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SPATIAL MODELING OF TSUNAMIS AND TSUNAMI INUNDATION ANALYSIS OF "PANJANG" BEACH IN BENGKULU CITY, INDONESIA

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ABSTRACT

Modeling the potential for tsunami inundation at tourist sites is required as a disaster mitigation effort. Spatial modeling through the application of Geographical Information System (GIS) is a method that can be used to assess the potential for inundation and the impact of a tsunami. This study aims to obtain a spatial description of the potential distribution of tsunami inundation in the tourist area of Panjang beach, Bengkulu City. Appropriate input parameters were derived from Digital Elevation Model (DEM) data, and satellite remote sensing and field data were analyzed through GIS. The slope parameter is derived from DEMNAS data belonging to the Geospatial Information Agency (BIG), land use is generated from open street map (OSM), and coastline distance created from vector map of the study area. The simulation of the tsunami height on the coastline using a scenario of 10 meters causes the land in the Panjang beach area to be inundated with an area of 1.4 – 3.5 km2 with a range of 415 – 765 meters from the coastline. The map of potential tsunami inundation resulting from spatial modeling provides the same inundation pattern as the tsunami inundation map issued by BNPB. The extent and range of the tsunami inundation are directly proportional to the height of the tsunami on the coastline, the higher the tsunami on the coastline, the wider the tsunami inundation, and the farther the tsunami range on the land. The results of this study can be used as initial information for the management of coastal areas as tourist sites related to disaster mitigation.

Keywords: *Spatial Modeling, Tsunami Inundation, DEMNAS, Panjang Beach, Bengkulu*

1. INTRODUCTION

Modeling the potential for tsunami inundation requires parameters and variables that are accurate and have similarities with the real in the field, because inundation modeling is a representation of the real conditions that exist in the research location (Hafeez & Zone, 2008). The parameters for modeling the potential for tsunami inundation are the topography and land use of the coastal area which are manifested in the form of DEM data and surface roughness value. The maximum reach and extent of tsunami inundation in coastal areas are strongly influenced by these two parameters. Another important parameter for the spatial model is the tsunami height at the coastline. The data of tsunami height on the coastline is used as a starting point to determine the maximum range and extent of tsunami inundation that can be generated. The tsunami height used in this study is the result of a study of the potential for high tsunamis on the coast of Bengkulu City.

This study aims to spatially model the potential distribution of tsunami inundation on the land and to assess its impact through mapping the maximum range and area of tsunami inundation using GIS. Tsunami modeling in coastal tourism areas is very important to do as an effort to minimize the potential risk of a tsunami disaster in the area (Sambah & Miura, 2014). The number of activities of residents and tourists in the Panjang beach tourist area of Bengkulu City needs to be anticipated and planned for the level of safety in the event of a tsunami disaster.

Inundation maps or tsunami hazard maps can be made by tracing historical tsunami data or modeling tsunamis. A method for estimating a tsunami disaster and the level of tsunami hazard and vulnerability can be done through spatial modeling (Fauzi, et al, 2020). The tsunami inundation model is a spatial model that is used to simulate the characteristics of the tsunami inundation through the calculation of the decrease in the height of the tsunami inundation on the mainland. The parameters used in this model consist of slope, surface roughness (land cover/land use), and tsunami height at the coastline (Berryman, 2006; and Smart et al., 2016). The tsunami spatial model is widely used by researchers in the geospatial field because it is easier to apply, but without considering the tsunami source and tsunami propagation factors (Mardiatno, 2008).

Spatial modeling of tsunami inundation potential is used to simulate the characteristics of tsunami inundation from the coastline to the mainland. Berryman (2006), in his research developed the Hill and Mader (1997) tsunami inundation model by adding the slope of the land. The development of this model succeeded in obtaining the average tsunami inundation from an area by finding the maximum and minimum inundation. The model developed by Berryman (2006) succeeded in attracting the attention of researchers in Indonesia to apply it in Indonesia. Several studies that use this model include research conducted by Putra (2008), Purbani (2012), Fauzi et al (2014), Zahro (2017), and Wahyuni (2020). Research conducted by Putra (2008) used the Berryman model to model the tsunami inundation in Banda Aceh City. This study succeeded in developing the coefficient of surface roughness values derived from several land uses. Purbani (2012) used the Berryman model to model the tsunami on Pulau We Banda Aceh with the help of the Builder model. The use of the Berryman model to model tsunami inundation in coastal areas was carried out by Fauzi et al (2014) on the coast of Bengkulu City, Zahro (2017) on the coast of Serang Regency, Banten, and Wahyuni (2020) on the coast of Kulonprogo DIY. These three studies use scenarios of tsunami height at the coastline through historical assumptions and approaches and the characteristics of tsunamis that can occur in coastal areas.

2. MATERIAL AND METHODS

2.1 DATA

The elevation data used in this study was obtained from the National Digital Elevation Model (DEMNAS). DEMNAS is built from several data sources including IFSAR data (5m resolution), TERRASAR-X (5m resolution) and ALOS PALSAR (11.25m resolution), by adding the stereo-plotting mass point data. The spatial resolution of DEMNAS is 0.27-arcsecond. The datum or vertical reference used is the Earth Gravitational Model 2008 (EGM 2008). The integrated data is added with mass points through the assimilation process. Mass points are points that contain three-dimensional coordinate information, namely x, y and z on the earth's surface. The assimilation process in DEMNAS data uses GMT-surface with a tension of 0.32.

Land use data uses Open Street Map (OSM) data and field surveys. Land use data converted to surface roughness values refers to the conversion carried out by Berryman (2016) and BNPB (2012). This study uses information on tsunami heights at the coastline based on data on Indonesia's maximum tsunami inundation potential issued by the National Disaster Management Authority (BNPB).

2.2 STUDY AREA

This research was conducted in Bengkulu City (Figure 1). Bengkulu City is an earthquake and tsunami prone area, because this area is directly opposite the Indian Ocean which is the meeting point of the Eurasian and Indo-Australian plates. In general, Bengkulu City is located at an altitude between 0-100 m/dpl, with sporadic distribution in every area of the city, causing a bumpy city morphology. The location with the highest point (up to 100 m/dpl) is in the southeast (Selebar sub district). While the lowest point (between 0 m/dpl – 10 m/dpl) is in the South, North and East, while the Bengkulu City Center itself is at an altitude between 10-25 m/dpl.

In 2020, the city has an estimated population of 371,828 with a total area of 151.70 square kilometers. Bengkulu City is located on the West Coast of Sumatra and faces the Indian Ocean. In this city, the local government through the Regional Disaster Management Agency (BPBD) has compiled a tsunami hazard mapping and tsunami evacuation route. The government works with community groups to develop evacuation maps and identify the best evacuation places (vertical and horizontal).

2.3 TSUNAMI MODEL

The potential for tsunami inundation modeling is made by developing the concept of water loss (Hloss) developed by Berryman (2006) and simple hydraulics principles developed by Smart et al., (2016). Both of these tsunami inundation models work in the spatial domain so that the model developed is a spatial model. The activity carried out in this stage is to examine the tsunami inundation model through a mathematical approach, so that the model variables and parameters can be well defined.

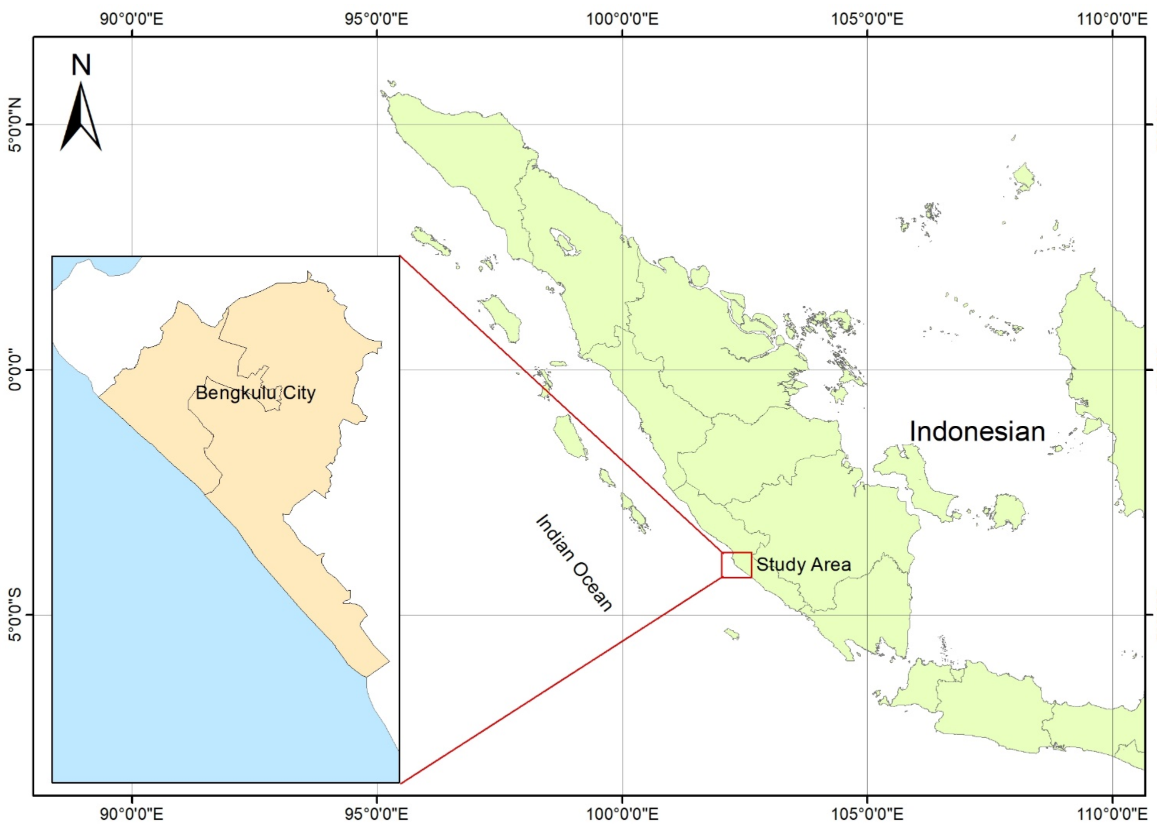

Figure 1. Map of study area

The Hloss method is a tsunami inundation model based on the height of the waves from the shoreline. This model is implemented using a cost-distance function which calculates g distance to the nearest source for each pixel, by minimizing the distance specified in a cost surface. The source for the function is the pixel value representing the ocean wave/ tsunami, and the cost surface is the pixel representing the tsunami wave height loss (Hloss). The Hloss equation is presented in equation 1.

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

Information:

H_{loss} : Decrease in water level per meter from inundation distance
n : Roughness surface coefficient
H_0 : The height of the tsunami waves at the coastline
S : Slope

The development of a tsunami inundation model by considering simple hydraulics was carried out by Smart et al., (2016). The tsunami inundation was studied from a one-dimensional perspective with the slope measured parallel to the direction of the tsunami. The equation for the distance of the tsunami inundation on land is given in equation 2.

$$L = \frac{3a}{2} ln\left(\frac{Y_s}{aS_0} + 1 \right) \qquad (2)$$

Information:

L : Tsunami inundation distance
Y_s : Run up height at the coastline
S_0 : Slope
a : Surface roughness

The tsunami inundation modeling follows the equation for decreasing the height of the tsunami inundation and the distance of the tsunami inundation on the mainland. The model parameters consist of the tsunami height at the shoreline, the surface roughness index value and the slope/elevation of the slope. The model building algorithm developed in this study is described as follows:

Input: Surface roughness value (n^2 or a)

Tsunami height at the coastline (*Ho* or Y_s)

Elevation (S)

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

Count $L = \frac{3a}{2} ln\left(\frac{Y_s}{aS_0} + 1\right)$

Output: *Cost Raster* H_{loss} (tsunami height)

L (tsunami inundation distance)

The next step is build a potential tsunami inundation model based on the Berryman Model through the creation of a Builder model algorithm. The results of the Builder model in the ArcGIS software are calculated and analyzed the distance of the tsunami inundation horizontally from the coastline to the mainland using the Cost Distance method. The results of the calculation of the cost distance will get the potential range of a tsunami in coastal areas. The calculation of the tsunami range using the Smart Model is carried out using the help of ArcGIS and Excel. The surface roughness data was developed from the research results of Smart et al., (2016).

3. RESULTS AND DISCUSSION

3.1 TSUNAMI SPATIAL MODEL FORMULATION

The tsunami inundation modeling using the Berryman equation using altitude data in the form of DEM data. DEM data is converted into radian data by utilizing the tool facilities contained in ArcGIS. Tsunami inundation modeling is used to estimate tsunami inundation from the coastline to the mainland and generally this model is developed through empirical methods. This model was developed through mathematical calculations based on the calculation of the loss of tsunami height per meter of inundation distance. The slope (*Sin S*) represents the straight line of the sloping side of a triangle, corresponding to the mean slope taken from the sloping soil profile (topography) of the coastline. In this way, *Sin S* compensates for the flat topography of the Hills and Mader equation (Pignatelli et al., 2009). The onshore tsunami inundation diagram resulting from the Berryman model is modified from the tsunami wave diagram developed by Pignatelli et al., (2009) as shown in Figure 2.

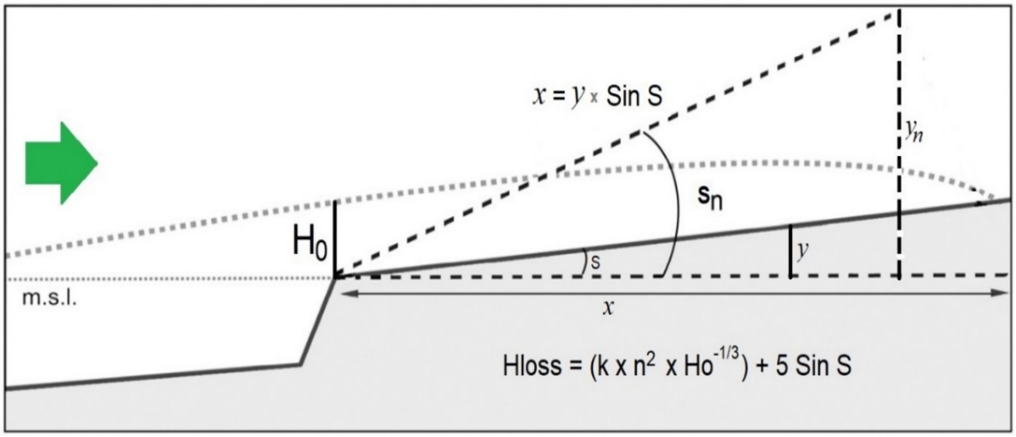

Figure 2. Tsunami wave diagram

3.2 MAPPING OF THE HEIGHT LOCATION/ELEVATION AND LAND USE

Research on tsunami inundation modeling begins with mapping the location/elevation and land use. The height of the research area is manifested in DEM data taken from DEMNAS. In addition to DEM data, the main data in tsunami inundation modeling is land use data sourced from open street map (OSM) data. Open Street Map or OSM is a web-based project for creating a free and open world map. OSM was built entirely by volunteers by conducting surveys using GPS, digitizing satellite images, and collecting and releasing publicly available geographic data. The research area for tsunami inundation modeling in this study is limited to two sub-districts, namely Ratu Samban and Ratu Agung sub-districts. The selection of these two sub-districts was used as research locations based on the fact that the coastal areas of these two sub-districts are favorite tourist sites in Bengkulu City. The number of tourists who visit the research site is very crowded, especially on weekend and holidays. The image map of the research area is presented in Figure 3.

3.3 DETERMINATION OF ELEVATION AND SURFACE ROUGHNESS INDEX

The altitude data used in this study is DEM data, namely altitude data taken from the ground surface which reflects the height of the ground surface. DEM data sourced from DEMNAS processed into altitude data in the form of slope radian format so that it can be included in the tsunami inundation model. From the DEM height data in the study area, it can be concluded that the elevation of the coastal surface of Ratu Samban and Ratu Agung sub-districts is a fairly gentle elevation (Figure 3). This condition causes the research area to be an area prone to tsunami disasters. Several public facilities are located in this area such as Bencolen Mall, Sport Center, Hotel and Cafe/restaurant.

Land use is using the land that is carried out optimally by utilizing all available resources in an effort to develop the using land in an area. The composition of built and undeveloped land in Bengkulu City is almost the same. The result of the interpretation of land use is converted into a surface roughness index value. The coefficient of surface roughness is distinguished by the type of detailed land use/land cover according to Berryman (2006) and BNPB (2012). The results of the interpretation and classification of land use are converted into surface roughness index values and presented in a table listing the surface roughness coefficient values (Table 1).

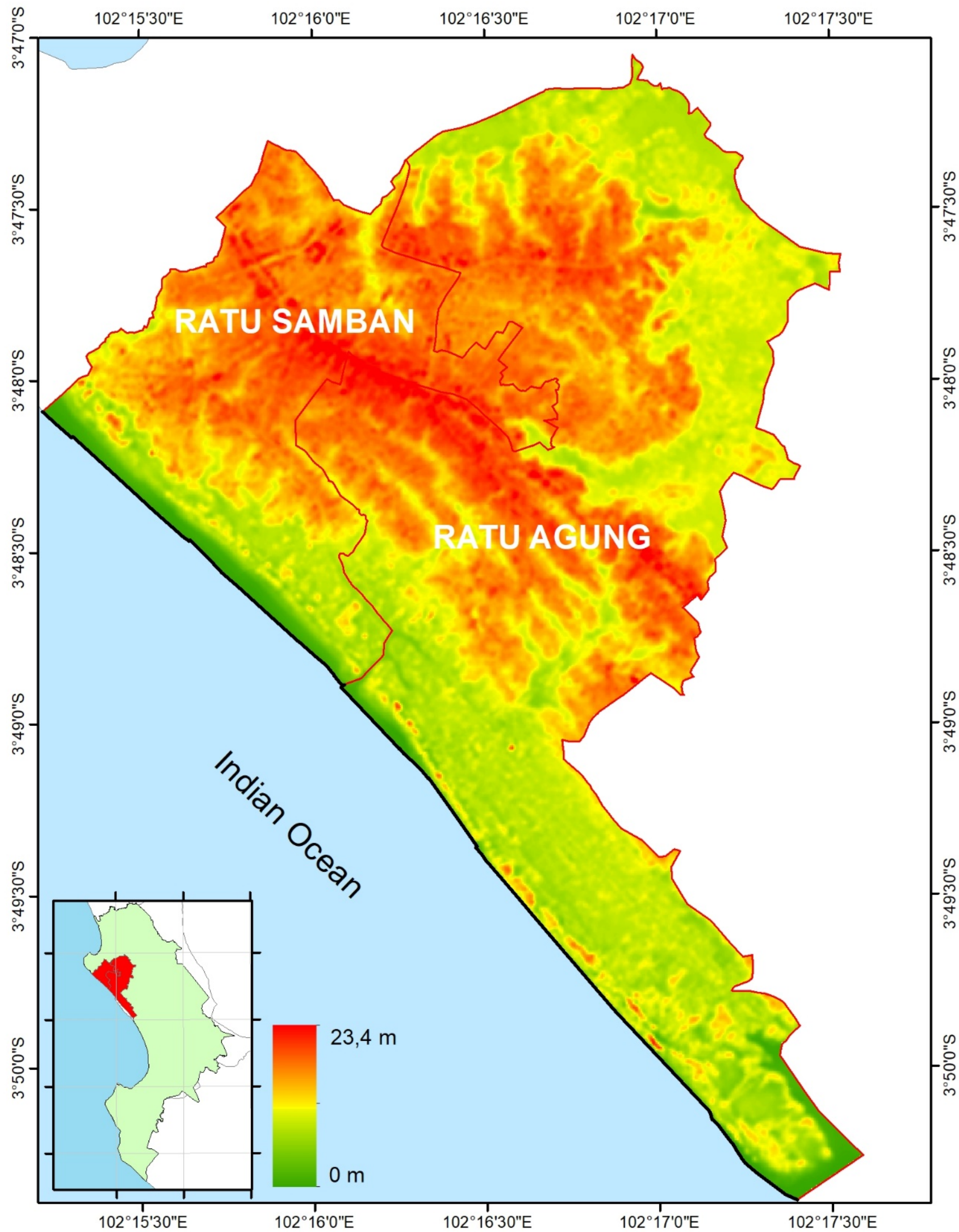

Figure 3. DEM map of ratu samban and ratu agung sub-districts

Table 1. List of surface roughness coefficient value

No	Type of land use	Surface Roughness Coefficient
1	Pond	0,010
2	River	0,007
3	Sand	0,018
4	Open field	0,015
5	Meadow	0,020
6	Ricefield	0,020
7	Empty land	0,015
8	Moor	0,025
9	Field	0,025
10	Plantation/coastal forest	0,035
11	Shrubs	0,040
12	Settlements/build-up land	0,045
13	Mangrove forest	0,025

Source: Berryman (2006); BNPB (2012);

3.4 TSUNAMI INUNDATION MODELING SIMULATION

The tsunami inundation potential model was designed by developing the concept of water level loss developed by Berryman (2006). In this concept, a mathematical calculation is carried out based on the calculation of the loss of tsunami height per 1 m of inundation distance (inundation height) calculated by considering the distance to the slope and surface roughness. The main data used for modeling tsunami inundation are elevation and surface roughness. The elevation data was extracted from the DEM map, while the surface roughness data was converted from the land use map.

The modeling input data in this study uses a resolution of 10 meters, this refers to the results of the research by Handayani (2014) and Marfai et al., (2018) that the tsunami inundation model is more accurate at medium data resolution. The greater the resolution of the input data, the wider the tsunami inundation area generated in the modeling. After obtaining the surface roughness index map and the DTM map, the modeling process was carried out following the equation given by Berryman (2006). To calculate the distribution of tsunami inundation on land, a cost distance analysis is used with the maximum distance value being the height of the tsunami on the coastline. The calculation of the cost distance results in the distribution of the tsunami inundation from the coastline to the mainland. The model used to model the tsunami inundation is Builder, this model is often referred to as a 'visual programming language' or often referred to as a tool used to create a script. Model Builder can be used to map out a repetitive workflow that involves many other jobs, making it easier for users to perform their tasks. The tsunami inundation model was designed using the Model Builder which was processed with ArcGIS software. The results of the calculation of the cost distance to the Hloss value produce the distribution of tsunami inundation on the mainland of the Ratu Samban and Ratu Agung sub-districts starting from the coastline. The inundated area is analyzed to find the area of inundation and the maximum range of tsunami inundation. The simulation results of tsunami inundation modeling for the three worst scenarios, namely Ho = 10 meters, using the Berryman equation are presented in Figure 4.

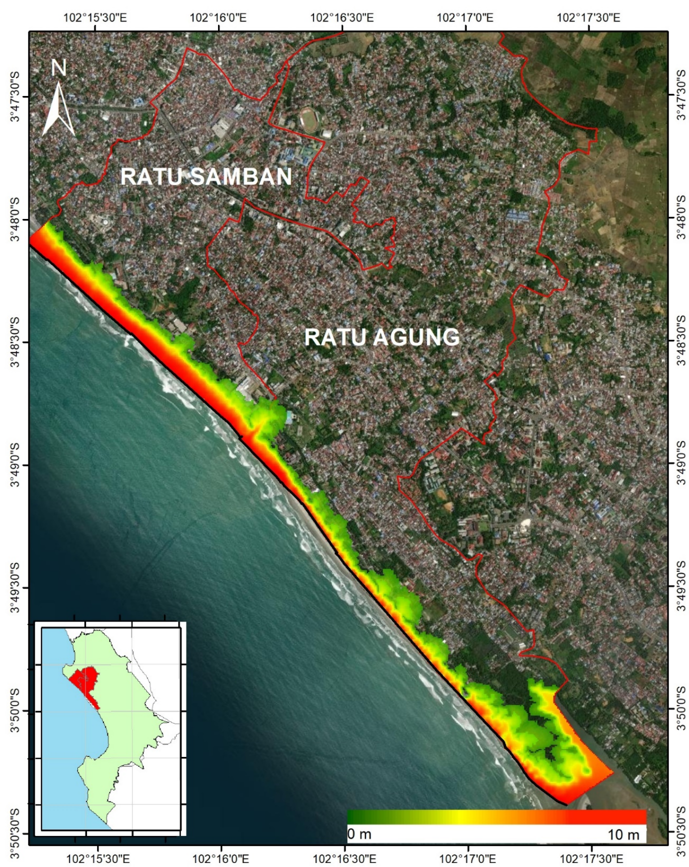

Figure 4. Simulation results of tsunami inundation modeling with the height of 10 meters

The development of a tsunami inundation model by considering simple hydraulic principles was carried out by Smart et al. (2016). The tsunami inundation was studied from a one-dimensional perspective with the slope of the coastline measured parallel to the direction of the tsunami and the difference in land topography was not taken into account. Both tsunami inundation models (Berryman and Smart) use the same input model, namely the tsunami height at the coastline. The results of measuring the reach of the tsunami inundation with a tsunami height of 10 meters on the coastline resulted in a maximum range of 621.89 meters for the Berryman model, 537.5 meters for the Smart model. While the minimum reach reaches 186.54 meters for the Berryman model and 312.3 meters for the Smart model (Figure 5). The difference in the maximum range of the two models, can be due to the two equations using different elevation and surface roughness classifications in the modeling. The Smart model uses 3 elevation classes, namely mild slope (0.01), moderate slope (0.5) and steep slope (0.2). The surface roughness coefficient values in the Smart model are divided into 4 classes of land cover types as shown in Table 2.

Table 2. List of surface roughness coefficient values

No	Onshore roughness condition	Aperture value a (m)
1	Smooth open ground, beach	200
2	Undulating open ground	100
3	Light buildings, coconut plantations	80
4	Dense vegetation, jungle	10

Source: Smart et al., (2016)

The analysis of the modeling results shows that the maximum range of tsunami inundation from the Smart model produces almost the same results as the Berryman model. The maximum range generated by the Berryman and Smart Models is presented in Figure 5.

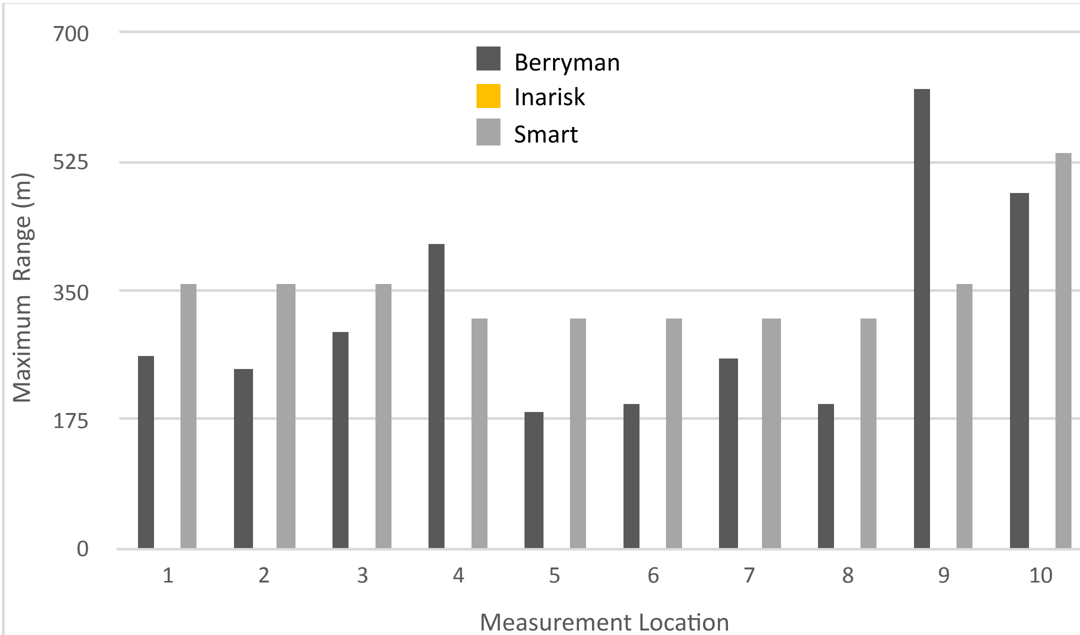

Figure 5. Maximum range of Berryman and Smart models

1. CONCLUSIONS

The use of GIS-based spatial models for modeling the potential for tsunami inundation provides an overview of the impact of tsunami inundation on land. In this study, three parameters are applied to create a tsunami inundation potential map. DEMNAS data can be used for modeling potential tsunami inundation for areas that do not yet have high-resolution DEM data. The tsunami inundation map shows that most tourist sites in Panjang beach Bengkulu are vulnerable to tsunamis. Most of the tourism infrastructure along the coast has a high vulnerability to tsunamis. The tsunami inundation pattern generated from the Berryman and Smart models shows the same thing as the inundation potential issued by BNPB. For a better modeling of the potential for tsunami inundation, it can be done by detailing the variation of the surface roughness value.

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