REMOTE SENSING–BASED ASSESSMENT OF TSUNAMI INUNDATION MODELLING IN SIBOLGA, WEST COAST OF SUMATRA ISLAND

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ABSTRACT: A total of 27 tsunamis caused by the earthquake occurred along the west coast of Sumatra region from 1681 to 2012. The 2004 tsunami on the west coast of Sumatra is the most destructive natural disaster in the last centuries, caused hundreds of thousands of people killed. Sibolga is the third-largest city in the region where was hit by the Indian Ocean tsunami around 107 minutes after the earthquake in December 2004. However, this area was not well observed in the tsunami-affected area in 2004. Thus, in this paper, we demonstrated how to calculate the tsunami inundation model, developed from basic empirical relation in a Geographic Information System (GIS) by integrating the wave height data record during the event and the remote sensing data. This approach is possible to calculate how far the wave impacts flooded inland. The result stated that the maximum inundation distance was around 201 m with the inundation depth average was 79 cm, respectively. The total inundated area was 149.9 ha which the high affected area mainly occurred in the fishing industry. The flooded condition due to tsunami might be worse in the future due to climate change (i.e., sea-level rise) and rapid urbanization (i.e., land cover change).

1. INTRODUCTION

One of the most catastrophic tsunami which drawn the attention of international community was Indian Ocean tsunami in Northwest coast of Sumatra region on December 26, 2004. This disaster caused 166 thousand people killed, 127 thousand people lost and economic loss about US$4.45 billion (Athukorala and Resosudarmo, 2005). Most of studies conducted research on tsunami in Aceh Province and Nias island, North Sumatra. However, in this paper, we focused in Sibolga City as the third largest city in Northwest coast of Sumatra region which also attacked by Tsunami around 107 minutes after the earthquake (Rabinovich and Thomson, 2007). Since these natural phenomena cannot be avoided, the destructive effect study of tsunami can be very helpful in developing the risk map. These can be used to estimate the recurrence time of incoming potential disaster and to estimate the maximum inland penetration of affecting waves. These information is necessary for establishing evacuation plan, including finding proper shelter location. Different research in relation to tsunami flooding have been performed; almost entirely, they utilize mathematical models to estimate the tsunami approaching the coastal area (for example: Tanioka and Satake, 1996; Titov and Synolakis, 1998; Pelinovsky et al., 2002; Tinti and Armigliato, 2003; Weiss et al., 2006). However, these approaches depend only on the hypothesis of wave behavior without concerning the morphological evidence.

Recent advancement of remote sensing technology allows to utilize the satellite imagery for mapping the spatial distribution of an area damage by natural disaster, including tsunami. Using satellite imagery is very useful since it delivers the morphological features and simultaneous image of an area. The morphological features in this paper refers to the physical form of an area such as land use pattern, elevation, slope, and shoreline. Moreover, with the help of Geographic Information System (GIS), integrating of multi criteria/attributes would be possible. However, most of studies on integration of remote sensing and GIS for tsunami were mainly focused on qualitative risk analysis or more a kind to vulnerability analysis using multi criteria (Sambah and Miura, 2016). Vulnerability analysis help for decision making process, but it is difficult to estimate the potential risk by the number such as causality rate, future projection and economic loss. Thus, in this paper, we conducted quantitative risk analysis by integrating the morphological and hydrodynamic data based on Pignatelli et.al., 2009 and Berryman, 2006 model. This model is a function of the wave parameters and the degree of roughness of the flooded topography which enables to estimate how far the impacting wave flooded inland. The aim of this study is to assess the areas affected by tsunami disaster such as damage area coverage, inundation depth and casualties rate by using satellite images analysis.

2. DATA AND METHOD

2.1 Study Area

The Sumatra region is considered as the most seismically active region in Indonesia, in particular in the western coast of Sumatra (Figure 1). Along the Sumatra region, there were 19 tsunami caused by earthquake from 1770 until 2005 (Puspito and Gunawan, 2005) and 2004 Tsunami was the highest number of fatalities where around two hundred and thirty thousand people died (Puspito and Gunawan, 2005). Sibolga, part of the northwestern of Sumatra region was located between 01° 42'N and 01° 46' N latitude and 98°46’ E and 98°48’E longitude as shown in Figure 1. This figure was constructed by overlaying topography (i.e., It was computed from Shuttle Radar Topography Mission (SRTM) of digital elevation model (DEM) with spatial resolution 30 m) and the natural color of satellite imagery (i.e. Landsat data with spatial resolution 30m) of the study area. It has a humid tropical climate and has a slope ranging from 0 to 59 degree. Sibolga is categorized as an urban area which located in the low land area and has the population density around 8 people/km^2. Generally, the land use in this island is dominated by built-up component (i.e., residential place, commercial place and industry). Moreover, this area was affected by tsunami on December 2004 with the maximum wave height was 2.6 m (NOAA, 2005). In this study, attributes known to affect tsunami inundation depth were applied. Those related to elevation, slope, surface roughness coefficient, shoreline and historical of tsunami event (i.e., wave height and run up)**.**

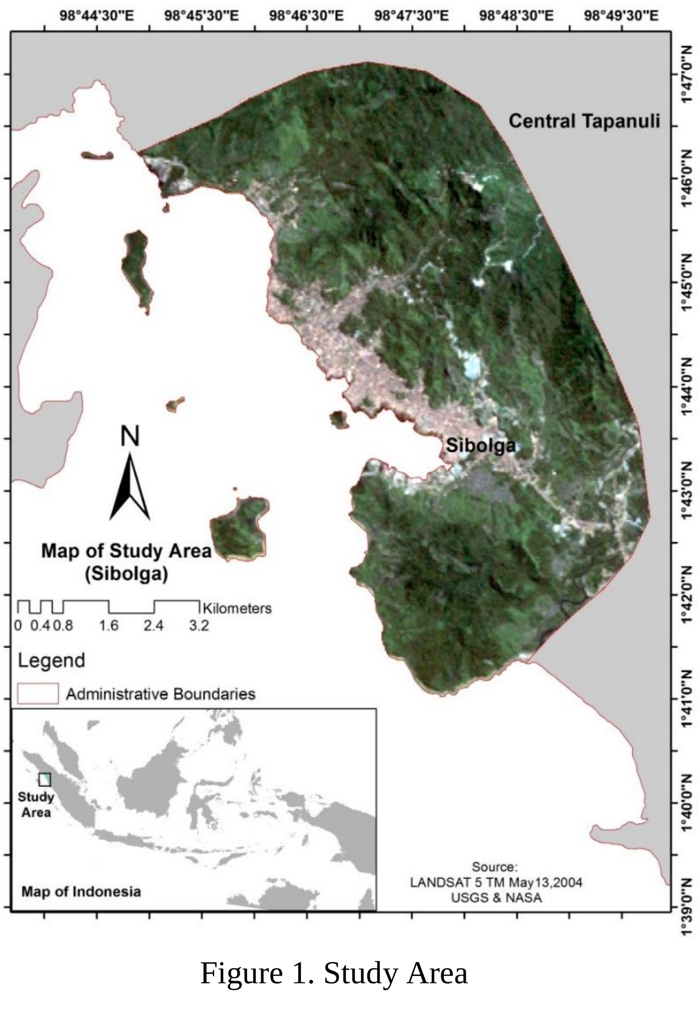

Figure 1. Study Area

2.2 Elevation

The key data layer applied in the assessment of tsunami inundation were elevation. Ideally, high spatial resolution of elevation data is required. However, high resolution of DEM data for Sibolga City was not available at geospatial agency of Republic Indonesia. Thus, we used 30m elevation of SRTM satellite data. The data can be downloaded at United States Geological Surveys (USGS) homepage (i.e., *http://earthexplorer.usgs.gov/*).

2.3 Slope

One of the most important components of elevation data was slope which referred as the rate of maximum change in the z-value in each grid of the image. The z-value is fundamental to fix slope estimation when the surface z units are different from the ground x, y units. The slope map was generated using the third-order finite difference method by Horn (Horn, 1981). Slope was created form the Digital Elevation Model of SRTM dataset.

2.4 Surface roughness coefficient

The surface roughness was influenced by the morphological features and vegetation textures. It shows an effective decrease for waves which are large in relation to the size of the obstacles in their paths. The roughness data was extracted by the land use data classification from satellite Landsat 5 Thematic Mapper (TM) data (*http://earthexplorer.usgs.gov/*) with Normalized Difference Vegetation Index (NDVI) approach as explained in Equation 1.

$$NDVI = \frac{\rho NIR - \rho Red}{\rho NIR + \rho Red} \tag{1}$$

Where ρNIR is reflectance of Near infra-red Band of Landsat 5 TM (0.77-0.90µm) and ρred is reflectance of red band of Landsat 5 TM (0.63-0.69µm). After calculating NDVI, threshold can be defined from each land cover by using reference of land cover map from Indonesia Geospatial Agency (*http://tanahair.indonesia.go.id*).

The roughness values used in this process were based on the Roughness Coefficient of Berryman, 2006 as shown in Table 1.

Table 1. Surface roughness coefficient (Berryman, 2006)

Land cover type	Roughness Coefficient
Water	0.007
Scrubs/Bush	0.040
Forest	0.07
Farmland	0.035
Open field	0.015
Agricultural land	0.025
Settlement/Built up area	0.045
Mangroves	0.025
Embankment	0.001

2.5 Shoreline

Shoreline was created using topographic vector map of study area with the validating process based on the Landsat satellite image analysis. Shoreline map as the result of Landsat satellite image analysis was applied the band-ratio process, where NIR (Near Infra-Red) and Green band was applied. This process will produce water-land boundaries in the coastal area where covered by vegetation, in which land areas without vegetation coverage will classify into the class of water.

By applying the band ratio of SWIR (Short Wave Infra-Red) and Green, shoreline will be created (Alesheikh et al, 2007).

2.6 Wave height

Tsunami wave height at the coastal area was depending on the earthquake magnitude and source to the site distance (Abe, 1979). However, in this paper, the wave height was assumed based on the maximum wave height on 26th December 2004 which was observed by tide gauge in Sibolga. It was obtained from the Russian team field survey data on Sumatra Island on January 20-29, 2005 (*https://nctr.pmel.noaa.gov/indo20041226/sibolga_nias.htm*)

2.7 Method

Pignatelli and Berryman numerical model were used in this study to assess tsunami inundation distance and depth. In this method, slope, surface roughness coefficient, shoreline and wave height were integrated as illustrated in Figure 2.

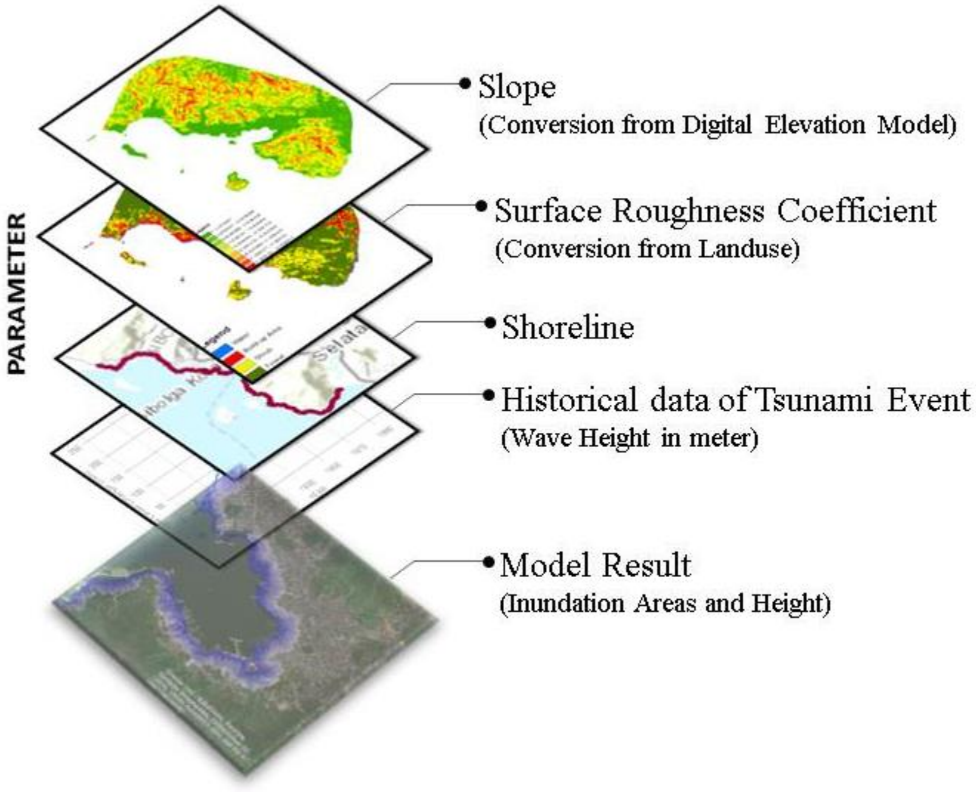

Figure 2. Step of Tsunami Inundation Model

Basically, the calculation was divided into two main equations:

A. Inundation Distance

The maximum horizontal distance inland that is reached by a tsunami, generally measured perpendicularly to the coastline called an inundation or inundation distance. The method used to determine the tsunami inundation using the following equation (Eq. 2) developed by Pignatelli (2009):

$$X_{max} = (H_t)^{1.33} * n^{-2} * 0.06 * cosS \qquad (2)$$

Where X_{max} is the maximum distance that the wave height can penetrate inland (in *meter*), H_t is the wave height at the coast (in *meter*), n is the surface roughness coefficient and S is slope of land surface (in *degree*).

B. Run-up Elevation

Run-up elevation was defined as the maximum elevation of tsunami waves above the mean sea level developed by Berryman (2006) as shown in Equation 3.

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

Where H_{loss} is the loss of tsunami height per 1 m of inundation distance. The equation was calculated by using ArcGIS *cost-distance tool* which sets the shortest cumulative cost to move across a cost surface which defined as a grid represents the loss in wave height (H_{loss}). In order to obtain the value of tsunami height loss per one meter of inundation distance in each grid based on Equation 3, the H_{loss} calculation result must be divided by the cell size (i.e., 30m). The basic concept of the tsunami flood inundation was illustrated in Figure 3.

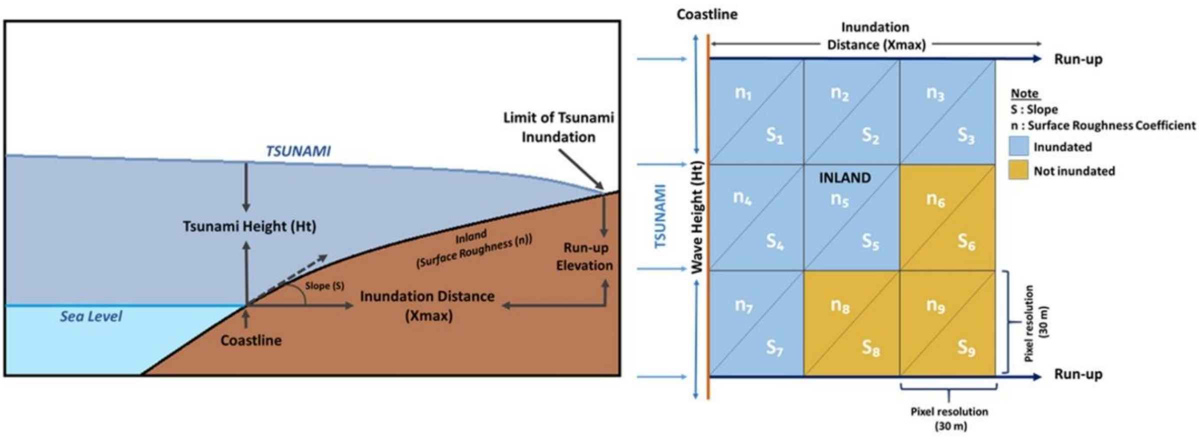

Figure 3. Tsunami flood inundation illustration (by Ranie Dwi Anugerah)

One matter in this study is the dependency of slope on travel direction where the slope function in ArcGIS calculates the absolute value of the maximum slope from DEM data and this may or may not be the slope in the direction of movement. As a result, the inundation distance tends underestimate.

3. RESULT AND DISCUSSION

Estimating tsunami inundation has been one of the challenging points since the number, height and wavelength of future tsunami will be highly depending on source, propagation and shoaling effect. This variability is also affiliated with the surface topography features such as vegetation, building, river and topographic irregularities and it will significantly affect where and how deep the inundation occurs. Moreover, high density of mangrove along coastline and the existence of reefs can also act as a barrier to reduce the effect of tsunami wave, as well as the islands with steep-sided fringing. Study about estimating tsunami inundation area using coastal vegetation density was carried out after the 2011 Japan tsunami and found that coastal vegetation also important feature in reducing tsunami wave (Sambah and Miura, 2016). In our inundation model approach, two keys data layers were used; elevation and surface roughness. The elevation data was applied to build a slope grid in the study area while roughness data was built by extracting land use data. All the data processing was run by ArcGIS 10.3.

The data which was recorded in Sibolga based on the 2004 Indian Ocean earthquake and tsunami stated that a wave height of approximately 2.6 m occurred at the open coast and this data was used for initial wave height. All necessary parameter which used in this analysis was shown in Figure 4. In addition, the model applied fixed roughness coefficient as shown in Table 1. As shown in Figure 4, the main activity of the Sibolga district mostly was located in the lowland area and very close to shoreline. This condition makes Sibolga district very vulnerable to water related disaster including Tsunami.

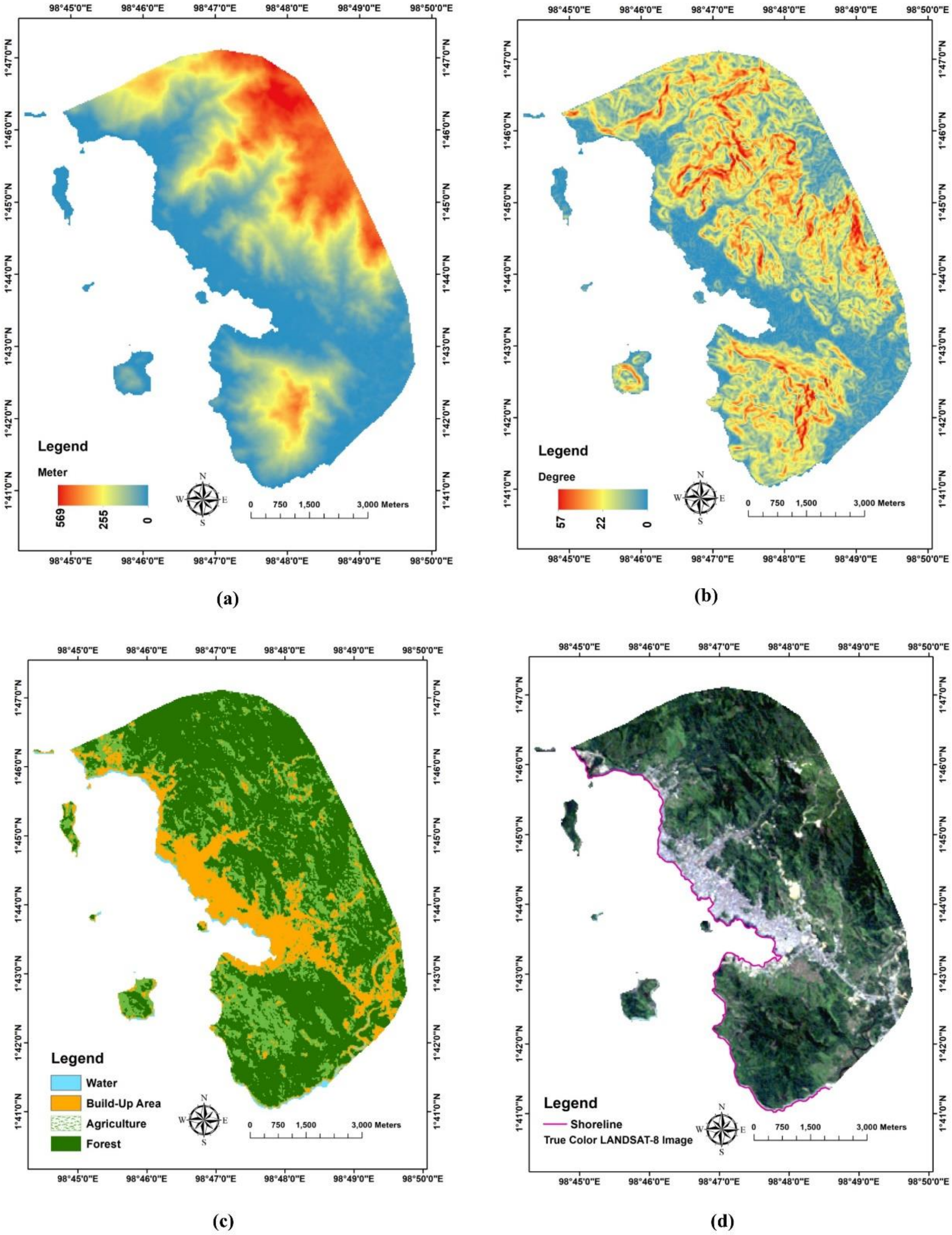

Figure 4. Parameters of Tsunami flood inundation;
(a) elevation; (b) slope; (c) roughness/landuse; (d) shoreline

Figure 5 shows the tsunami inundation simulation, where the blue color of the image indicates the tsunami inundated areas and the inundation depth. The result stated that the inundation maximum distance was 201m and the inundation depth was ranged from 0 - 2.6 meter. The affected area mainly located in the build-up area, in particular at the fishery industry and residential area with the total coverage around 149 ha (i.e., 13.8 % of Sibolga city). The detail of affected area by tsunami was shown in Table 2. The inundation depth average by tsunami (i.e., out of the coastline area) was around 76 cm and it has same agreement with the field survey which was conducted by Russian Academy (i.e., 60 cm) (NOAA,2005).

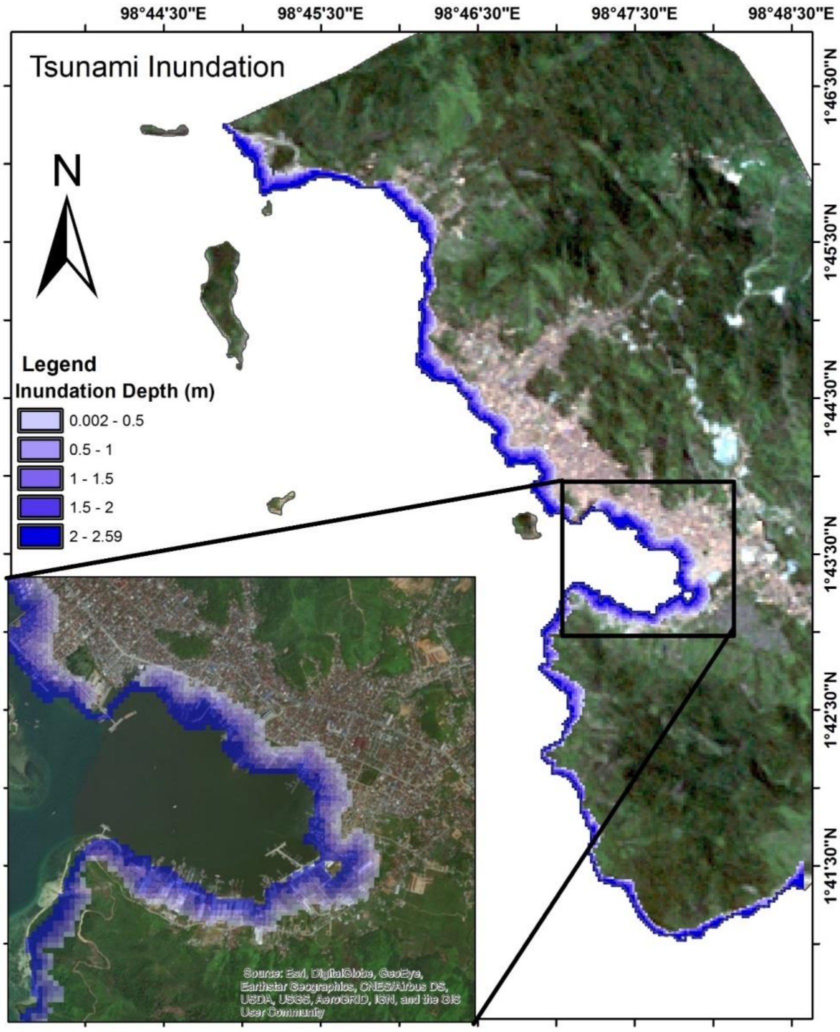

Figure 5. Tsunami Inundation Depth

Table 2. affected area

Inundation Depth (m)	Area (Ha)
0-0.5	31.31
0.5-1	7.21
1-1.5	7.5
1.5-2.6	103.88
Average depth: 76 cm	

Various study of affected area due to tsunami has documented casualties as a proportion of population (e.g. Imamura et al., 1995; Leynet et al., 2003). Imamura et al., 1995 and Leynet et al., 2003 revealed that the tendency of death rate varies linearly with tsunami inundation depth. Since our purpose was to estimate the injuries and death, we used Berryman (2006) model which estimated proportion of causalities (i.e., injuries and death) among the population at risk as shown in Equation 4.

$$c = 0.085(d - 0.3) \qquad (4)$$

Where *c* represents the causality rate and *d* represents the inundation depth. The value of 0.3 is the depth where the risk of being killed/ injured is negligible. In this study, the causality rate was ranged from 0% to 19%, with the average around 4% (i.e., out of the coastline area). However, Sibolga is very dense population where low slope area is mainly residential place and some of the Sibolga citizen live in the coastline area. As a consequence, the causalities rate will be higher, approximately at 16% of the population was affected. In addition, people who live in coastal area of Sibolga were categorized as poor family which indicated by semi-permanent house. This condition made Sibolga very vulnerable for tsunami in the future. The casualties model was referred to historical tsunami data. Thus, some limitation appeared as the following: the data employ to high velocity tsunami waves and so the models are likely to overestimate casualties and secondary impacts such as water and food supplies contamination have not been included.

Together with the tsunami risk map, the inundation map as a result of the study can be used as basic spatial information for tsunami disaster mitigation. In order to prepare for the evacuation purpose, both evacuation route and evacuation building design is necessary (i.e., no evacuation building available in this city since the highest building is only up to 2nd floor). For future projection, this impact due to tsunami could be higher since sea level rise is tending to increase and land cover changes.

4. CONCLUSION

In this paper, we have examined the tsunami affected area in Sibolga include the casualties rate by remote sensing approach. The average inundation depth due to the tsunami was around 79 cm which had the same agreement with survey data. The affected area mainly in the build-up area which had the casualty rate about 4%, respectively. As along in the coastline area were built house, the casualties rate might be higher. This affected area could be worsening since sea level rise is tending to increase and land cover is tending to change.

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