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ASSESSING TSUNAMI VULNERABILITY AREAS USING SATELLITE IMAGERY AND WEIGHTED CELL-BASED ANALYSIS

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ABSTRACT: The application of multi-criteria analysis followed by weighted cell-based processing is one of the methods for tsunami vulnerability mapping. In this study, vulnerability due to tsunami disaster in coastal area of East Java Province Indonesia was carried out. Appropriate input criteria were derived from Digital Elevation Model data, satellite remote sensing and survey data. The criteria applied were elevation, slope, coastal proximity, river proximity, coastal type, and land use. Five classes of vulnerability were defined from low to high vulnerability. Digital Elevation Model from Aster GDEM was applied for creating elevation and slope map, while ALOS satellite image was used in land use mapping. Moreover, vector map of East Java coastal area was used for creating coastal type, coastal proximity, and river proximity map. Analytical hierarchy process was applied in the calculation of parameter's weight, and it described that elevation was the highest weight. The area that identified as slightly high and high class of tsunami vulnerability spread in the coastal area which has a lower elevation and predict as inundated area. Most of the area was urban areas with low vegetation density. The high vulnerability areas were mostly found in the coastal area with the sloping coast type. The result presented here can aid as a basic data for city planning related to disaster mitigation and for the evacuation process and management strategy during disaster.

Keywords: Tsunami vulnerability, Weighted cell-based, Geo-spatial data

1. INTRODUCTION

Assessing tsunami vulnerability areas can provide basic information that is important for tsunami disaster risk management plans and mitigation. Tsunami vulnerability assessment is essential to disaster management planning. This includes pre-planning appropriate response activities in order to minimize the impact of disaster and all possibilities that will happen. This also plays an important role in preparing and mitigating for the future events [1].

Geologically, the south coast of Java Island is in the confluence of two major plates meet each other, Eurasian and Indo-Australian, where the movement of tectonic plates in this area will cause an earthquake that could trigger a tsunami. Based on the historical data of the earthquake event that followed by a potential destructive tsunami in the period of 1991 to 2006, recorded a tectonic earthquake in the Indian Ocean which triggered the tsunami on the southern coast of East Java, namely on June 3, 1994. A magnitude of 7.8 Mw, earthquake triggered a tsunami that affect southern coastal areas of Banyuwangi, East Java with estimated death toll reached 215 people [2]. The same events have the possibility to occur again in the same area in near future.

The development of geo-spatial analysis in the concept of a multi-criteria analysis for disaster management study provides an important integrated contribution in conducting a tsunami vulnerability assessment. A multi-criteria approach will be integrated into geo-spatial analysis. The study aims are to assess the vulnerability areas due to tsunami disaster and to analyse vulnerability area to different land use type. The use of multi-criteria and weighted cell-based analysis to assess the tsunami vulnerability areas was introduced in this study, in which this approach has not been applied before.

2. METHODS

2.1 Study Area

The study area includes coastal area of Jember District, East Java Province, Indonesia (Fig. 1). This area is one of the important areas for marine fisheries resources along southern part of Java Island, Indonesia.

This area also affected by tsunami event along coastal area of East Java on June 3, 1994, as the result of an earthquake at a depth of 15 km near the east end of the Java trench in the Indian Ocean [2].

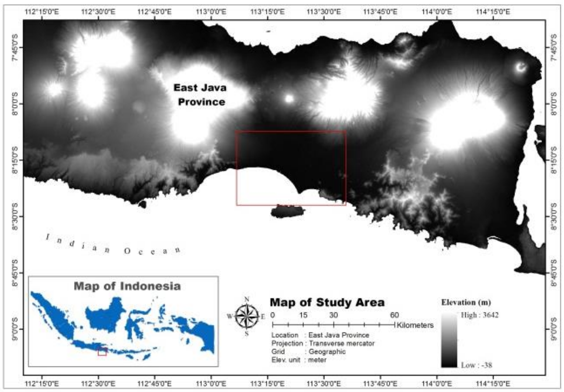


Fig. 1 Study area.

2.2 Dataset

ALOS satellite imagery with the instrument of panchromatic (PRISM) in the spatial resolution of 2.5 m and the Advanced Visible and Near Infrared Radiometer type 2 (AVNIR-2) with the spatial resolution of 10 m was analysed for land use observation. The elevation data was obtained from The ASTER Global Digital Elevation Model (ASTER GDEM) version 2. The Advanced Space-borne 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) [3]. In addition to prepare coastal morphology data, digital vector map of the study are was applied.

3. CRITERIA AND GEO-SPATIAL DATA PROCESSING

3.1 Criteria Construction

Vulnerability mapping has been carried out using the parameters elevation, slope, coastal distance, river proximity, coastal type, and land use. The steps of analysis are data collection, surface analysis of DEM data, vector map extraction, land use mapping, and multi criteria processing using pair-wise comparison analysis (see Fig. 2 and Fig. 3).

The two steps of this concept are the design and construction phases. The design phase includes the selection of criteria which is used for the vulnerability assessment, while the construction phase describes the process of geo-spatial data. Each of those criteria weighted based on analytical hierarchy process due to lack of knowledge regarding the impact level of each criteria.

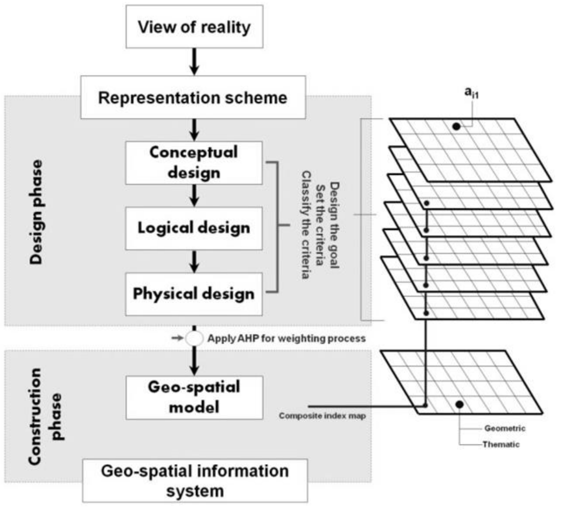


Fig. 2 General methodology adopted in this study.

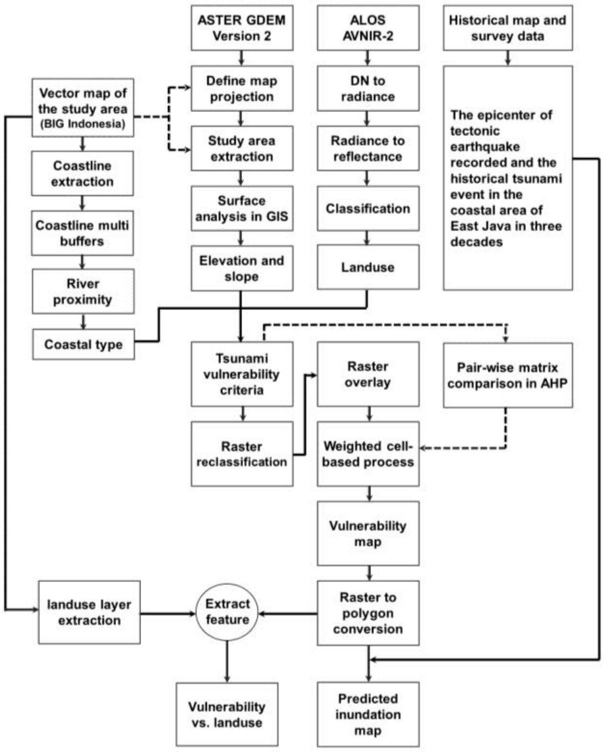


Fig. 3 Flow diagram of data processing.

3.2 Geo-spatial Data Processing

A set of criteria that describe the physical vulnerability are ; (1) elevation, that generated using ASTER GDEM version 2 data (downloaded from http://gdem.ersdac.jspacesystems.or.jp/; (2) slope, which is generated from elevation data; (3) coastal proximity, which is calculated the distance from coastline to the land using multi-buffering and was set based on the possibility range of the tsunami to reach the land; (4) river proximity; (5) coastal type; and (6) land use, as the result of ALOS AVNIR-2 image classification.

Slope was generated using Eq. (1). The rates of change (delta) of the surface in the horizontal (dz/dx) and vertical (dz/dy) directions from the center cell determine the slope. At a given point on a surface z=f (x,y), S is defined as a function of gradients at X and Y (i.e., West-East and North-South) directions.

$$\mathbf{S} = \sqrt{\left(\frac{\delta z}{\delta x}\right)^{2} + \left(\frac{\delta z}{\delta y}\right)^{2}} \qquad (1)$$

Coastal distance generated using vector map provided by Indonesia Geo-spatial Authority, and created using Eq. (2).

$$\boldsymbol{log}\mathbf{X}_{max} = \boldsymbol{log}\mathbf{1400} + {}^{\mathbf{4}}/_{\mathbf{3}}\, \boldsymbol{log}\left({}^{Y_0}/_{\mathbf{10}}\right) \qquad (2)$$

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

Land use map generated from supervised classification process of ALOS image. Land use class was divided into five classes. We select representative samples for each land use class in the reflectance value of digital image. The classification of land use was based on the spectral signature defined in the training set. Maximum likelihood classification was applied in the supervised process.

Criteria was calculated using its vulnerability value range as shown in Table 1 and Table 2, while map of tsunami vulnerability based on the criteria described in Fig. 4, Fig. 5, Fig. 6, Fig. 7, Fig. 8, and Fig. 9

Table 1 Tsunami vulnerability value range (a)

Vulnerability class	Elevation (m)[1]	Slope (%)[2]	Landuse[3]
High	<5	0-2	Urban
Slightly high	5-10	2-6	Agriculture
Moderate	10-15	6-13	Bare soil
Slightly low	15-20	13-20	Water
Low	>20	>20	Forest

[1] [4]
[2] [5]
[3] [6]

Tsunami vulnerability maps based on elevation and slope (in Fig. 4 and Fig. 5) show vulnerability classes of slightly high and high were found to the western side of coastal areas. This area was identified as urban and agricultural areas, with the slope range between 0-13% and elevation of 0-15 m. The highest elevation (1185 m) was found in the eastern side of the study area and was classed as a low vulnerability to tsunami.

Table 2 Tsunami vulnerability value range (b)

Vulnerability class	Coastal proximity (m)[4]	River proximity (m)[5]	Coastal type[5]
High	<293	0-100	V bay
Slightly high	293-514	100-200	U bay
Moderate	514-762	200-300	Cape
Slightly low	762-1032	300-500	Straight
Low	>1032	>500	Neutral

[4] Based on Eq. 2 calculations
[5] [7]

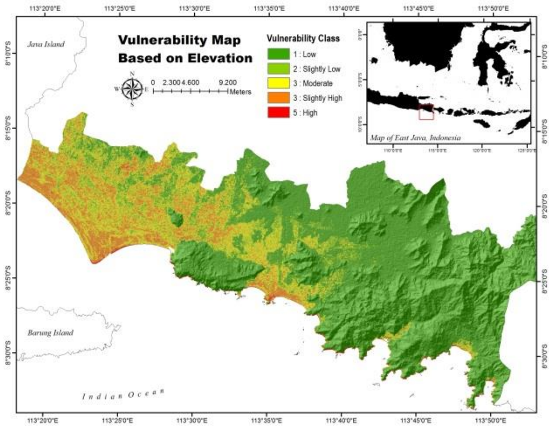


Fig. 4 Tsunami vulnerability map based on elevation.

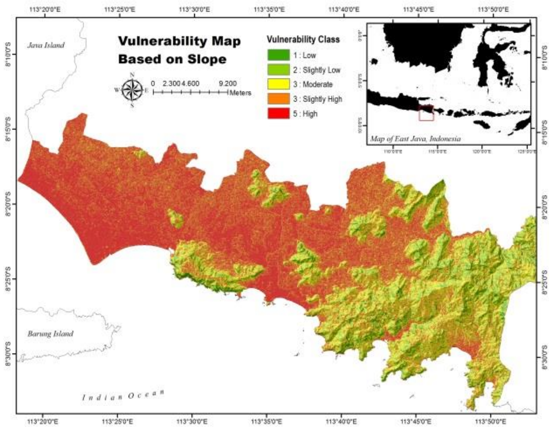


Fig. 5 Tsunami vulnerability map based on slope.

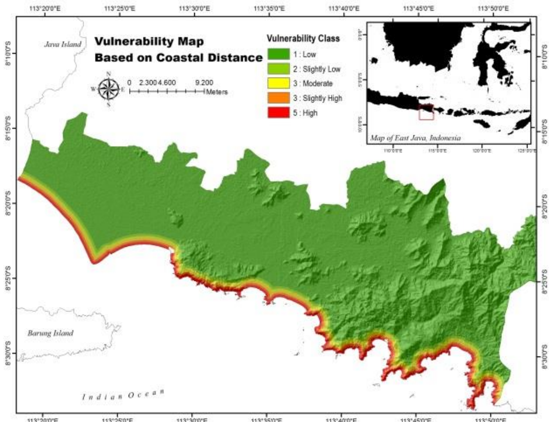


Fig. 6 Tsunami vulnerability map based on coastal proximity.

The tsunami vulnerability map based on coastal distance (in Fig. 6) was calculated based on the historical data collected during previous tsunami events by USGS. Minimum run up recorded in the study area was 3.1 m. The calculation of Eq.2 describes that 3.1 m of run up will reach 293m of the proximity from coastline to land, while in the proximity range of 1032 m will have 11.2 m of run up.

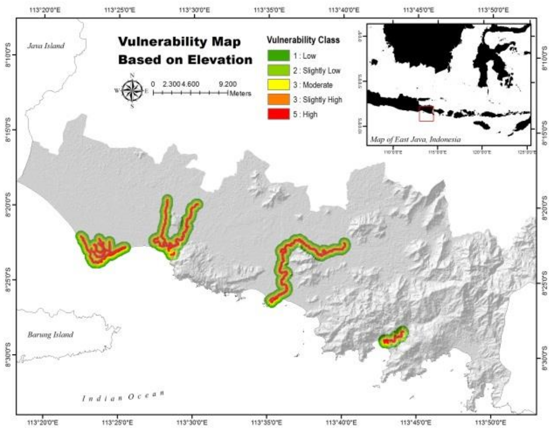


Fig. 7 Tsunami vulnerability map based on river proximity.

As shown in Fig 7, rivers were identified in four different areas. Rivers can play an important role in expanding the impact of the damage during 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 [8].

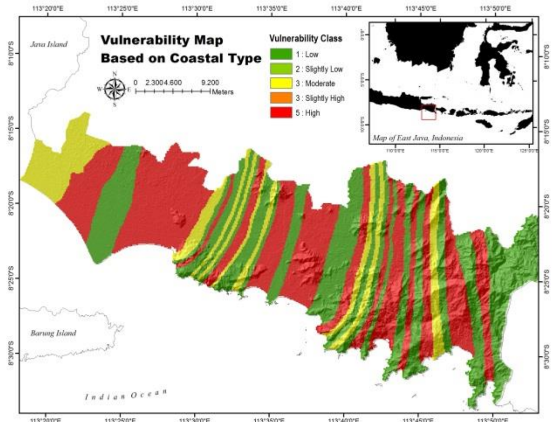


Fig. 8 Tsunami vulnerability map based on coastal type.

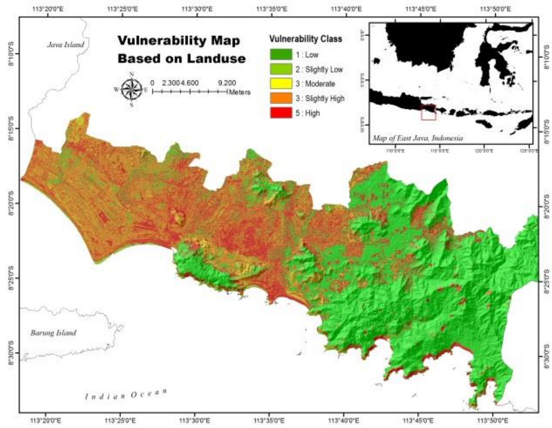


Fig. 9 Tsunami vulnerability map based on land use.

In the classification of tsunami vulnerability based on land use (Fig. 9), urban area represents a high class of tsunami vulnerability. Low density urban area was classified as bare soil and forested areas as the area with the lowest vulnerability to tsunami damage. High density of vegetation can have a significant effect on protecting the land from tsunami [9].

4. VULNERABILITY ASSESSMENT

4.1 Weighted Cell-based

Weighted overlay is a technique for applying a common measurement scale of values to diverse and dissimilar inputs to create an integrated analysis. Weighted overlay also is a type of suitability analysis that helps in analysing site conditions based on multiple criteria. By identifying and rating areas based on criteria, 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 are displayed in grid cells within this paper. Cells are then classified based on its value to five classes of vulnerabilities; represent low, slightly low, medium, slightly high and high vulnerability. Grouping cells in this raster data followed zonal function operation. Each cell is encoded based on the criteria that make up a zone.

Weighted linear combination is very straightforward in a raster GIS and factors are combined by applying a weight value to each followed by a summation of the results to create a vulnerability map using Eq. (3) [11].

$$Vulnerability = \sum (W_i \cdot X_i) \qquad (3)$$

Where, Wi is the weight values of the parameter i, and Xi is the potential rating of the factor.

4.2 Tsunami Vulnerability Mapping

In order to create the vulnerability map, each raster cell of the criteria was calculated to its weight. The weight of each criterion was calculated using pair-wise comparison matrix and normalized matrix processing until 6th iteration (see Table 3).

Table 3 Pair-wise comparison matrix

	Normalized principal eigenvector (6th iteration)						
	c.1	c.2	c.3	c.4	c.5	c.6	%
c.1	0.28	0.29	0.353	0.288	0.184	0.273	28
c.2	0.187	0.194	0.176	0.231	0.184	0.182	19
c.3	0.14	0.194	0.176	0.231	0.245	0.136	18
c.4	0.112	0.097	0.088	0.115	0.184	0.182	12
c.5	0.187	0.129	0.088	0.077	0.122	0.136	13
c.6	0.093	0.097	0.118	0.058	0.082	0.091	9

CI = 0.032, CR = 2.6%

c.1 : elevation; c.2 : slope; c.3 : coastal proximity; c.4 : river proximity; c.5 coastal type; c.6 : land use

The comparison matrix of each parameter (c.1 until c.6) as shown in Table 3 was calculated using Saaty scale of AHP (1 to 9 scales) [12]. Fig. 10 shows the output map as a result of weighted cell-based analysis. In the comparison matrix, elevation has the highest score out of other criteria, and is considered to be more important than slope, coastal proximity, river proximity, and land use. In term of coastal distance, even if the area is close to coastline, a higher elevation will have low vulnerability. The elevation parameter is considered the only reliable parameter of the tsunami magnitude to vulnerability functions on buildings that can be observed or measured following all tsunami events, while water depth during a tsunami will differ according to the ground elevation [13]-[1].

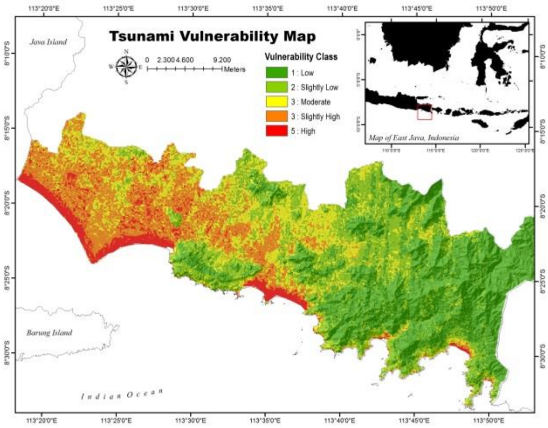


Fig. 10 Tsunami vulnerability map.

5. DISCUSSION

Vulnerability is the characteristics of a person or group and their situation that influences their capacity to anticipate, manage, resist, and recover from the impact of a hazard. It also represents the susceptibility of a given population to damaging effects from exposure to hazardous events [14]-[15]. Class of vulnerability could be based on physical criteria, such as elevation, slope, coastline proximity, and land use. Some research also put the criteria of coastal geomorphology, coastal ecosystem resources, direction of tsunami wave, and distance from river [1]-[7]-[8].

Coastal ecosystem including mangrove areas and reefs can be a barrier zone to reduce the effect of tsunami wave, as well as the islands with steep-sided fringing is only at moderate risk from tsunamis. Tsunami 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. This is depending on the water depth, the coastal geomorphology, and the direction of tsunami wave. Moreover, rivers can be a tsunami flooding strips and brings the tsunami wave to the hinterland.

During the 2011 Tōhoku's tsunami, some of the most dramatic flooding occurred close to the river, where flood water washed across large tracts of farmland and urban area. Research conducted by scientists at Tōhoku University suggests that waves from the tsunami travelled nearly 50 kilometres upstream from the coastal area (mouth of the Kitakami River) [16].

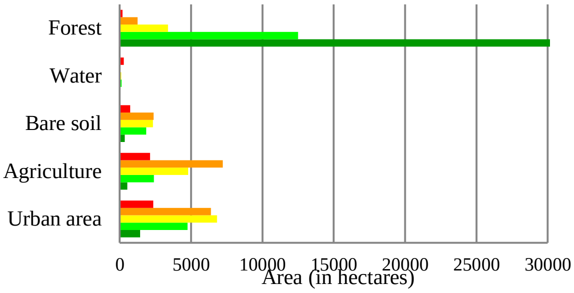
The use of pair-wise comparison matrix helps in the analysis of spatial multi criteria where all of the parameters used in this study were calculated based on its weight factor to create vulnerability map. Research conducted in coastal area of Miyagi Prefecture, Japan [8] also describes the application of pair-wise comparison matrix in weight calculation for each parameter. The result of this research shows a similar pattern of high class of tsunami vulnerability area to the real tsunami inundation area during the 2011 Tōhoku's tsunami [8]. The calculation of weight as a result of pair-wise comparison matrix was created from expert judgment. Expert knowledge about the weight scale of each parameter is a necessity, so that every parameter was weighted not equally since the individual importance of each parameter. Other research on tsunami vulnerability in Alexandria was applied all parameter in equal weight due to the limitation of knowledge regarding to the study area [17].

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 [18]. 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 [19].

The historical data of run up height in study area was used to assess tsunami inundated areas. Spatial analysis through grid overlay between historical run up height and tsunami vulnerability classes shows the inundated area may spread along the high class of vulnerability where the elevation was less than 20 m (Fig. 12 and Fig. 13). Inundated area mapping is important for preparing the evacuation route and evacuation building. Elevation more than 20 m indicates the area may select as evacuation area.

In the process of weighted overlay, elevation is the parameter that has the highest weight (28% of six parameters). Most of the area that identified as slightly high and high class of tsunami vulnerability is developed areas (urban areas) with low vegetation density. Previous research [20] stated different ways in which coastal vegetation may reduce the impact of tsunami. Vegetation will stops driftwood and other flotsam, reduces water flow velocity and inundation depth, provides a life-saving snare for people swept off land by a tsunami run-down, and amasses wind-blown sand and create dunes, which act as a natural barriers against tsunamis [20]. However, in the case of a huge tsunami event, narrow belts of coastal vegetation may be ineffective in providing protection, and in some cases may create more damage because of uprooted trees flowing inland [21].

The cell overlay of tsunami vulnerability map and land use map described that urban area was an area with high tsunami vulnerability due to the spread of urban area almost in the flat area of coastal zona with low elevation and low density of coastal vegetation (Fig. 11). This area also identified as a potential area of tsunami inundation (Fig. 12), which is illustrated flat area with low elevation from the coastal line until 3000 m to the hinterland (Fig. 13). Moreover, forest area was an area with low tsunami vulnerability, and it found almost in all of the east part of study area.



	Urban area	Agriculture	Bare soil	Water	Forest
5	2344.00	2139.00	742.00	282.00	191.00
4	6388.27	7229.85	2379.87	53.51	1262.98
3	6825.22	4801.37	2333.54	108.81	3379.93
2	4761.21	2404.74	1854.33	125.12	12495.11
1	1420.97	528.22	348.55	41.41	33422.98

1 : low; 2 : slightly low; 3 : moderate; 4 : slightly high; 5 : high

Fig. 11 Overlay graph of tsunami vulnerability class and land use (in hectares).

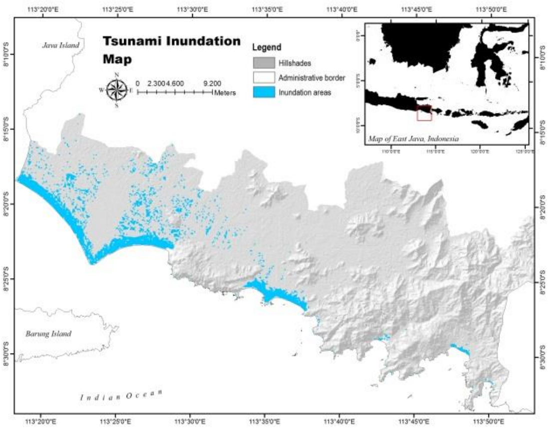


Fig. 12 Tsunami inundation prediction.

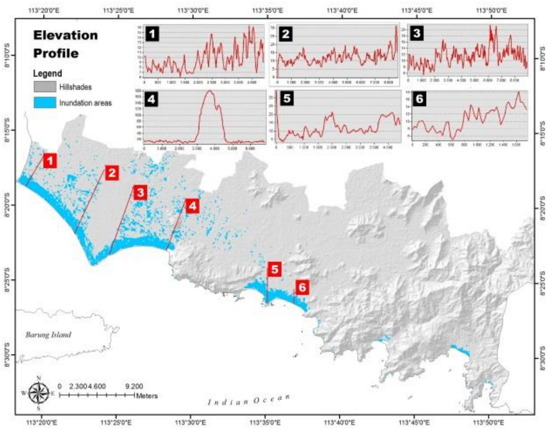


Fig. 13 Elevation profile along inundation areas.

Based on the study of Spatial Tsunami Wave Modelling for The South Java Coastal Area, Indonesia [22], it was characterised the south coastal area of East Java with 2 m up to 8 m high of tsunami waves. The model also described that time lag of tsunami run up in between high and low water run-up in this area was 10 minutes delay due to more gentle slope of the ocean floor morphology.

6. CONCLUSIONS

The application of multi criteria analysis followed by weighted cell-based processing is useful for tsunami vulnerability mapping. It can be used for the evacuation and reconstruction plan due to tsunami disaster. The combination of raster weighted overlay in the geo-spatial data analysis indicated the vulnerability area due to tsunami and described the possibility area that could be affected by tsunami wave. The weight of each parameter was calculated by pair-wise comparison matrix of expert judgment, in which every parameter was weighted not equally. Parameter of elevation was 28% of weight, while land use has the lowest weight (9%). Tsunami inundated area was indicated in the high class of vulnerability with the elevation less than 20 m. The spatial overlay result of tsunami vulnerability to land use classes describe that high class of tsunami vulnerability 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 displayed. Several parameters can be applied, such as land cover, geological structures, coastal type, and tsunami wave direction. In addition, the social and economic parameters also can be added, such as population density, type of building, household income, and business centre.

7. ACKNOWLEDGEMENTS

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