International Journal of GEOMATE, April, 2018 Vol.14, Issue 44, pp.96-101
Geotec., Const. Mat. & Env., DOI: https://doi.org/10.21660/2018.44.7127
ISSN: 2186-2982 (Print), 2186-2990 (Online), Japan

INTEGRATED SATELLITE REMOTE SENSING AND GEOSPATIAL ANALYSIS FOR TSUNAMI RISK ASSESSMENT

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*Corresponding Author, Received: 11 June 2017, Revised: 2 Dec. 2017, Accepted: 30 Dec. 2017

ABSTRACT: Tsunami risk is defined as a combination of the danger posed by tsunami hazard, the vulnerability of people to an event (exposure), and the probability of destructive tsunami or likelihood of the tsunami occurring. Tsunami risk is also defined as the mathematical calculation of tsunami vulnerability and tsunami hazard, and it can be assessed using a spatial multi-criteria. The study applied the combination of the element at risk to assess tsunami risk area along the coastal area of East Java Indonesia off the Indian Ocean. Remote sensing approach followed by geospatial analysis into tsunami risk assessment along with the existing perspective evolving the role of Geographical Information System. The existing physical vulnerability parameter was analyzed and evaluated. All parameters in both tsunami vulnerability and tsunami risk assessment were analyzed through weighted overlay in geospatial analysis, in which the criteria's weight was calculated through Analytical Hierarchy Process. The results were provided as thematic maps of tsunami vulnerability and tsunami risk. Tsunami risk map described five classes of risk from very low to very high based on the geospatial analysis. It described that coastal area with low elevation identified as high risks to the tsunami. The coastal area with high density of vegetation described a low level of tsunami risk. The existence of river and another water canals along coastal area were also identified as important parameters in generating tsunami risk map. Risk map highlights the coastal areas with a strong need for evacuation capacities, including evacuation route and evacuation building.

Keywords: Tsunami Risk, Remote Sensing, Geospatial Data, Vulnerability

1. INTRODUCTION

A tsunami is a series of waves generated in an ocean by a disturbance such as an earthquake, landslide, volcanic eruption, or meteorite impact. An earthquake can generate a tsunami in the overlying water. It can be generated when the sea floor abruptly deforms and vertically displaces the overlying water. When tectonic earthquakes occur beneath the sea, the water above the deformed area is displaced from its equilibrium position. Waves are formed as the displaced water mass, which acts under the influence of gravity, attempts to regain its equilibrium. When large areas of the sea floor elevate or subside, a tsunami can be created [1-3].

South coast of Java Island as a part of Indian Ocean is in the confluence of two major plates meet each other, Eurasian and Indo-Australian, where the movement of tectonic plates will create an earthquake and generate a tsunami. A potential destructive tsunami in the period of 1991 to 2006, recorded a tectonic earthquake in the Indian Ocean and generated tsunami on the southern coast of East Java, namely on June 3, 1994. A magnitude of 7.8 Mw hit southern coastal areas of East Java and causing casualties of 215 people [4]. Due to the tsunami is a recurring event, create an appropriate disaster mitigation is important. Tsunami risk mapping is one of the approaches needed for tsunami disaster preparedness.

Tsunami risk mapping combines the results of the tsunami vulnerability and tsunami hazard (Fig.1). Assessing tsunami vulnerability can provide important information for tsunami disaster risk management plans and mitigation. This also plays an important role in preparing and mitigating for the future events [5,6]. A risk of a tsunami disaster is defined as the mathematical product of tsunami vulnerability and tsunami hazard; it refers to the expected loss from a given hazard to a given element at risk [7]. A disaster is a function of the risk process. Risk results from the combination of hazards, conditions of vulnerability and insufficient capacity to reduce the potential negative consequences of risk. Risk assessment combines the results of the hazard and vulnerability assessments [8-10].

Moreover, disaster risk assessment is a qualitative or quantitative approach to determine the nature and extent of disaster risk by analyzing potential hazards and evaluating existing conditions of exposure and vulnerability that together could harm people, property, services, livelihoods and the environment on which they depend.

This is includes the identification of hazards, a review of the technical characteristics of hazards (location, intensity, frequency and probability), the analysis of exposure and vulnerability (the physical, social, health, environmental and economic dimensions), and the evaluation of the effectiveness of prevailing and alternative coping capacities with respect to likely risk scenarios [8]. Traditionally risk assessment urges at determining the likelihood of specific losses and damages, which includes population, economy, supporting environment and institutional structures [5].

Satellite remote sensing approach combined with geospatial analysis using Geographical Information System (GIS) for disaster mitigation study provides an important integrated contribution in conducting a tsunami risk assessment. This study assesses tsunami risk area through an integrated satellite remote sensing data and geospatial analysis in the south coastal area of East Java. This is important for tsunami early warning and mitigation. The general concept of the study is shown in Fig 1.

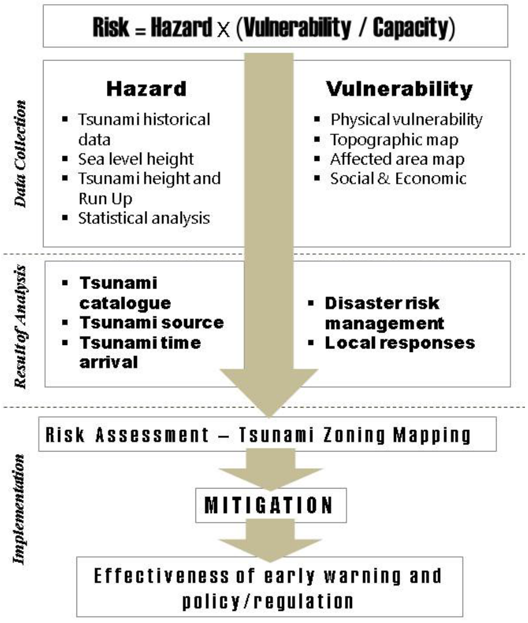

Fig. 1 General concepts of the study

2. METHODS

2.1 Study Area

The study was applied at the south coastal area of East Java, focusing on the coastal area of Jember District, Indonesia (Fig. 2). The coastal area of Jember district was known as one of important marine fisheries resources spot in East Java. This area also affected by 1994 tsunami event along the coastal area of East Java. The tsunamigenic earthquake occurred on June 3, 1994, in the Indian Ocean about 200 km south of Java. The earthquake, which had a surface-wave magnitude of 7.2 and a moment magnitude of 7.8 at 10.51°S and 112.87°E, generated a devastating tsunami that took the lives of more than 200 East Java coastal residents; with maximum run-up value of 9.50 m was measured at Rajekwesi area, east part of the study area [11,12].

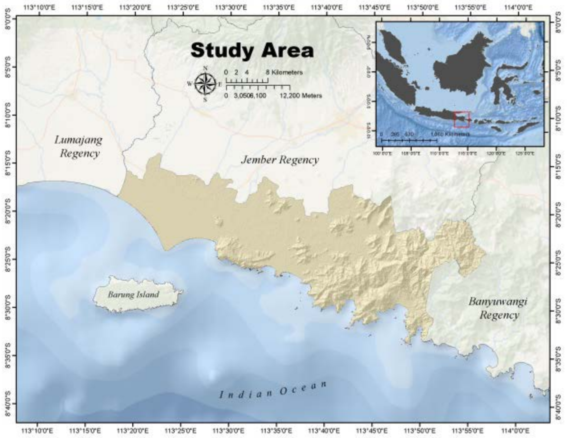

Fig. 2 Study area.

2.2 Dataset

Seismic data of the study area from 1992 to 2014 collected from The *United States Geological Survey* (USGS), and downloaded from *http://earthquake.usgs.gov/earthquakes/search/*. was used as a supporting parameter for tsunami vulnerability in which further will generated the seismic map. In order to map the land cover of the study area, ALOS satellite imagery with the instrument of the Advanced Visible and Near Infrared Radiometer type 2 (AVNIR-2) with the spatial resolution of 10 m was analyzed.

In addition, to creating tsunami vulnerability map, Digital Elevation Model (DEM) from The ASTER Global Digital Elevation Model (ASTER GDEM) version 2 was applied to generate elevation and slope map. The Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) GDEM is a joint product developed and made available to the public by the Ministry of Economy, Trade, and Industry (METI) of Japan and the United States National Aeronautics and Space Administration (NASA). Moreover, vector base map of East Java Indonesia was applied to prepare vector data of coastal morphology, coastal line, and river.

3. RESULT AND DISCUSSION

3.1 Geospatial Analysis for Tsunami Vulnerability Mapping

Vulnerability mapping has been generated using the parameters elevation, slope, coastal proximity, river proximity, coastal type, and land use. Together with hazard or capacity, tsunami vulnerability is one of the parameters in assessing tsunami risk. The cell-based analysis was applied in combining all parameters through GIS process. The classes of coastal proximity in meter (Fig. 3) was calculated based on the measured run-up and water height in the surveyed area during the last tsunami event in the coastal area of East Java, June 3, 1994. It was calculated using algorithm [13,14] :

$$\boldsymbol{log}\mathbf{X}_{\boldsymbol{max}} = \boldsymbol{log}\mathbf{1400} + {}^{\mathbf{4}}/_{\mathbf{3}}\,\boldsymbol{log}\left({}^{\boldsymbol{Y}_{\mathbf{0}}}/_{\mathbf{10}}\right) \tag{1}$$

X_{max} is the maximum reach of the tsunami over land, and Y_0 is the height of the tsunami at the coast.

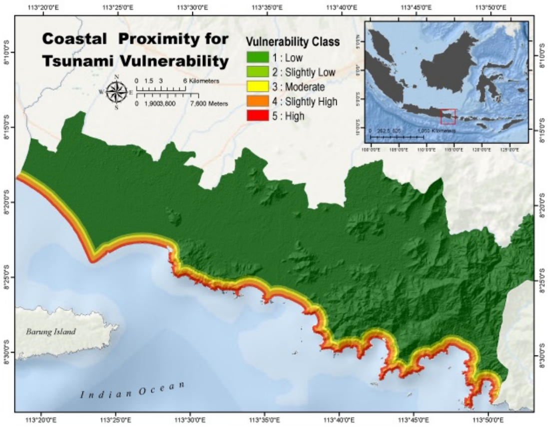

Fig. 3 Coastal proximity map for tsunami vulnerability

Moreover, land use map was generated from supervised classification process of ALOS/AVNIR-2 image. The reflectance value of ALOS image applied in maximum likelihood classification and generated five classes of land use in the study area. Before calculating parameters for tsunami vulnerability mapping, each parameter should be re-classify based on tsunami vulnerability classes, using criteria described in Table 1.

Table 1 Parameter classification based on vulnerability classes. [13][14][15][16]

Parameters	**Vulnerability Classes**				
	5	**4**	**3**	**2**	**1**
Elevation (m)	<5	5-10	10-15	15-20	>20
Slope (%)	0-2	2-6	6-13	13-20	>20
Coastal type	-	Bay	Straight	Cape	-
Land use	Urban	Agriculture	Bare	Water	Forest
Coastal proximity (m)	<293	293-514	514-762	762-1032	>1032
River proximity (m)	<100	100-200	200-300	300-500	>500

Raster overlay for tsunami vulnerability mapping was done based on the weight of parameters. Weights were calculated using Analytical Hierarchy Process (AHP). The weighted overlay is a technique for applying a common measurement scale of values to diverse and dissimilar inputs to create an integrated analysis. The weighted overlay also one of the suitability analysis based on spatial multi-criteria processing [13,17]. Vulnerability map was generating by applying a weight value to each parameter in raster data format.

The calculation applied;

*Vulnerability = [elevation*0.28] + [slope*0.19] + [coastal_ proximity*0.18] + [river proximity*0.12] + [coastal type*0.13] + [land use*0.09]*, as the result as shown in Fig. 4.

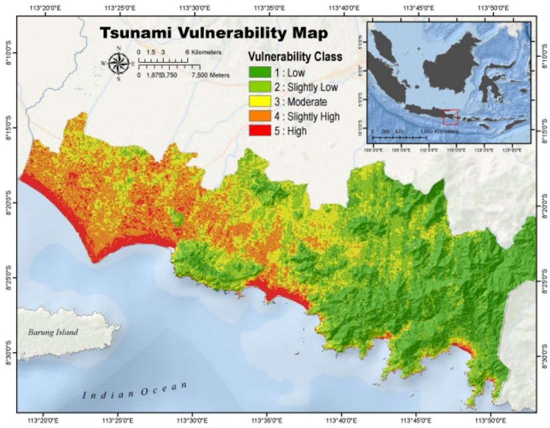

Fig. 4 Tsunami vulnerability map

The use of AHP analysis in generating the weight of parameters in which applied in weighted raster overlay describes five classes of vulnerability due to the tsunami in the coastal area of the study area (Fig. 4). It describes that western part of the study area, mostly in the class of slightly high to the high class of tsunami. This area was identified as a flat area with land use class of urban area and agriculture. The associated dataset required for the vulnerability assessment including a number of buildings, typologies of buildings, number of floors, or age of the building.

The coastal area exposed to tsunami inundation, the buildings and infrastructure are not uniformly at risk within the flood zone [18,19]. The probability of damage is related both to vulnerability and to the tsunami wave energy. Damage level to buildings depends on building type and on inundation depth [20] or could depend on the density of vegetation around the coastal that assumed will reduce tsunami impact. Assessing tsunami vulnerability in the urban area has to consider that individual building will interact differently with a tsunami depending on a number of parameters [18,19]. Various parameters that affect the resistance of the building interact to generate a real class of building vulnerability [20,21].

3.2 Seismic and Run Up Analysis

Seismic data are physical observations or measurements, seismic sources, seismic waves, and their propagating media. The purpose of processing seismic data is to learn something about the Earth's interior. It needs to figure out some specific relations between the intended targets and measurable parameters in order understand certain aspects of the Earth [22].

All initial tsunami warnings are based on rapid detection and characterization of seismic activity. Because of the fundamental differences in nature between the solid earth in which an earthquake takes place and the fluid ocean where tsunami gravity waves propagate, the vast majority of earthquakes occurring on a daily basis do not trigger appreciable or even measurable tsunamis. It takes a large event (magnitude >7.0) to generate a damaging tsunami in the near-field and a great earthquake (magnitude >8.0) to generate a tsunami in the far-field [23].

The study area was identified as a high number of the seismic point with the depth average of 1 to 5 km and the range of magnitude 1 until >6. As the result, the coastal area of East Java can be classified as a highly vulnerable to tsunami. Based on historical data, it was a magnitude of 7.8 Mw in the depth of 18 km and latitude of -10.477º/longitude of 112.835º, caused a big tsunami and affected to the coastal area of East Java, including in this study area (Fig. 5).

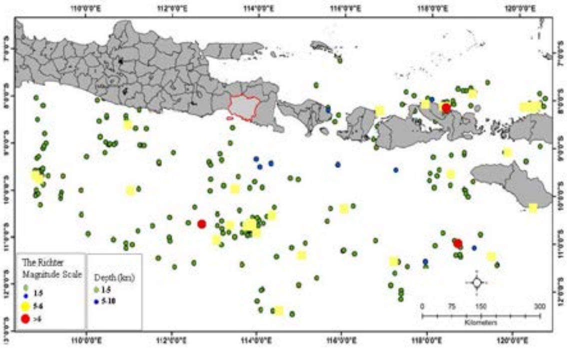

Fig. 5 Seismic data in the Indian Ocean from 1992 to 2004 from U.S. Geological Survey.

Figure 5 illustrated that based on the U.S. Geological Survey data of seismic intensity around Indonesia, it was recorded that the range of magnitude was 1 to 6.3 Mw. It describes the typical effects of earthquakes of various magnitudes near the epicenter. The intensity and thus ground effects depend not only on the magnitude but also on the distance to the epicenter, the depth of the earthquake's focus beneath the epicenter, the location of the epicenter and geological conditions.

The magnitude of 1 – 6.3 was classified as micro to strong effect or I until VII to X in Mercalli intensity. It was categorized that the damage to a moderate number of well-built structures in populated areas. Earthquake-resistant structures survive with slight to moderate damage. Poorly designed structures receive moderate to severe damage. Felt in wider areas; up to hundreds of miles/kilometers from the epicenter and strong to violent shaking in the epicenter area.

The historical tsunami event of 1994 was used as a basic data for run up analysis. The maximum run-up was recorded at Tempurejo district (11.2 m), and minimum run-up was 3.1 m in the area of Puger district. The run-up analysis described seven points of a run-up point along the coastal area of Jember Regency. Tsunami run-up parameter is one of the important parameters in determining tsunami risk due to this parameter is the main parameter in hazard criteria.

The last survey reported by [11] described that in the North West part of the study area, Cape Pelindu, a small fishermen village where a fishery created a sort of barrier to the sea water, separating houses from the open sea. The fishery defense wall and three typical straw houses were destroyed. According to eye-witnesses, three big waves followed each other, the third one being the biggest. The measured maximum water height was 3.20 m and the maximum water ingression was about 350m.

The next area was Puger district where no evidence of a tsunami could be observed in the harbor. But just a few kilometers westward, in a place called Tambak Getem, the tsunami left visible marks on the beach: the keeper of a fishery reported that he weakly felt the shock and about 15 minutes later three big waves flooded the beach, the last penetrating about 300 m in the land. The measured maximum water height was 5.85 m [11].

Close to the area of Puger district, it was a big river. In general, rivers were identified in four different areas. Rivers can play an important role in expanding the impact of the damage during a tsunami event. The run-up of the tsunami reaches the hinterland not only through the low elevation of the area but also through rivers. Rivers also act as flooding strips transporting inundation [13,24].

3.3 Tsunami Risk Assessment

Vulnerability refers to the potential for casualty, destruction, damage, disruption or another form of loss in a particular element. Risk combines this with the probable level of loss to be expected from a predictable magnitude of hazard (which can be considered as the manifestation of the agent that produces the loss). The risk is thus the product of hazard and vulnerability. It is an essentially hypothetical quantity, in that it can only materialize in the form of disaster impacts [25,26].

Risk, vulnerability, and hazard are the three factors or elements which we are considering here in this pseudo equation. Another definition of risk given by Factor analysis of information risk which may be related to disaster is 'the probable frequency and probable magnitude of future losses. [27]

The numeric value of risk can be calculated as the product between vulnerability and hazard level. Since vulnerability level ranges from 1 to 5 and hazard level ranges from 1 to 4, the risk level of each vulnerable element will be given by:

$$\boldsymbol{R = V \cdot \frac{H}{4}} \tag{2}$$

R is a risk, V is a vulnerability, and H is a hazard. R must be an integer number ranging from 1 to 5, where 5 stands for the maximum risk level. Once risk level has been calculated it will be possible to plot it on a risk map by the process of GIS. Risk map also generated using weighted cell-based overlay. Weighted overlay analysis allows the user to combine weight and rank several different types of information and visualize it, so multiple factors can be evaluated at once [10].

All parameters generated tsunami risk map was displayed in grid cells. Cells were then classified based on its value to five classes of risk; represent low, slightly low, medium, slightly high and high risk. Grouping cells in this raster data followed zonal function operation. Each cell is encoded based on the criteria that make up a zone.

Tsunami risk map (Fig. 6) in the area of East Java, as the result of this study, applied weighted linear combination. This approach processed in a raster GIS in which factors were combined by applying a weight value to each followed by a summation of the results using equation of $\sum\ (W_i\ \cdot\ X_i)$, where Wi is the weight values of the parameter i, and Xi is the potential rating of the factor [28][29].

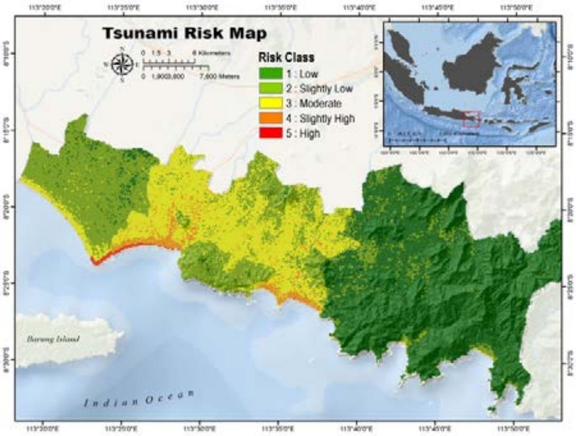

Fig. 6 Tsunami risk map.

3.4 Discussion

Tsunami risk map describes that risk level in the study area divided into five classes. Moderate until the high class of tsunami risk was found in the western part. This area mostly covered by flat elevation with a rare density of coastal vegetation and high density of the urban area. In the previous tsunami event, run up of 4.85 – 5.85 m was recorded in this area.

The high density of mangrove in coastal areas and reefs can be a barrier to reduce the effect of the tsunami wave, as well as the islands with steep-sided fringing is only at moderate risk from tsunamis. Study about predicting 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 when hit the coastal area [24]. The high density of mangrove along coastal area has the capacity to minimize the negative impact of a tsunami wave. Dense mangrove forests growing along coastal areas can help reduce the devastating impact of tsunamis and coastal storms by absorbing some of the waves' energy. When the tsunami struck India's southern state of Tamil Nadu on 26 December, for example, coastal areas in with dense mangroves (area of Pichavaram and Muthupet) suffered fewer human casualties and less damage to property compared to areas without mangroves [30].

Tsunamis waves may undergo extensive refraction and create a process that may converge their energy to particular areas on the coastal areas and increase the heights. High risk of a tsunami is depending on the water depth, the coastal geomorphology, the direction of the tsunami wave, and the existence of rivers or other water canals. Fig. 6 described that the high class of tsunami risk was identified in the area of Puger district. The total area of tsunami risk in the study area is described in Table 2 and Table 3.

Table 2 Tsunami risk area

No.	Risk level	Cell	Area (m^2)	Area (Ha)
1	Slightly low	2,981	298,100	29.81
2	Low	39,643	3,964,300	396.43
3	Moderate	1,784	178,400	17.84
4	High	153	15,300	1.53
5	Slightly high	-	-	-
	Total	44561	4456100	445,61

Table 3 Percentage of tsunami risk level in different district

District	Risk percentage (%)					Total (%)
	Slightly low	Low	Moderate	High	Slightly High	
Kencong	-	92.55	7.44	-	-	100
Gumukmas	-	87.48	10.84	1.66	-	100
Puger	-	81.01	16.81	2.71	-	100
Wuluhan	1.11	97.69	1.16	0.017	-	100
Ambulu	0.69	91.58	7.71	-	-	100
Tempurejo	12.42	87.37	0.18	0.004	-	100

Four districts in the study area was classified as high risk of the tsunami; Gumukmas (0.70 Ha), Puger (0.79 Ha), Wuluhan (0.001 Ha), and Tempurejo (0.001 Ha). Moreover, moderate to low level was in the district of Ambulu, Wuluhan dan Tempurejo. The level of tsunami risk for each district was different due to the topography or land cover of the area. Puger was an area that most affected based on tsunami risk mapping. Land use in Puger was mostly covered by urban area and the area with low elevation, low density of vegetation, and close to the big river. This area is one of the important marine fisheries activities in East Java province.

The use of pair-wise comparison matrix helps in the analysis of multi-criteria data where all of the parameters used in this study were calculated based on its weight factor to create vulnerability and also risk map. The calculation of weight as a result of pair-wise comparison matrix was created from expert judgment. Tsunami vulnerability research in Alexandria was applied all parameter in equal weight due to the limitation of knowledge regarding the study area [31].

The high vulnerability areas were mostly found in the coastal area with the sloping coast type. Elevation and slope play an important role in governing the stability of a terrain. Tsunami vulnerability research in Bali, Indonesia shows the distribution of vulnerability is not uniform and physically it is highly influenced by coastal proximity, elevation, and slope [32][13]. Tsunami risk map that described here based on the integrated approach and to is provided to the people in the study area in the near future due to less information about tsunami risk in the study area.

4. CONCLUSIONS

Tsunami risk can be assessed using the application of multi-criteria analysis followed by weighted cell-based processing in which DEM data was applied. The result performs here can be used for the evacuation and reconstruction plan due to the tsunami disaster. Also, this will be important basic information in determining the evacuation route and evacuation building. Moreover, the final target of tsunami risk mapping is to reduce the effect of the tsunami by generating a good mitigation plan.

The combination of raster weighted overlay in the geospatial data analysis indicated the vulnerability and risk area due to the tsunami and described the possible area that could be affected by the tsunami. The weight of each parameter was calculated by pair-wise comparison matrix of expert judgment, in which every parameter was weighted not equally.

By applying overlay process for tsunami risk map and existing land use will describe which area need first to be evacuated when tsunami comes.The result of weighted overlay illustrated that high class of tsunami vulnerability and tsunami risk mostly in the class of urban area, while forest area was indicated in the low class. The more parameters that are applied, the more detailed is the assessment that can be analyzed and displayed.

5. ACKNOWLEDGEMENTS

Authors are thankful to Ministry of Research, Technology and Higher Education Indonesia for financial support, METI and NASA for the Aster GDEM version 2 products, Japan Aerospace Exploration Agency (JAXA) for the ALOS images, BIG Indonesia for providing the basic map of the study area, and U.S. Geological Survey for seismic data. We also thank Laboratory of Disaster Prevention System, Yamaguchi University, Japan and Laboratory of Marine Resources Exploration, Brawijaya University Indonesia

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