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Research Paper

Tsunami Risk Analysis with Run-up Variation Scenario Based on Modeling of Geographic Information System on Sibolga City North Sumatera

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Abstract

This study aims to analyse the tsunami risk level based on scenarios of tsunami run-up variation in the coastline of Sibolga City. The input data on the model are a surface roughness map obtained from quick bird satellite imagery interpretation, slope map obtained from Indonesian Earth Map and run-up variation scenario with height 5, 10, 15, 20, and 25 meters. Tsunami risk level modelling was prepared using inundation height variables and land use vulnerability. The relationship between run-up height and tsunami risk level was analysed using simple linear regression. The total area of inundation was obtained based on the order of run-up variation by 1,35 km^2, 1,92 km^2, 2,47 km^2, 3,27 km^2, and 4,15 km^2 while the area of high-risk category based on the order of run-up variation by 0,41 km^2, 0,77 km^2, 1,08 km^2, 1,46 km^2, and 1,95 km^2. The result of linear regression between the run-up height and the width of the inundation area showed a positive correlation. Each 1-meter elevation of run-up will expand the inundation area by 0,14 km^2. High run-up variables with high-risk areas also have a positive correlation. Each 1-meter of run-up will expand high-risk area at 0,75 km^2.

Keywords: *Tsunami risk; Run-up variation scenario; Geographic Information System*

1. Introduction

Tsunami is one of the most potent disasters in Indonesia [1]. Based on data compiled during the period 1600-1999, 105 tsunami have occurred in Indonesia [2]. Indonesia is a country which prone to tsunamis, especially in the areas which closed to subduction zones between the Eurasian, Indo-Australian and Pacific Plate. The Indonesian seismic zone map shows that 290 cities or about 60% of the 481 cities in Indonesia located in areas prone to earthquakes [3]. Most of the cities located in coastal areas that also traversed by tectonic plate meeting paths which have potential disasters including tsunamis. In fact, about 126 district in Indonesia are categorized as high-risk tsunamis [4]. Tsunami in Aceh which happened in 2004 became a disaster that reminds all communities to be able to build an early warning system to cope with a potential tsunami, especially in the western coastal region of Sumatra, including Sibolga City.

The small scale of Tsunami Disaster Risk Index Map in North Sumatera [5] shows Sibolga City is an area which has moderate of tsunami, but based on the City and Regency Tsunami Risk Index of 2013 [6], Sibolga is categorized as a high-risk tsunami area. It is very difficult to observe the vulnerable locations of tsunami in detail in small area such as Sibolga. In addition, the small scale of tsunami risk maps are difficult to use as a basis to determine the evacuation routes in tsunami disaster mitigation planning. Currently, data availability and information need to be complemented and improved. Thus, the planning of tsunami disaster management in Sibolga City can be formulated properly.

These problems can be solved by preparing data and information which is appropriate, fast, in accordance with the needs, and easily accessible. Related to this problem, Geographic information systems which developed very rapidly in recent years can be used as a solution method. Preparedness systems need to be built with accurate data sources and information and efficient and effective methods.

2. Methodology

Sibolga City was chosen as a research area because this location directly opposite the Eurasian and Indo Australia subduction zones, so it is potentially affected by the tsunami. Sibolga is also the oldest port city in Indonesia which has very high industry and shipping activities. In 2017, the port of Sambas which is the main port in Sibolga City is designated as a priority port in the west coast of Sumatra [7]. Sibolga city located at 1° 42'20,16"-1°46'16,32" North and 98°45'6,84"-98°49'3,36" East. The total area of Sibolga City is approximately 21.30 km^2. There are 4 islands in Sibolga City, namely Poncan Gadang Island, Poncan Ketek Island, Sarundik Island, Babi Island, and Bangke Island [8]. The city of Sibolga is surrounded by Tapanuli Tengah regency in the north, east and south, while the south is bordered by the Tapiannauli bay that faces to the Indian Ocean. Basically, Sibolga City already has documents of disaster management plan 2014-2018 and Tsunami Disaster Evacuation Line 2014-2018, but the document did not show the tsunami risk level based on the variation of tsunami run-up assumption. Therefore, this study will be presented the level of risk tsunami based on scenario of run-up variation in the coastline of Sibolga City.

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Fig 1: Map of location study

This modeling used Geographic Information System. Data processing was done using ArcGIS 10.1 software. The tsunami risk is derived from hazard and vulnerability variables [9]. Hazard variables were arranged using surface roughness map, slope gradient maps, and run-up height. The surface roughness map is derived from the land use map which interpreted from the Quickbird image of Sibolga city with acquisition year in 2016. This image was obtained from google earth. Preparation of surface roughness coefficient refers to the table of surface roughness coefficient of land use [10], [11].

Table 1: Roughness Coefficient

Landuse	Roughness Coefficient
Sea water	0,001
River water / ditches	0,007
Pond Water	0,010
Artery Road	0,010
Collector Road	0,010
Local Road	0,013
Water Swamp	0,015
Clear land	0,015
Sand	0,018
Grass	0,020
Farmland	0,020
Swamp forest	0,025
Field	0,030
Garden	0,035
Shurbs	0,040
Building	0,045
Forest	0,070

Slope map was derived from digital elevation model (DEM) maps which compiled using contour data of *Peta Rupa Bumi Indonesia* (1:50.000) consists of Sibolga Sheet (NLP 0617-62) and Adiankoting (NLP 0617-64). DEM maps were made using topo to raster tools with 1-meter pixel in size. Run-up height used assumption of height variation 5, 10, 15, 20, and 25 meters. All input data were stored in raster form with 1-meter pixel in size. The tsunami inundation model was developed using the [10]:

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

Where:

H_{loss} : The decrease of height of water per meter from the inundation distance
n : Coefficient of surface roughness
H_0 : Run-up (meters)
S : Slope (degree)

Preparation of tsunami inundation model maps use the cost distace tools to obtain a dynamic model of water level reduction from the shoreline. The vulnerability variable used in this research was land use. The vulnerability weight was determined based on the level of impacted land use. The type of settlement land use had the highest weight because this land use was the most vulnerable affected area, and the weight will be smaller according to the value of affected landuse. Tsunami risk modeling was constructed using Risk Notation [12].

$$Risk = Hazard \times Vulnerability \quad (2)$$

The correlation between the inundation area and the area of tsunami risk with run-up was analyzed by simple linear regression. The results will show the correlation of width of inundation area and high-risk area at each 1-meter run-up.

3. Results and Discussion

A. Land Use and Surface Roughness Interpretation using Quickbird Imagery

The results of the interpretation indicate that the number of land use classes in the study area was 16 classes. The most dominant land use was forest by 16.12 square kilometers (75.67%). Furthermore, settlements were the second largest land use by 3.02 km^2 (14.19%), while the percentage of other land use is less than 5%. The distribution of settlements in Sibolga City is generally close to the coastline (Figure 2). This condition affects the physical vulnerability. The settlements which close to the shoreline will be particularly vulnerable affected rather than the settlements that are far from the coastline. Along the coastline, there is no green belt which can reduce the strength of tsunami waves. This condition causes the settlements become very vulnerable to impact because tsunami waves will hit the settlement directly.

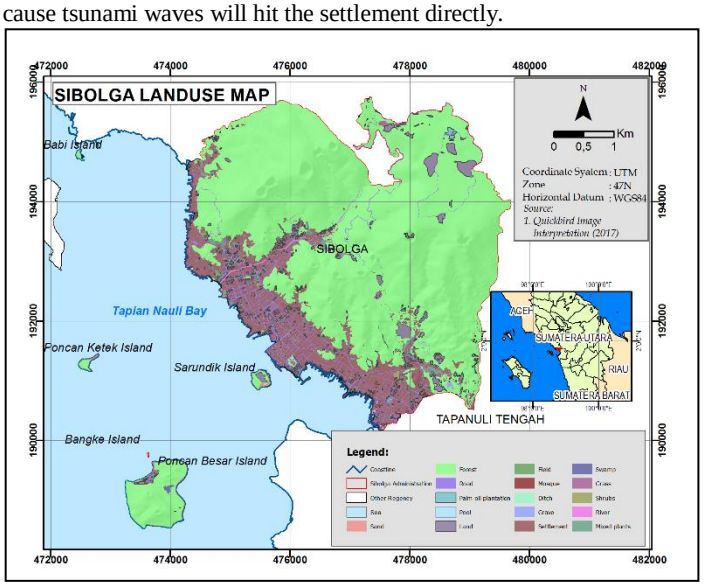


Fig 2: Landuse Map

Table 2: Landuse Distribution

Landuse	Area (km^2)	Area (%)
1. Sand	0.064	0.30
2. Forest	16.120	75.67
3. Road	0.674	3.16
4. Palm Oil Plantation	0.020	0.09
5. Pool	0.003	0.01
6. Clear Land	0.896	4.21
7. Field	0.001	0.001
8. Mosque	0.005	0.02
9. Ditch	0.003	0.05
10. Grave	0.010	0.04
11. Settlements	0.008	14.19
12. Swamp	3.023	0.08
13. Grass	0.012	0.44
14. Shrubs	0.094	0.13
15. River	0.028	0.21
16. Mixed Plants	0.045	1.40
Total	21.303	100.00

Source: Quickbird Interpretation (2017)

Based on the surface roughness map (Figure 3) it can be seen that the maximum of surface roughness coefficient of the study area is 0.07 while the minimum value is 0.001. The most dominant coefficient is 0,070 which covered 16.44 km^2 (77,16%) of the research area, whereas the minimum coefficient value of surface roughness (0.001) covered 0,01 km^2 (0,02%). The Distribution of surface coefficient of study area can be seen in Table 3.

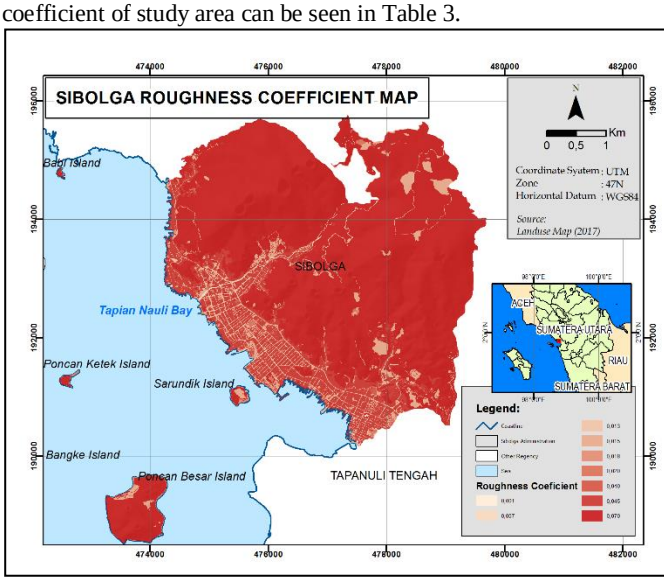


Fig 3: Roughness Coefficient Map on Location Study

Table 3: Landuse Distribution

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Total	21.303	100.00

Source: Quickbird Interpretation (2017)

B. Slope of Location Study

The data which used to construct DEM maps are contours and coastlines. The number of contours that used is 59 lines with contour interval 12,5 meters. The highest contour of the research area is 475 meters from sea level while the lowest point is 0 meters along the coastline. Based on the DEM map, it can be seen that the height range of study area is 0-73.2 meters (Figure 4). The most dominant height is more than 50 meters with an area of 7.162 km^2 (33.61%), while the height of the smallest area is 30-40 meters which covered 3.215 km^2 (15.09%) of the research area. Based on the slope map, it can be seen that the slopes at the study area ranged from 0 to 76.60°. The locations which have slope more than 8° are generally far from the shoreline. Meanwhile, there is a steep location which is near the coastline around the northern of Sibolga city.

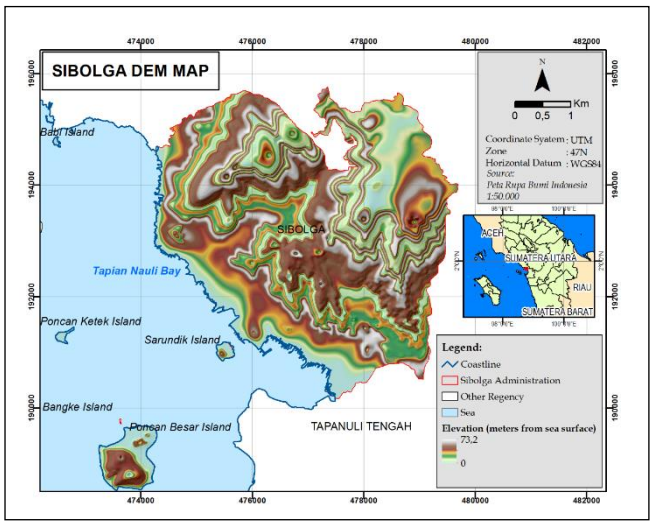


Fig 4: DEM Map of location study

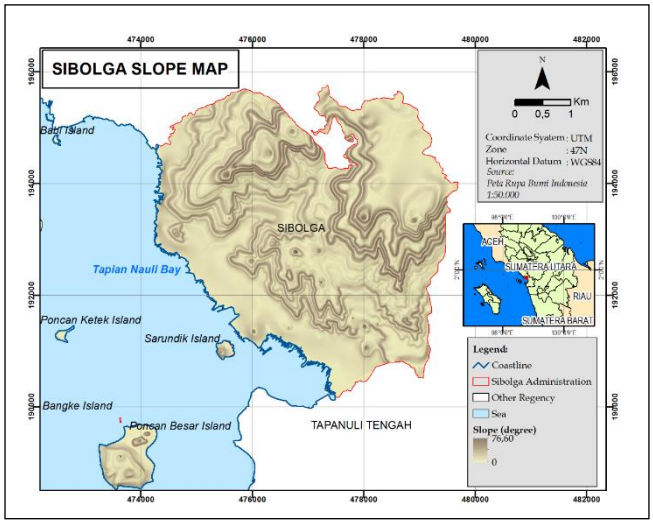


Fig 5: Slope Map of Location Study

Table 4: Distribution of slope of location study

Slope	Area (km^2)	Area (%)
0-8	10,178	47,76
8-15	4,076	19,13
15-25	3,010	14,12
25-40	2,420	11,36
>40	1,626	7,63
Total	21,310	100

Source: Map Analysis (2017)

Based on Table 4, it can be seen that the dominant slope of the location study is 0-8 degrees with an area of 10.178 km^2 (47.76%). This slope is categorized flat and commonly used to build settlement. The distribution of flat slopes is started from the coastline up to 1 km towards the mainland. Flat areas are also found in the northeast of the research area which is the border area between Sibolga and Tapanuli Tengah Regency.

C. Tsunami Inundation Model

Tsunami inundation modeling was conducted to show areas that are categorized as dangerous from the impact of inundation which caused by the tsunami. The most destructive inundation is happened if the height of inundation is more than 3 meters [4]. In this inundation modeling, it was used 5 assumptions of the run-up consists of 5, 10,15,20 and 25 meters. This selection was done to compare the hazards that posed from the lowest run-up to the highest run-up which happened. The result of tsunami inundation modeling is shown in Figure 6.

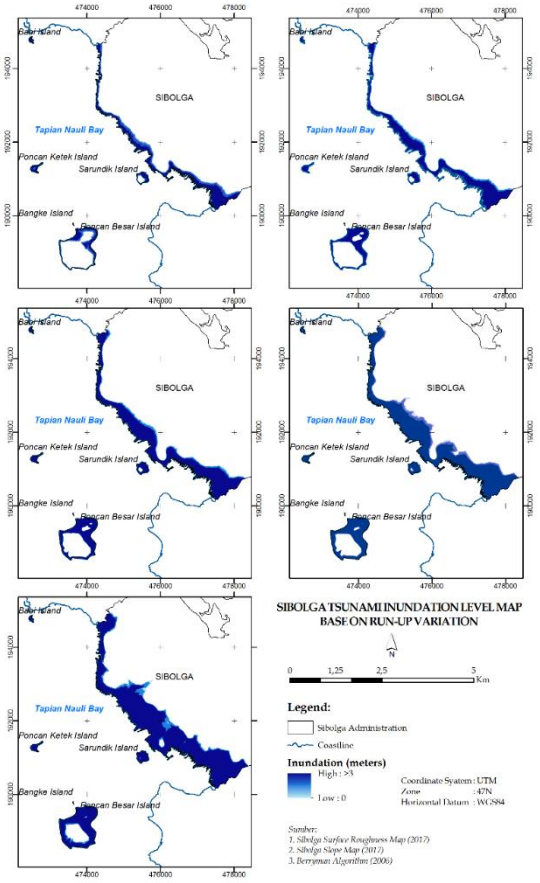


Fig 6: Tsunami Inundation Modelling Map on location study

Table 5: Distribution of Inundation Area base on Run-up Variation

Inundation	Run-up									
	5		10		15		20		25	
	km2	%	km2	%	km2	%	km2	%	km2	%
0-1	0.13	9.8	0.10	5.0	0.11	4.4	0.16	4.8	0.14	3.48
1-2	0.34	25.3	0.21	10.7	0.21	8.6	0.33	9.96	0.35	8.41
>3	0.87	64.9	1.62	84.3	2.15	87.0	2.79	85.27	3.66	88.11
Total	1.35	100	1.93	100	2.48	100.00	3.27	100.00	4.15	100.00
% from total area	6.32		9.03		11.61		15.34		19.47	

Source: Analysis of Inundation Modelling (2017)

Based on Table 5, the area of inundation is varies in each run-up. At run-up of 5 meters, the width of the inundation area is about 1.35 km^2 or 6.32% of the total research area. In a 25 meters run-up scenario, the inundation area is about 4.15 km^2 or 19.47%. The increasing of inundation area is 13.5% between run-up 5 meters and 25 meters. Furthermore, the linear regression graph between the inundation area and run-up (Figure 7) shows a positive correlation. The run-up which is higher at the coastline will cause the area of inundation is more wide. The increasing of 1-meter run-up will increase the inundation area by 0.14 km^2.

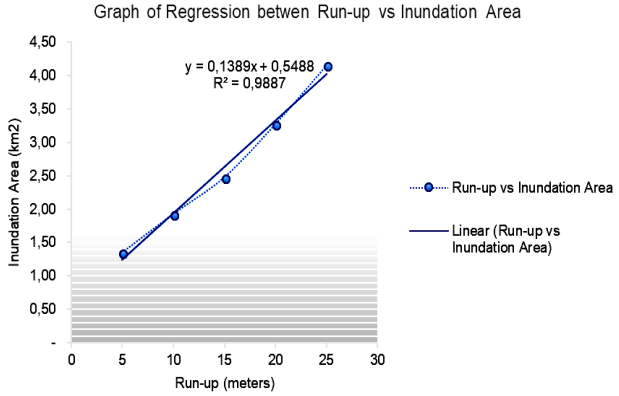


Fig 7: Regression of Run-up vs Inundation Area

In the Figure 7, it can also be seen that there is a significant increased in inundation area when run-up is more than 15 meters. This result indicates that the height of location did not have effect if the run-up height reaches 15 meters. However, the size of the tsunami inundation will not be more than 20% of the total research area because the elevation which is more than 25 meters above sea level is approximately 80% so that it cannot be reached by a tsunami inundation. The farthest reach of the inundation is at run-up 25 meters which reach 1.17 km from the coastline.

D. Tsunami Risk Level

Tsunami risk modeling in this research was obtained from the tsunami hazard aspect which shown by the tsunami inundation map and the vulnerability aspect was gained from the land use map. The classes of land use which have highly vulnerable will have the high score. For example, settlements which have populations are likely to be particularly vulnerable to impacts rather than agriculture area, fields, or forests that are not populated. The risk level is divided into 3 classes: high, medium, and low. The results of tsunami risk modeling of the research area can be seen in Figure 8.

High-risk areas which marked in red are increased in extent in line with the increasing of run-up (Fig. 8). At a run-up height of 5 meters, the area of high, medium, and low-risk areas is relatively the same. At run-up 10 meters, the wide of high-risk areas did not increase significantly. However, at run-ups from 15 to 20 meters, there is a significant increase in the area of high-risk levels. In the small islands, there is no high-risk area either at run-up of 5 meters or 25 meters because there are no settlements. The island is inhabited only in Poncan Gadang Island but the area is very small.

Table 6: Distribution of risk level area base on run-up variation

Risk Level	Inundation area (km^2) base on run-up variation (meters)				
	5	10	15	20	25
Low	0.51	0.49	0.55	0.69	0.79
Medium	0.43	0.67	0.84	1.12	1.42
High	0.41	0.77	1.08	1.46	1.95
Total	1.35	1.92	2.47	3.27	4.15

Source: Analysis Result (2017)

Table 6 shows that the increasing of high-risk areas is in line with the increasing of run-up height. The average increase in high-risk areas in the five run-up variations is 0.66 km^2 while in the medium risk class, the average increase of the five run-up variations reached 0.46 km^2. In the low-risk class, there is slightly increased in the area The average increase of inundation area in low-risk class is 0.21 km^2. Even in this risk class, there is a decrease of area at run-up 5 meters to 10 meters by 0.02 km^2.

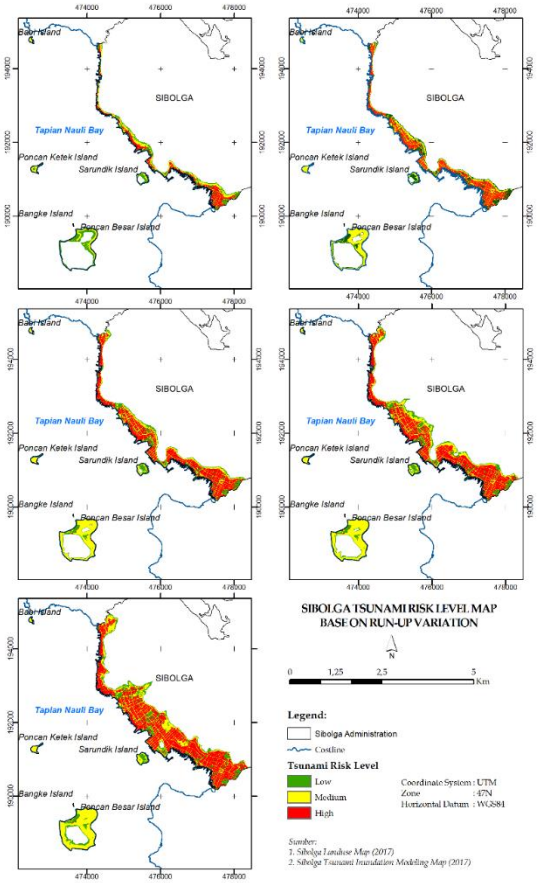


Fig 8: Tsunami Risk Model Map on Location Study

In figure 9 it can be seen that there is a positive correlation between the run-up height and the area of high-risk areas. The increasing of run-up will increase the area of high-risk areas. Based on the linear regression equation, it can be seen that the increase of 1-meter of run-up height will increase the area of high-risk by 0.075 km^2.

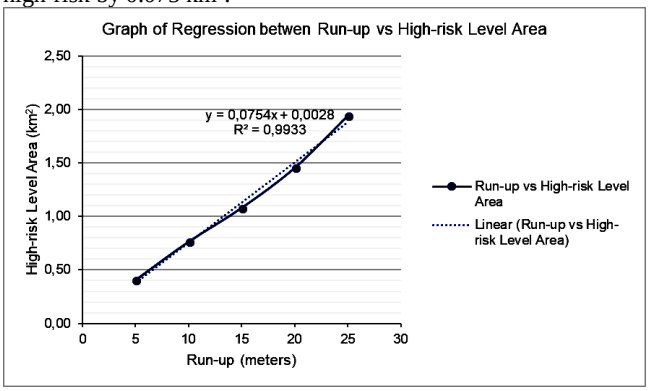


Fig 9: Linear Regression Chart between Run-ups and High-Risk Area

4. Conclusion

Most of the Sibolga City residential areas are in high-risk areas if tsunami run-up on the coastline reach more than 15 meters in height.

a. There is a positive correlation between the run-up and the width of the inundation area. where in every 1-meter increase of run-up can rise the inundation area by 0.14 sqkm.
b. Run-ups and high-risk areas also have a positive relationship, where the increase of 1-meter run-up can increase the area of high-risk by 0.75 sqkm

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