Ternate Island and analyzing the potential impact on coastal land use. This research combined detailed remote sensing data and geographic information system methods to assess the coastal hazard models. A very detailed resolution remote sensing imagery of Pleiades and detail resolution imagery of SPOT 7 are used as input for physical parameter extraction. DEMNAS (Digital Elevation Models Nasional) data as a topographic parameter is used in potential tsunami and coastal flood hazard area coverage. A numerical model is applied to assess the tsunami hazard model using surface roughness, slope, and run-up scenarios based on historical data. At the same time, the coastal flood model integrates sea level rise parameters and average tidal waves. The research results are believed to contribute as important input data for disaster management based on the sister island concept in Indonesia.

1. Introduction

Indonesia is located on the unstable subduction zone of three major active tectonic plates. They are the south-eastward moving Eurasia plate, the northward moving Indo-Australia plate, and the westward-moving Pacific plate [1]. They meet as a subduction zone under the ocean which has high seismic activity, thus generating a tsunami. Parallel to the subduction zone, more than 400 volcanoes formed, of which 130 of them are active volcanoes [2]. This geological process induces Indonesia as the largest archipelagic country in the world [3], with 17,395 islands and 108,000 km coastal length [4,5].
Coastal areas and small islands in unsafe zones like Indonesia are highly exposed to tsunamis due to earthquakes and volcanism [6,7]. In addition to earthquakes and volcanism, Indonesia's coastal areas and small islands are also highly vulnerable to climate change. Future climate change causes changes in sea level, waves, storms, and river flows that vary and experience an increasing trend every year [8–10]. Based on tide gauges and altimetry observations, sea-level rise increased from 1 mm/year during the period 1901-1990 to 2.1 mm/year during the period 1970-2015 and continued to increase to 3.6 mm/year during the period 2006-2015 [11,12]. In Indonesia's ocean, the mean sea level rises from 3.5 mm/year to 6 mm/year, as shown in Figure 1.

Consequently, most coastal lowlands and small islands are threatened with permanent inundation in the future. Furthermore, sea-level rise affects seawater's tidal amplitude, causing more damage during storms, waves of coastal erosion, seawater intrusion, and others [13–16]. This coastal hazard affects the livelihood of coastal communities, including causing infrastructures damage, agriculture and fisheries losses, as well as environmental health problems [17].

![Figure 1. Mean Sea Level Trend in Indonesian Ocean from January 1993 to December 2020. Source: Aviso Satellite Altimetry Data, 2020](image)

Based on the environmental risk outlook 2020 analyzed by Clisby and Nichols [13], 15 cities worldwide are at risk of drowning. Jakarta is the riskiest city from a combination of pollution, dwindling water supplies, extreme heat stress, natural hazard, and vulnerability to climate change [18]. As a central government and economic activity, Jakarta has rapid infrastructures and population growth [17,19,20]. Coastal areas have rich resources and good accessibility, making them attractive to be developed as urban areas. In addition to Jakarta, many large and small cities have developed in coastal areas and small islands, such as Tanjung Balai, Semarang, Pekalongan, Surabaya, Balikpapan, Manado, and Ternate.

Ternate is one of the cities developed on a small island. Like other small islands, urban areas with government functions and socio-economic infrastructure development along the coast. The coastal city of Ternate is located on the middle slope of Gamalama volcano with a distance of less than 6 km from the main crater. This condition causes the city of Ternate to have multiple hazards, both coastal hazards (sea-level rise, coastal erosion, coastal flood, tsunami) and volcanic eruption. A small island with a multi-hazard has a limited area that needs exceptional disaster management. The sister island concept can be one of the strategies to be applied in disaster management on small islands, primarily to provide evacuation places in an emergency. Sister island is a network system built between the community and government on a disaster-prone island with a safe surrounding island to prepare for an organized evacuation procedure [21]. Hazard should be comprehensively assessed as one of the main documents for sister island. This paper focuses on tsunami and coastal flood hazards modeling in Ternate Island and analyzing the potential impact on coastal land use as the initial step in disaster management and policy-making in Ternate City.
2. Research Location, Data, and Method

2.1. Study Area

Ternate Island is located in eastern Indonesia, precisely in North Maluku. Administratively, the island of Ternate is a territorial unit with the name Ternate City (Figure 2). Ternate Island is divided into five districts areas, including Ternate Island, North Ternate, West Ternate, Central Ternate, and South Ternate, with a total population of 194,477 inhabitants (Table 1) in 2020. Most of the settlements concentrated in the eastern and southern coastal areas at North Ternate, Central Ternate, dan South Ternate district. The management of Ternate has developed, one of which is marked by the increase in administrative areas from 7 to 8 districts in 2016, namely West Ternate district, which is an expansion of Pulau Ternate district.

Figure 2. Ternate Island and its location in the North Maluku Province, Indonesia

![Figure 2. Ternate Island and its location in the North Maluku Province, Indonesia](image)

Table 1. Population in Ternate by District

| No. | District             | Total Population |
|-----|----------------------|------------------|
|     |                      | 2016  | 2017  | 2018  | 2019  | 2020  |
| 1   | Pulau Ternate        | 16,892| 17,233| 8,720 | N/A   | 8,735 |
| 2   | West Ternate         | -     | -     | 9,326 | N/A   | 8,788 |
| 3   | South Ternate        | 75,019| 76,794| 78,300| N/A   | 74,329|
| 4   | Central Ternate      | 61,893| 63,385| 63,960| N/A   | 53,643|
| 5   | North Ternate        | 53,341| 54,561| 55,981| N/A   | 48,982|
| 6   | Moti                 | 5,001 | 5,094 | 5,404 | N/A   | 4,811 |
| 7   | Batang Dua Island    | 2,812 | 2,861 | 3,055 | N/A   | 2,791 |
| 8   | Pulau Hiri           | 3,124 | 3,183 | 3,359 | N/A   | 2,922 |
|     | Total                | 218,082| 223,111| 228,105| 233,208| 205,001|

Source: BPS-Statistics Indonesia, 2021

Ternate is a small island with the specific characteristics of a volcanic island, a small population (compared to the main island, Halmahera Island), and limited resources and accessibility. This condition makes this area require different development management. Rijanta [22] describes several factors that hinder development in small islands: small economic scale, physical and social isolation, out-migration and population dynamics, limited opportunities, limited availability of clean water for large-scale economic activities, a strong influence on the economic season, vulnerability to disasters, and conflicts between service requirements and population thresholds. The vulnerability to disasters is
an important aspect, considering that Ternate has the highest social risk and vulnerability index among the islands in North Maluku Province [23].

2.2. Tsunami modeling

A numerical model was applied in tsunami inundation modeling using slope, surface roughness, and wave height simulation. Slope data were derived from the extraction of national digital elevation model (DEMAS) data produced by the National Geospatial Agency (BIG) (Figure 3a). The slope parameter performs as a reducer of the incoming tsunami waves to the mainland. In this research, the slope is made in degrees which are then converted into radians.

Surface roughness data were created by extracting detailed scale land use maps from very high and high spatial resolution imagery interpretation and converting each polygon into a grid/raster dataset (Figure 3b). In this case, SPOT 7 (2019-2020) and Pleiades (2020) were used as primary data on land use mapping. The assumption used in the surface roughness parameter is that the roughness of land cover affects the propagation of tsunami waves. The rougher the surface, assume the more it can dampen tsunami waves, while the smoother the land cover, the lower the damping power against tsunami waves. Conversion from land use attribute to roughness coefficient refers to Table 2. Wave height value was adopted from historical tsunami data [24] where recorded maximum water height of 10 meters in 1859 tsunami triggered by seven magnitudes earthquake close to Ternate Island and minimum water height as 1.2 meters in 1846. Besides, this model also considers predicted maximum tsunami height at the cost for 100- and 500-year return period in Ternate City with 3 meters and 12.3 meters, respectively.

Figure 3. Slope parameter derived from DEMNAS elevation data (a) and roughness index extracted from land use map (b)
3. Built-up areas, areas covered with scattered highstand vegetations, beach, beach ridge-swale complex 0.035
4. Forests, jungle, rough lava flows, saltmarsh, cliffs 0.070

Source: Hills and Mader (2007) in Bryant (2008); Kotani (1998) in Latief dan Hadi (2007)

In this research, a numerical model for tsunami inundation adopt equation modified by McSaveney and Rattenbury (2000) as expressed

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

where \( H_{loss} \) is the wave height loss per meter of inundation distance, \( H_0 \) refers to the wave height value at the coast, \( n \) is the surface roughness coefficient, and \( S \) refers to the slope. In this model, Hloss data roles as tsunami attenuation factor, which is used as data input in cost-distance analysis in ArcGIS. Cost distance analysis determines the least cumulative cost to travel over a cost surface from the shoreline.

2.3. Coastal flood modeling

The coastal flood modeling in this research combines two phenomena such as tidal waves and sea-level rise (SLR). The tides data downloaded from the Geospatial Information Agency website, tides.big.go.id, for over the last three years data (range from 2019 to 2021). The ERGTIDE application processed the data to calculate average data, such as the highest and lowest water spring. Sea-level rise in raster format data is obtained from Aviso Satellite Altimetry Data (https://www.aviso.altimetry.fr/) in Figure 18. Based on multi-mission sea level trends data, the trend of sea-level rise in Ternate Island in 1993-2019 is estimated to be 4.48 mm/year or 0.0045 m/year. The highest water spring and sea-level rise are combined to predict coastal floods during the predicted year. A simple method in GIS, DEM slicing, was used to generate the tidal value flood in 2050, 2075, and 2100.

**Figure 4.** 3-year tidal data processing into the highest and average tidal values using ERGTIDE

| No. | Land use/land cover                                                                 | Surface roughness coefficient (n) |
|-----|------------------------------------------------------------------------------------|----------------------------------|
| 1.  | Open field without crops, mudflat, ice, coastal plain, swamp/back swamp, floodplain, alluvial plain | 0.015                            |
| 2.  | Rice fields                                                                        | 0.020                            |
| 3.  | Built-up areas, areas covered with scattered highstand vegetations, beach, beach ridge-swale complex | 0.035                            |
| 4.  | Forests, jungle, rough lava flows, saltmarsh, cliffs                               | 0.070                            |
3. Result and Discussion

3.1. Tsunami model and potential damaged area

Historical data [24] recorded 11 tsunami events from 1673 to 2019 in Ternate Island, with the highest wave recorded was 1.2 m in 1846. It also recorded 10 meters wave height triggered by 7 Magnitude Earthquake in Sidangoli, the West Coast of Halmahera Island, North Maluku (northeast of Ternate Island) in 1859. On the other hand, Horspall et al. [6] reported the chance (%) districts in Indonesia that will experience a major tsunami warning (tsunami > 3 m) in any given year. Maximum tsunami height at the coast over 100-, 500-, and 2500-year return periods are predicted to be 3.0 m, 12.3 m, 25.5 m, respectively, with a 1% probability of tsunami with a height at the coast > 3 m each year. Based on the historical tsunami data, this research adopts the value of 1.2 m, 3.0 m, 10 m, and 12.3 m wave height as tsunami model input scenarios.

![Figure 6](image)

**Figure 6.** Tsunami inundation model with 1.2 m (a), 3 m (b), 10 m (c), and 12.3 m (d) wave height scenario

Based on the modeling results with wave height scenario of 1.2 m, 3 m, 10 m; and 12.3 m (Figure 6), tsunami inundation seems to be underestimated and show a slight difference in wave heights.
simulation. For example, the result of modeling tsunami inundation with a maximum height of 12.3 m does not show a significant distribution on the coastal elevation conditions of Ternate Island. This issue can be influenced by the input DEM data that still reflects the land cover height, even though it has been pre-processed to minimize the land cover effect.

Research by Heintz & Mahoney [25] proposed an uncertainty aspect of the model results due to the presence of wave forces that are not considered in numerical modeling and terms of evacuation safety. Therefore, the maximum tsunami run-up elevation was considered to be 30% higher than the value predicted by numerical simulation modeling or from tsunami inundation maps. Likewise, the minimum recommended elevation for a tsunami protection area is the maximum anticipated tsunami run-up elevation at the site plus 30%. Then 30% of the run-up was added to accommodate this uncertainty factor and modeled by the DEMNAS slicing method (Figure 7).

Based on the tsunami model and land use map, 35 land uses with a total area of 1,706.03 hectares have the potential to be affected by tsunami inundation (Figure 8). The most area affected is the eastern and southern coastal area where the settlements and facility concentrated. Dwellings are predicted to be the most affected by tsunami inundation with 779.80 hectares or 45.7%, followed by forests (243.91 ha), mixed forest (172.46 ha), and transportation (84.99 ha). Also, an area of 69.08 hectares airport to be predicted inundate based on the model.

Figure 7. Tsunami inundation model with 12.3 m wave height scenario and uncertainty factor by 30% of run-up height

Figure 8. Tsunami inundation model with 12.3 m wave height scenario and uncertainty factor by 30% of run-up height
3.2. Coastal flood model and potential damaged area

In this research, the coastal flood model combines high tides and annual sea level rise trends in 2050, 2075, and 2100 as shown in Table 3. The high tide is assumed to be constant during the predicted year, while sea level rise is multiplied by the year difference from data (2019) to the predicted year. At the highest tides, the sea is predicted to rise by 0.98 m, 1.09 m, and 1.2 m in 2050, 2075, and 2100, respectively. Figure 9 shows the coastal flood inundation model in Ternate Island, where the southeast coastal is the most affected area. In comparison, most northern and western coastal areas are predicted not to be prone to sea-level rise.

Table 3. Projected Sea Level Rise in 2050, 2075, and 2100 at Highest Water Water Spring

| Year | High Tides (m) | Multiplier (data year difference) | SLR (m) | Combination of SLR and High Tides (m) |
|------|----------------|----------------------------------|---------|-------------------------------------|
| 2050 | 0.84           | 31                               | 0.140   | 0.98                                |
| 2075 | 0.84           | 56                               | 0.252   | 1.09                                |
| 2100 | 0.84           | 81                               | 0.365   | 1.20                                |

Based on the coastal flood inundation model, at least 28 land use types with a total of 150.3 hectares are prone to coastal flood in 2100. In the first predicted year, 2050, there will be 26 land uses equivalent to 139.4 hectares that may be inundated by coastal flood. The inundated area is predicted to increase by 3.6% to 144.4 hectares in 2075 and 7.6% in 2100, with two more land uses. As in the tsunami model, dwellings also be the greatest area predicted to affect this coastal flood modeling, with a total area of 41.6 hectares in 2050. It is projected to rise by 5.5% to 43.9 ha and 12.4% to 46.7 ha in 2075 and 2100, respectively. The next large area predicted to be inundated in 2050 are open land (14.96 ha), transportation (13.8 ha), and mixed forest (11.4 ha). Also, other essential land uses, such as forestry, retail, shops, harbor, and agriculture, are affected with the area between 4 to 10.2 ha each.

The average Indonesian sea-level rise is predicted to increase along with sea surface temperature rise after 2000 [26]. These trends project that sea level will rise 40 cm ±20 cm in 2050 and 56 cm ±32 cm in 2080 and continue to rise 80 cm ±40 cm by 2100. Compared to the predicted sea-level rise in Table 3, ICCSR's projection predicts a higher sea-level rise. This condition means that the model coastal flood could worsen, and the total area damage may be wider than predicted in this research.
Figure 9. Projected coastal flood in 2050, 2075, and 2100

Figure 10. Potential inundated area based on coastal flood model in 2050, 2075, and 2100
3.3. Model Validation

The available digital elevation model of the study area is the national digital elevation model (DEMNAS) provided by BIG. The National DEM is built from several data sources, including IFSAR data (5 m resolution), TERRASAR-X (5 m resolution), and ALOS PALSAR (11.25 m resolution), by adding the stereo-plotting mass point data. DEMNAS has a spatial resolution of 0.27-arcsecond or equal to 8.33 meters [27]. DEMNAS is pre-proceed (refined) before being applied to be input model. The accuracy of refined DEMNAS is obtained from comparing the altitude values in the field as measured by profiling and the DEMNAS's sample points height values. The comparison resulted in the height difference for each sample point, which was then calculated to RMS and linear errors. The calculation results show that the refined DEMNAS has a LE90 (linear error with 90% confidence) of 12.08. Compared to standard mapping accuracy published by Geospatial Information Agency [28], it categorized to class 3 accuracy of 1:25,000 mapping a scale.

The land use map as input for tsunami modeling data and the calculation of the potential damaged area was also tested for accuracy. The accuracy assessment was done by comparing the current land use (in the field) with the land use map resulting from image interpretation at sample points. It resulted in an overall accuracy of 89.7%, meaning that the land use map generated as an input model has met the minimum accuracy requirements (tolerable accuracy) of 80% (Sutanto, 2013). Both DEMNAS and land use map used in this research meet the accuracy for model input data. Nevertheless, the models (coastal flood and tsunami) cannot be validated, considering the tsunami model is predictive based on historical data.

3.4. Hazard mitigation in Ternate Island

Tsunami and coastal floods can trigger environmental impacts, such as inundation at coastal areas, an increase of coastal erosion, the subsidence of a small island, an increase of intrusion on the mass of rivers and lands, and the sudden change of wind pattern at sea [26]. To minimize or reduce the impact of disasters, the regional government of Ternate City has formulated policies related to spatial management and disaster mitigation through regional spatial planning (RTRW) 2012-2032 [29]. The policy mainly in tidal wave and tsunami disaster-prone zones such as restrictions and prohibitions on the use of disaster-prone zone space, construction of evacuation facilities (paths, shelters, evacuation sign), development of early warning systems, and development of natural and artificial structures to prevent abrasion. Structural mitigation has been done to control coastal flooding such as embankments in the coastline. However, the tsunami and coastal flood model shows that there are still coastal areas that are potentially affected, especially dwellings and transportation facilities, including the airport.

4. Conclusion

Sea level rise has been accelerating by a few millimeters per year. This phenomenon occurs in almost all coastal areas of the world, including small islands in Indonesia. A small island with a high population concentration in the coastal area makes Ternate Island more vulnerable to experiencing coastal hazards, such as tsunami and coastal floods. Based on the modeling in this study, dwellings are the area that has the greatest potential to be affected by the coastal flood and tsunami, especially on the eastern to the southern coast. Prevention has been done and written in regional government regulation as a mitigation effort. However, both potential hazards are still a threat to the community close to the coastline.

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