

GEOSPATIAL MODEL OF PHYSICAL AND SOCIAL VULNERABILITY FOR TSUNAMI RISK ANALYSIS

* Abu Bakar Sambah^{1,2}, F. Miura³, Guntur¹, Sunardi¹, and A. F. Febriana¹

¹Faculty of Fisheries and Marine Science, University of Brawijaya, Indonesia; ²Marine Resources Exploration and Management Research Group, University of Brawijaya, Indonesia, ³Faculty of Engineering, Yamaguchi University, Japan

*Corresponding Author, Received: 01 Jan. 2019, Revised: 27 Jan. 2019, Accepted: 25 Feb. 2019

ABSTRACT: Tsunami risk assessment is required to support preparedness activities and effective disaster reduction. In this study, the analysis of physical and social vulnerability for tsunami risk assessment was applied for tsunami mitigation activities in coastal areas. The analysis was applied in the southern coastal area of East Java, Indonesia. The application of Geographical Information System (GIS) was used to capture, store, manipulate, analyze, manage, and visualize geographic data used for tsunami risk analysis. GIS makes possible in integrating a complex layer of the geographic phenomenon and the parameter of tsunami vulnerability. In this case, the spatial overlay of physical and social vulnerability was done using spatial multi-criteria approach. Physical vulnerability parameters analyzed in this study were elevation, slope, land use, and distance from the coast. While the social vulnerability parameters include the number of population, age distribution, number of women, and people with disabilities. The results described the visualization of possible damage and loss areas that may result from a tsunami attack. The analysis illustrated that the most vulnerable areas of the tsunami were areas with low elevation, very sloping slopes, areas that close enough to the coastline and the land use type of residential class. The areas with high vulnerability class also illustrated by social vulnerability parameters especially population density. The estimates of affected areas due to tsunamis can help the decision-makers in mitigating the possible consequences of tsunamis, managing the emergency response related to the tsunami disaster, and developing plans for recovery and reconstruction after the tsunami event.

Keywords: Geospatial, Tsunami, Vulnerability, Risk

1. INTRODUCTION

The tsunami disaster has been considered a major disaster such that many types of research have been done to assess both its vulnerability and risk for coastal areas. Tsunami risk assessment has been done to quantify the potential damage and losses area due to tsunami [1]–[2]. Tsunami risk assessment needs an integrated analysis of geospatial data related to the tsunami hazard and the element of risk [3]. In order to assess tsunami risk, the assessment of vulnerability is necessary. In common, risk assessment implies two dimensions; the assessment of hazard (external part), and the assessment of vulnerability (internal) [4]. Tsunami vulnerability is analyzed after the evaluation of tsunami potential and probability. It depends on how close the communities are to the hazard source, and their social and economic characteristics [5]. Vulnerability also defines as “*The conditions determined by physical, social, economic, and environmental factors or processes, which increase the susceptibility of a community to the impact of hazards*” [6]. Vulnerability is trans-disciplinary and multi-dimensional, which covers social, economic, physical, political, engineering

and ecological aspects and dimensions [7].

The negative impact of tsunami occurrence in coastal areas is not a recent phenomenon, but the model of study for assessing the impact damage, vulnerability, and risk is a relatively new trend [8]. The project of Coastal Risk Analysis for Tsunamis and Environmental Remediation (CRATER) has been applied for assessing tsunami vulnerability in the coastal area using the parameters of infrastructural, geomorphological, and ecological features, elevation, coastal proximity, and parameters of land use [9]. Moreover, the Ppathoma Tsunami Vulnerability Assessment (PTVA) model has been applied also for providing initial assessments of building vulnerability [10]–[11]–[12].

The Indian Ocean includes South area of East Java Indonesia is located at one of the most active geological subduction zones. During December 2004 and July 2006 most recent seaquakes followed by huge tsunamis and it is expected to occur also in the near future [7]. Highly destructive tsunamis have been recorded at a number of locations in South Java, Indonesia (East Java in June 1994, Cilacap and Pangandaran in July 2006) [13]–[14]. It affected almost every sector of the

economy, including agriculture, fishery, tourism, transportation, housing, and health [15].

In order to construct better disaster mitigation due to the tsunami, appropriate analysis related to the tsunami vulnerability and risk assessment is necessary. The application of geospatial analysis for tsunami vulnerability and risk assessment has also applied using remotely sensed dataset [12]–[16]–[17]–[18]–[19]. Another geospatial approach has also applied soil type, urban form and social dataset for assessing potential natural hazard [20] and has determined the tsunami-vulnerable area by comparing the map tsunami-affected area and the topography data, which is related to land elevation, land use class, and the distance from the coast [21]. This study tried to assess the potential of the affected area as the impact of the tsunami, in which tsunami vulnerability areas will be calculated using both physical and social vulnerability parameters.

2. METHODS

2.1 Research Area

Tsunami vulnerability mapping using physical and social vulnerability parameter was applied in the coastal area of Blitar district, East Java, Indonesia (Fig. 1). This area is bordered by District of Malang, East Java on the East part. It also directly faces the Indian Ocean on south part.

Geographically, Blitar district is located at the southern of East Java with a height of 167 meters above sea level, at coordinates of 111° 40' - 112° 10' East longitude and 7° 58' - 8° 9' South latitude. Blitar district has a 45 km-long coastline with 26,100 hectares of 4 nautical miles areas, and 63,330 hectares of 12 nautical miles.

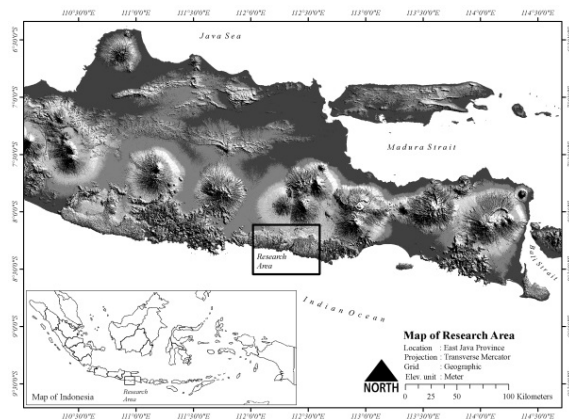


Fig. 1 Research area.

2.2 Dataset

In order to create tsunami vulnerability map of the research area, the parameter of both physical

and social vulnerability was collected. Physical vulnerability parameter includes elevation, slope, land use, and coastal proximity. Moreover, social vulnerability parameter consists of population density, gender, age, and disabilities. The elevation and slope data were created from the ASTER Global Digital Elevation Model (ASTER GDEM) version 2. Aster GDEM was collected from <https://gdex.cr.usgs.gov/gdex/>. The analysis of Landsat 8 OLI satellite image was applied to create a land use map. Landsat image was collected from <https://earthexplorer.usgs.gov/>. In addition, to preparing coastal proximity, digital vector map of the research area was applied. Social vulnerability data was collected from Indonesia Central Bureau of Statistics.

3. GEOSPATIAL ANALYSIS

Data analysis was done through geospatial analysis. The analysis consists of four steps (Fig. 2). It starts with data acquisition, pre-processing, geospatial analysis, and result. Data consist of two data type, raster and vector dataset. ASTER GDEM was applied for elevation and slope data as one of the physical vulnerability data. Moreover, Landsat 8 OLI satellite image as raster data was applied in order to create a land use map.

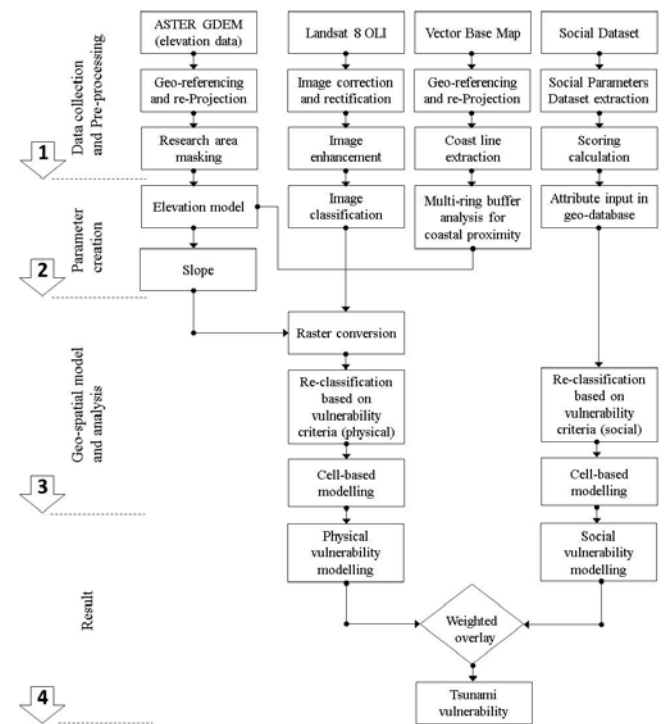


Fig. 2 Research step.

Vector data includes a base map of the research area, and it was applied for creating coastal

proximity, the distance from coastline to the hinterland. All parameters were classified into five classes based on physical tsunami vulnerability. Social vulnerability data was taken from Indonesia Central Bureau of Statistics. Data were classified and scored based on the criteria of social tsunami vulnerability. It consists of population density, gender, age, and disabilities.

Data analysis for creating tsunami vulnerability map, as a combination of physical and social tsunami vulnerability, was done using cell-based modeling in the term of geographical information system. All parameter applied in the model was converted to a raster dataset. This data consists of a matrix of cell and were classified in different weight. The weighted overlay is a type of suitability analysis that helps in analyzing geographic data based on multiple criteria. Weighted overlay allows the user to combine the weight of several different types of information and visualize it, in which multiple factors can be evaluated at once [22]–[23]. The illustration as described in Fig. 3.

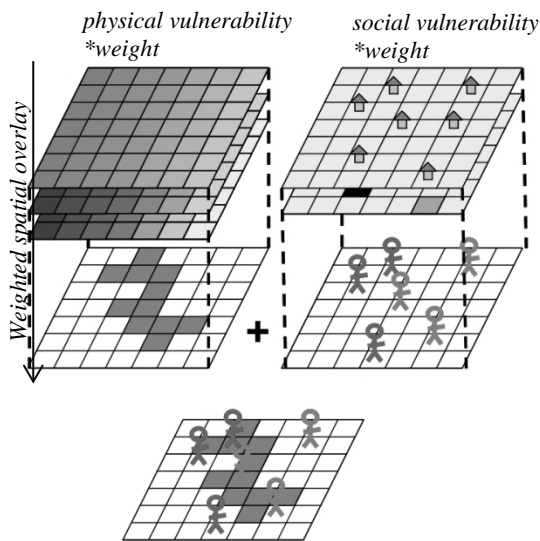


Fig. 3 Illustration of weighted overlay through cell-based modeling.

3.1 Physical Vulnerability

Four physical vulnerability parameters were converted to raster cell type and analyzed using a weighted overlay to create a map of tsunami vulnerability. Raster cells of all parameters were classified based on its value to five classes of vulnerabilities represent low, slightly low, medium, slightly high and high vulnerability. The vulnerability classes and its weight as described in Table 1, and tsunami vulnerability map as described in Fig. 4.

Table 1 Physical vulnerability classes and weight [12]–[24]–[25]–[26]

Parameters	Weight (%)	Vulnerability Classes				
		5	4	3	2	1
Elevation (m)	45.94	<5	5-10	10-15	15-20	>20
Slope (%)	25.53	0-2	2-6	6-13	13-20	>20
Land use	11.81	Urban area	Agriculture	Bare soil	Water	Forest
Coastal proximity (m)	16.71	0-293	293-514	514-762	762-1032	>1032

1=low, 2=slightly low, 3=medium, 4=slightly high and 5=high vulnerability

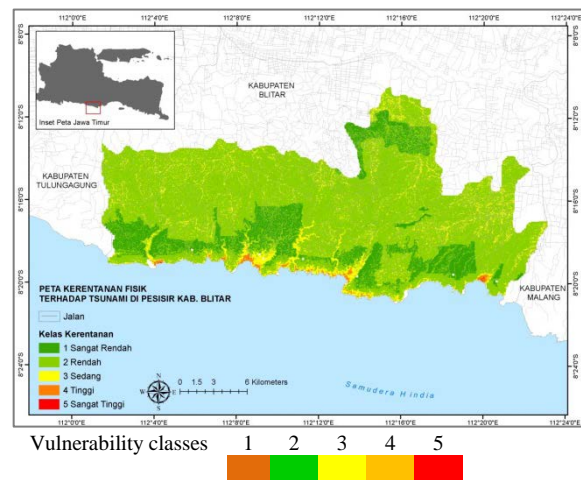


Fig. 4 Tsunami vulnerability map based on the physical parameter

Figure 4 describes the tsunami vulnerability map in the coastal area of Blitar district based on physical parameters. Diverse elevation of research area causes a different level of vulnerability. In some coastal areas close to the ocean covered by high cliffs and it described a low class of tsunami vulnerability. The area of high vulnerability is found only in areas with elevations close to 0 or less than 5 meters. This area identified as a bay area with some settlement

3.2 Social Vulnerability

The social vulnerability can be defined as the exposure of groups or individuals to unexpected changes and disruption to livelihoods [27]. Social vulnerability also can be measured as a result of social and place inequalities [28].

Moreover, it defined also as the limitation of a community to the impact of natural disasters that influence its ability or resilience in order to mitigate, recover, and preparedness from the impacts. [29]. Social vulnerability map was created using four parameters and weighted equally. The

calculation was based on the criteria as described in Table 2. Social vulnerability map as described in Fig. 5.

Table 2 Social vulnerability criteria and weight [3]

Parameters [a]	Σ [b]	Proportion* [c]	Score** [d]	Weight [e]
Population density	P	[b]/total population	[c]/maximum proportion	25
Gender	G	[b]/total woman	[c]/maximum proportion	25
Age***	A	[b]/total age	[c]/maximum proportion	25
Disabilities	D	[b]/total disabilities	[c]/maximum proportion	25

* determine the factor of each village divided by number per sub-district

** the same value for all places on all the social variables

*** number of elderly and children

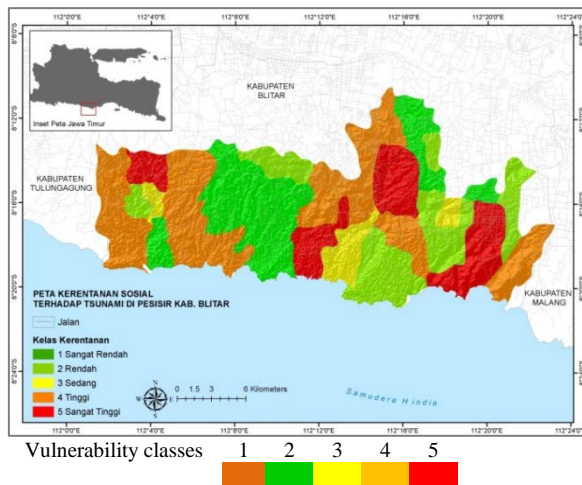


Fig. 5 Tsunami vulnerability map based on social parameter

4. DISCUSSION

Vulnerability represents the susceptibility of a given population to damaging effects from exposure to hazardous events [30]–[31]. The combination of physical and social parameters for assessing tsunami vulnerability area using cell-based modeling is one of the approaches in order to support risk analysis. Cell-based modeling calculated every single pixel of the parameter based on its score and weight. The analysis follows arithmetic logic as below.

$$\text{Vulnerability} = \sum W_i X_i \quad (1)$$

$$\text{Total vulnerability} = \sum (\text{physical vulnerability} \times \text{weight}) + (\text{social vulnerability} \times \text{weight}) \quad (2)$$

Total vulnerability illustrated the vulnerability area due to the tsunami in which four parameters of physical vulnerability and four parameter of social vulnerability were combined (spatial overlay) as described in Fig. 6.

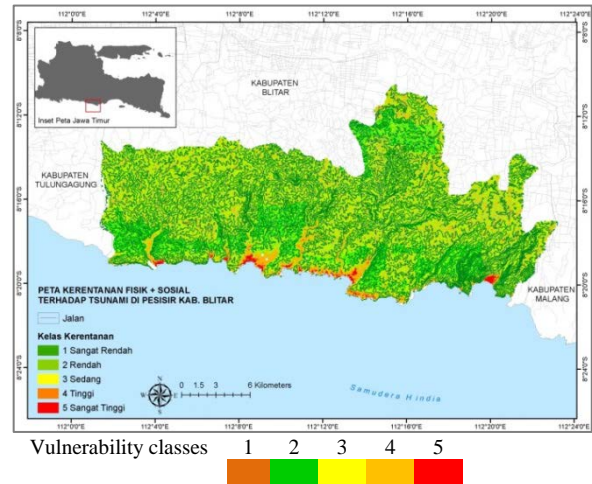


Fig. 6 Tsunami vulnerability map

Table 3 Total vulnerability area

No	Vulnerability classes	Area (Ha)
1	low	50,3204
2	slightly low	176,5883
3	medium	824,6320
4	slightly high	383,9447
5	high	4,2357

Vulnerability maps as described in Fig. 6 includes the information of total area per vulnerability classes (Table 3) may be good for a communication tool for disaster preparedness [32]. The information on the map also plays an important role in an effective early warning system. People often do not understand their risk; the social vulnerability map provides information on village or sub-districts with relatively high vulnerability. By integrating the physical and social vulnerability in the early warning system, coastal communities will be aware of their risks. As consequent, it will enhance the community’s preparedness for a tsunami.

5. CONCLUSIONS

The geospatial model followed by the weighted cell-based processing described the good result in assessing tsunami vulnerability area.

The combination of physical and social vulnerability parameters in the model also described good approaches in order to create tsunami vulnerability map. The map is important in determining the possibility area that could be affected by the tsunami wave. The result illustrated important information in many applications to support disaster risk management and mitigation strategies. Furthermore, in order to obtain an accurate tsunami vulnerability map and inundation map, this method can be applied by adding other vulnerability parameter such as coastal ecology (coral reef), barrier island, coastal type, and also tsunami direction.

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