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Spatial multi criteria approach for tsunami risk assessment

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Abstract. Tsunami risk is defined as mathematical product between vulnerability and hazard. Tsunami risk also refers to the estimated loss from a given hazard to a given element at risk, and it is defined as a combination of tsunami hazard, tsunami vulnerability, exposure, and event probability. Besides tsunami vulnerability, tsunami risk is assessed by a number of criteria. This study applies the combination of element at risk to assess tsunami risk area along coastal area of East Java Indonesia. The study introduces the spatial multi-criteria analysis into tsunami risk assessment along with the existing perspective evolving the role of GIS. In this study, the existing vulnerability parameter was analysed and evaluated. The analysis was done using GIS-based spatial multi criteria approach. All parameter were analysed through weighted overlay using analytical hierarchy process and geospatial analysis. The results are provided as thematic maps of tsunami vulnerability map and tsunami risk map. Tsunami risk maps as a result from this study illustrate five levels of risk from very low to very high based on geospatial analysis. It describes that coastal area with low elevation was at high risk to tsunami, similar to that indicated in tsunami vulnerability map. Coastal area with high density of vegetation describes a low level tsunami risk. The existence of river and other water stream along coastal area are also 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.

1. Introduction

The application of satellite remote sensing and Geographical Information System (GIS) has become an integrated, well-developed, and successful tool in disaster research for effectiveness of risk management and disaster mitigation. An overview is given of the use of spatial data with emphasis on satellite remote sensing data, and of the approaches used for hazard assessment [1][2]. The development of satellite remote sensing and its applications enables the use of satellite imagery for identifying the distribution of areas damaged by tsunami disaster. Satellite images have the advantage of being able to deliver simultaneous images of large areas [3][4][5].

In earthquake related research, post-event hazard-related applications deal mainly with the quantification and measurement of earthquake-induced changes of land surface. Several aspects of pre-event earthquake hazard analysis are tackled by means of satellite remotely sensed data, especially by applying high spatial resolution of satellite imagery. In pre-event geological observations, remote sensing addresses the need for quantitative observational parameters on landforms or land cover

changes. In addition, with the aid of GIS, spatial multi-criteria analysis helps prioritize the decision-making process using geo-reference data. Spatial multi-criteria analysis is vastly different from conventional multi-criteria decision making techniques, due to the inclusion of an explicit geographic element. In contrast to conventional multi-criteria decision making techniques, spatial multi-criteria analysis applies information on both the criterion values and the geographical positions of alternatives, in addition to the decision-maker's preferences with respect to a set of evaluation parameters [6][7].
A variety of methods exist to assess the risk of different hazards [8]. However, applications on tsunami risk are very limited. There is still no generally adopted method to assess tsunami risk. The assessment of tsunami hazard and risk is therefore an important issue that must be addressed to identify the risk to populated areas and the surrounding land use.

Based on the geological aspect, 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 as a trigger of tsunami event. An earthquake event that is 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 [9]. It can be stated that the coastal area of East Java is vulnerable to tsunami disaster, and based on the historical event mentioned above this event have high possibility of occurrence in near future. It is expected that future tsunamis can have a higher impact due to the land use changes, increasing population and built areas and decreasing vegetation areas. To mitigate future tsunami events, it is necessary to understand and analyze this phenomenon in more detail using integrated approaches.

The study aim is to assess tsunami risk in the coastal area of East Java using spatial multi-criteria analysis together with the analysis of satellite imagery.

2. Methods

2.1. Dataset

Tsunami vulnerability area in the coastal of East Java was created from the Digital Elevation Model (DEM) collected form SRTM data. DEM data also applied 10 meters resolution from NextMap World 10. 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 which will be used to generate seismic map. In order to map the land use of study area, Landsat 8 OLI satellite imagery with the spatial resolution of 30 m was analyzed. Moreover, vector base map of East Java Indonesia was applied to prepare vector data of coastal morphology, coastal line, and river.

Table 1. Dataset

	Location	Product	Resolution		Source
Digital Elevation Model	Coastal area of East Java	SRTM V-4.1	3 arc-second	90m	CGIAR-CSI
	Coastal area of Malang District	NextMap World 10		10m	NextMap
Land use	Coastal area of Malang District	Landsat 8 OLI		30m	
Vector map	East Java	Vector map ; point, polyline, polygon		UTM Zona 49S	BIG Indonesia

2.2. Study Area

The study was applied at the south coastal area of East Java, focusing on the coastal area of Malang District, Indonesia (Figure. 1). The coastal area of Malang district was known as one of important fishing port in East Java. This area was also affected by 1994 tsunami event along 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; [10][11]. Moreover, the general method of the study as described in Figure 2.

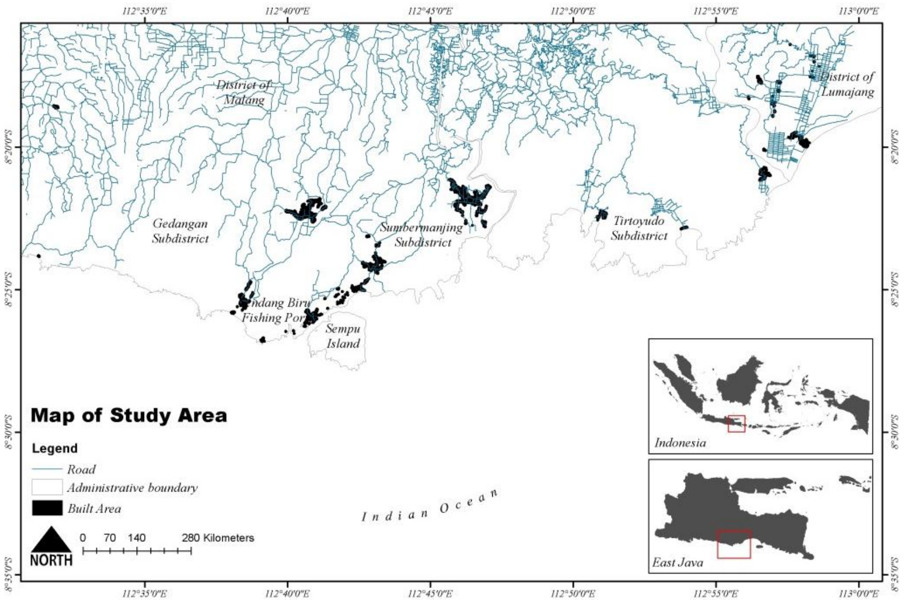

Figure 1. Study area.

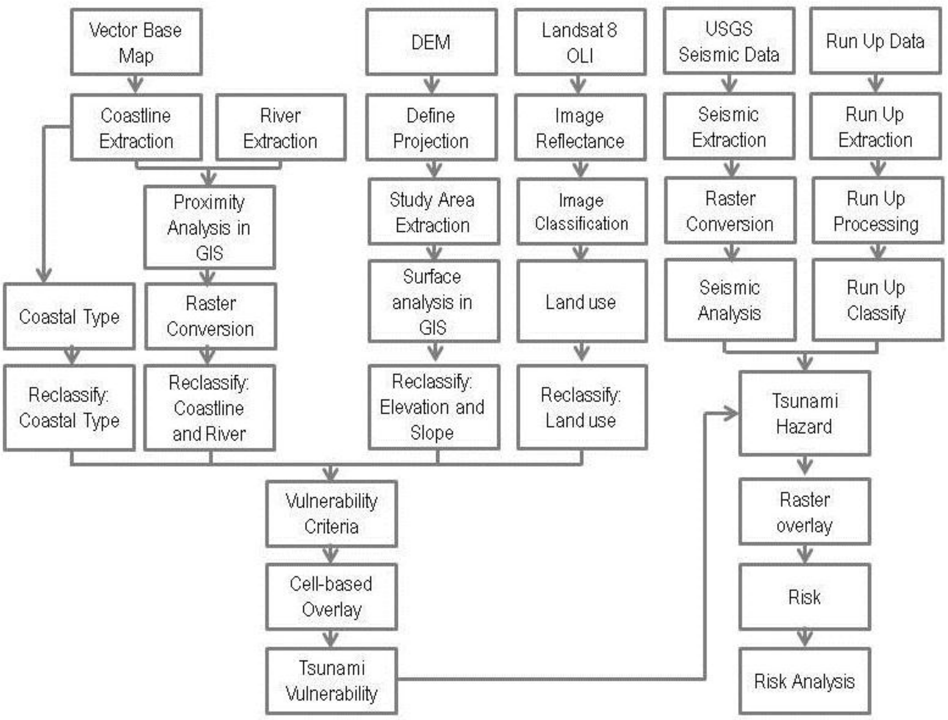

Figure 2. General method

In general, the analysis consists of two main goals, assessing tsunami vulnerability areas and assessing tsunami risk. To create tsunami vulnerability map, the parameter of elevation, slope, coastal proximity, river proximity, and land use was analyzed and overlaid based on cell-base modelling in GIS. In order to assess tsunami risk area, seismic data and historical run up data was calculated. Raster overlay approach in GIS was applied in assessing tsunami risk map in which both tsunami vulnerability map and tsunami hazard data were analyzed.

3. Result and Discussion

3.1. GIS Approach for Vulnerability Mapping

The vulnerability to a tsunami is a function of a number of physical as well as social parameters that include amongst others: distance from the shore, depth of flood water, construction standards of buildings, preparedness activities, socio-economic status and means, level of understanding and hazard perception and amount of warning and ability to move away from the flood zone. Thus, a tsunami vulnerability analysis should be developed that includes as many of these factors as possible in order to gain a more realistic picture of spatial and temporal patterns of physical and social vulnerability [12]. In order to derive a number of parameters describing physical vulnerability a digital surface model and a Digital Elevation Model (DEM) were generated and consequently the building height derived. The information layers have been integrated in a GIS together with other geographical information layers (building outlines, coastline, etc.) and an integrative physical vulnerability analysis was performed. The vulnerability analysis in this study is composed of two parts, field data collection and satellite data processing which are described in Sections 2.

Vulnerability mapping has been generated using the parameters elevation, slope, coastal proximity, river proximity, and land use. Elevation and slope were created from SRTM elevation and also Nextmap world 10 elevation data (Figure 3). Together with hazard or capacity, tsunami vulnerability is one of the parameters in assessing tsunami risk. Cell-based analysis was applied in combining all parameter through analysis of geo-spatial.

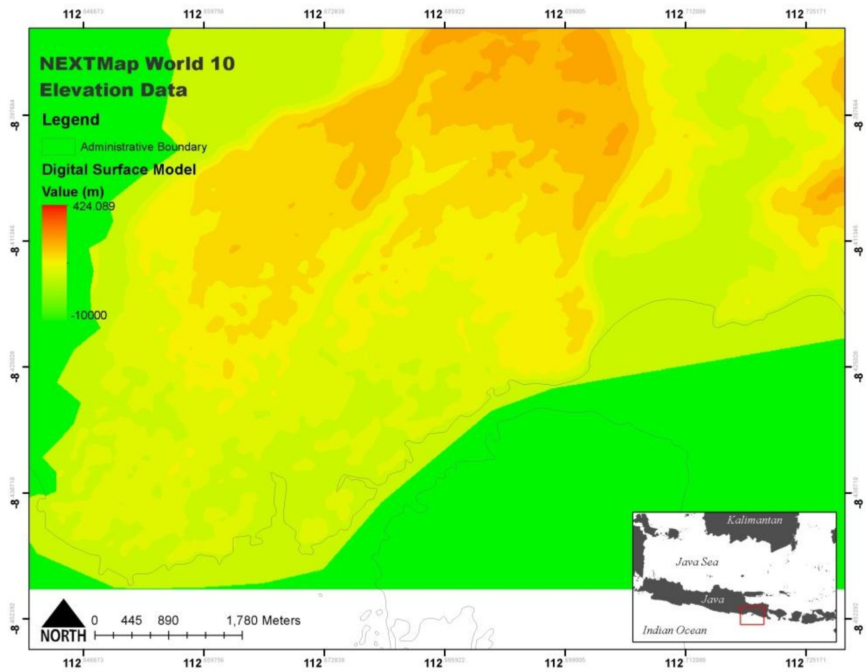

Figure 3. Nextmap world 10 elevation data of Malang district coastal area

Moreover, land use map was generated from supervised classification process of Landsat 8 OLI satellite image. Reflectance value of satellite image applied in maximum likelihood classification and generated five classes of land use in the study area. Each parameter constructing tsunami vulnerability was applied to raster reclassification based on tsunami vulnerability classes using the criteria as described in Table 2.

Table 2. Vulnerability classes for each parameter [2][13][14][15] (from 1 for least vulnerable to 5 for most vulnerable)

Parameters	Vulnerability Classes				
	5	4	3	2	1
Elevation (m)	<5	5 – 10	10 – 15	15 – 20	>20
Slope (percent)	0 – 2	2 - 6	6 - 13	13 - 20	>20
Coastal Proximity (m)	<200	200 - 500	500 - 1000	1000 - 1500	>1500
River Proximity (m)	0 -100	100 - 200	200 - 300	300 -500	>500
Land use	Urban	Agriculture	Bare soil	Water	Forest

Raster overlay for tsunami vulnerability mapping was done based on the weight of parameters. Weights were calculated using Analytical Hierarchy Process (AHP). 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 one of the suitability analysis based on spatial multi-criteria processing [2][16]. Vulnerability map was generated by applying a weight value to each parameter in raster data format. Figure 4 shows tsunami vulnerability map based on different parameters.

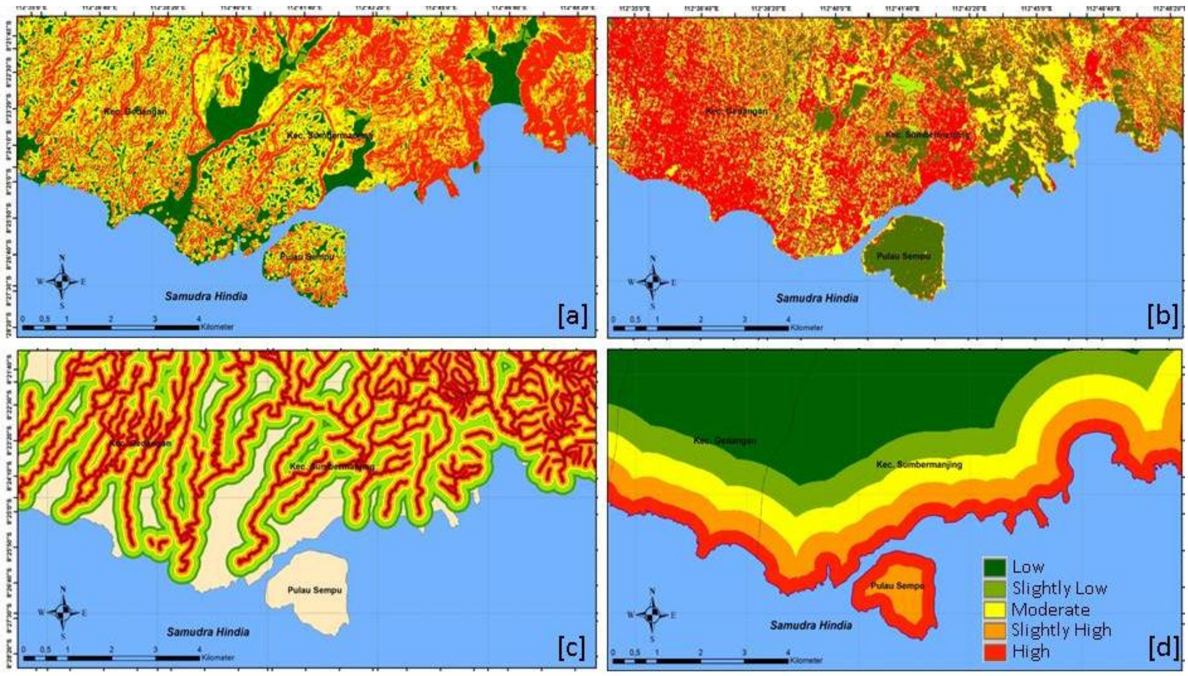

Figure 4. Tsunami vulnerability map based on; [a]slope; [b] land use; [c] river proximity; [d] coastal proximity.

The use of AHP analysis in generating weight of parameters in which to be applied in weighted raster overlay describes five classes of vulnerability due to tsunami. It describes that the western part of study area mostly falls in the class of slightly high to high class of tsunami vulnerability. This area was identified as flat area with land use class of urban area, bare soil, and agriculture. Within the coastal area that is exposed to tsunami inundation, the buildings and infrastructure are not uniformly at risk within the flood zone [17][18]. The probability of damage is related to both vulnerability and the tsunami wave energy. Damage level to buildings depends on building type and on inundation depth [19] or could depend on the density of vegetation around the coast that is assumed will reduce tsunami impact. Assessing tsunami vulnerability in the urban area has considered that individual buildings will interact differently with a tsunami depending on a number of parameters [17][18]. Various parameters affecting the resistance of the building interact to generate a real class of building vulnerability [20]. Although land boundary reflection brought an effect on the position of the maximum wave height to a certain extent, as the limits of the incident waveform and distances between the observation points and shore, it was not the dominant influence factor of the special waveform [21].

3.2. Seismic And Run Up Analysis

Seismic data are physical observations or measurements of seismic sources, seismic waves, and their propagating media. The purpose of processing seismic data is to learn 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 with a high number of seismic points with the depth average of 1 to 5 km and the range of magnitude 1 to greater than 6. As a result, coastal area of East Java can be classified as highly vulnerable to tsunamis. Based on historical data, it was a magnitude of 7.8 Mw in the depth of 18 km and latitude of -10.477º and longitude of 112.835º that caused big tsunami and affected the coastal area of East Java (see seismic map on Figure 5).

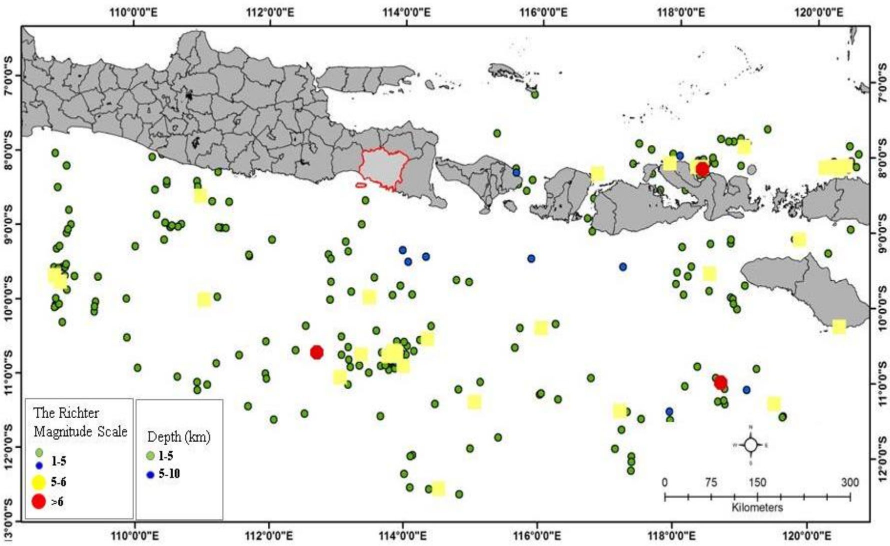

Figure 5. Seismic data in Indian Ocean close to coastal area of East Java from 1992 to 2004 from U.S. Geological Survey

Figure 5 illustrates 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. 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. Magnitude of 1 – 6.3 was classified as micro to strong effect or I to VII in Mercalli intensity. It was categorized based on 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.

The historical tsunami event of 1994 was used as a basic data for run up analysis. Maximum run up was recorded at Tempurejo subdistrict, Jember district (an area in the eastern part of study area) (11.2 m), and minimum run up was 3.1 m in the area of Puger subdistrict. Tsunami run up parameter is one of the important parameters in determining tsunami risk due to this parameter being the main parameter in hazard criteria. In general, 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 [1][2].

3.3. Tsunami Risk

The term risk can have a different meaning in different applications or languages therefore it is necessary to clarify some basic definitions related to risk. In our understanding, the risk is the product of the likelihood that an undesired event such as a tsunami will happen within a specific period of time, and its consequences. In order to measure risk, it is necessary to define its characteristics, which are described in the process of risk analysis. Tsunami risk analysis is a very complex process which requires knowledge of the tsunami In mathematical form, the following general expression can be used $R = H \times V$, in which R = risk, H = probability of tsunami hazard occurrence, and V = vulnerability of the elements at risk (as described on Figure 6).

Tsunami risk assessment is a relatively new and growing discipline that is being developed from "generic" risk approaches, which are usually applied to the general field of technological risk management [8]. Tsunami risk map in the study area (Figure 7) describe that high and slightly high risk of tsunami was found in the area of low to flat elevation. These areas were identified as bare soil and urban area. Sempu island can act as a barrier island in reducing the tsunami impact to the main land as long as the high density of vegetation including mangrove also can act as the green sea belt to reduce the impact of tsunami wave when it hits the coastal area.

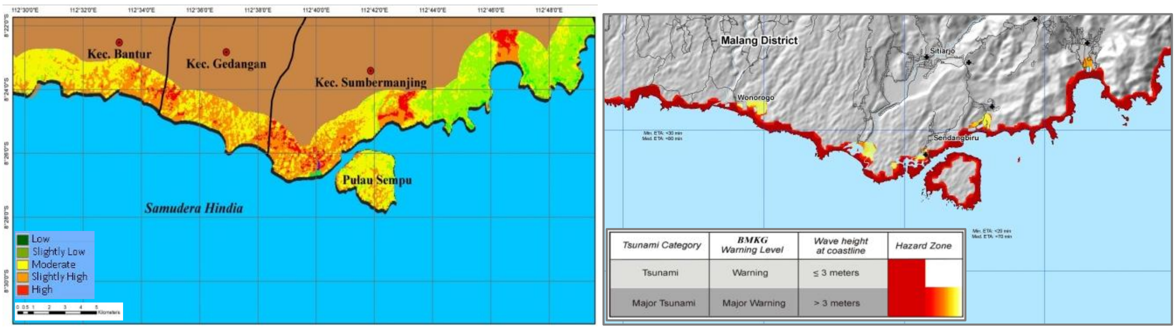

Figure 6. Tsunami vulnerability/V (left) and hazard map/H [24] (right)

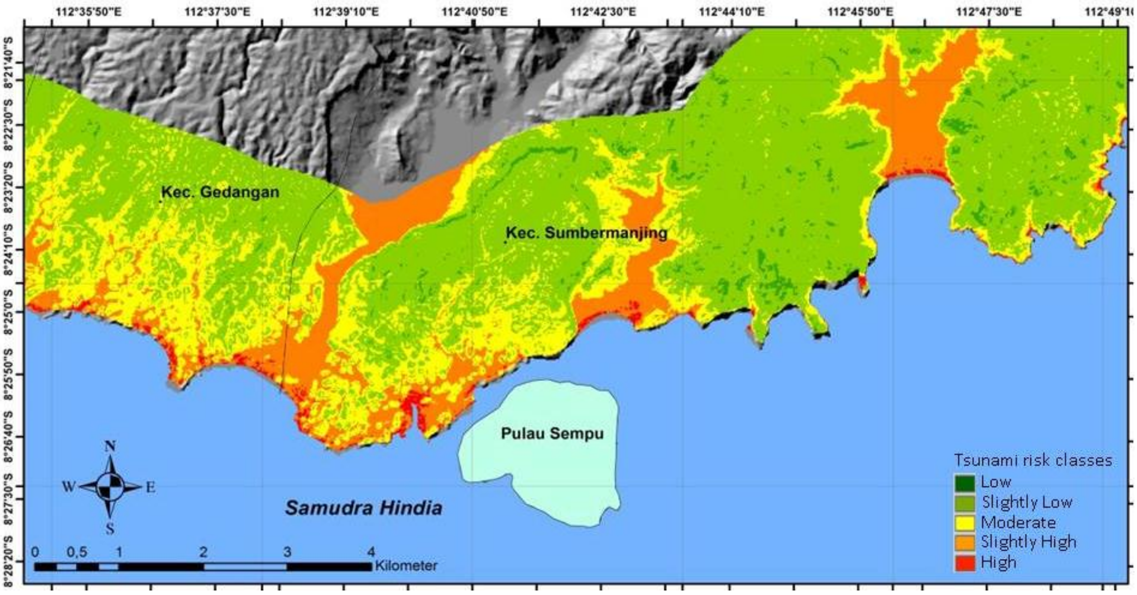

Figure 7. Tsunami risk map

4. Conclusion

Tsunami risk can be assessed using the application of multi criteria analysis in GIS in which DEM data was applied. The result obtained here can be used for the evacuation route and evacuation building planning. The result is also important as basic information in effectiveness of tsunami mitigation. The combination of raster weighted overlay in the geo-spatial data analysis indicated the vulnerability and risk area due to tsunami and described the possibility area that could be affected by 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, it will describe which area that first needs to be evacuated when tsunami comes. The result of weighted overlay illustrated that high class of tsunami vulnerability and tsunami risk occurs 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 analysed and displayed.

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