Satellite image analysis and GIS approaches for tsunami vulnerability assessment

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Abstract. Dynamic interactions of the land zone and the ocean, human activities, and also natural hazards such as tsunamis can affect the changing of coastal areas. Tsunami historical events illustrated that the topographic elevation of the coastal area could be important physical parameters for creating tsunami vulnerability areas. The integrated approaches of spatial multi-criteria in the term of Geographical Information System (GIS), the analysis of satellite image, and social parameter analysis were used to map the risk area due to tsunami. This study tried to assess the distribution of tsunami vulnerability area in coastal area of Banten, western part of Java Island, Indonesia. The study applied GIS analysis, satellite image analysis, and the integration of participatory approaches through Analytical Hierarchy Process for the tsunami vulnerability assessment. Vulnerability parameters applied elevation, slope, coastal proximity, coastal shape, and land use is divided into five classes of vulnerability. Based on the land use parameter, plantation area was the widest area included in the category of medium class of tsunami vulnerability, while the very high class of tsunami vulnerability was the irrigated rice field. Very high vulnerability areas were found in the west coastal areas of the sub-districts of Labuan Pagelaran, Patia, Sukaresmi, and Panimbang. The results illustrated in this study can be used as one of the important basic information for creating tsunami risk map. SIG based analysis can aid in a wide range of disaster assessment and facilitate regional planning for management and mitigation of natural disasters such as tsunamis.

1. Introduction
The coastal areas of Sumatra and Java, especially the southern region, are areas that are categorized as highly vulnerable to the impact of the tsunami due to their location that directly face the Indo-Australian Plate. The movement of the plates in this region triggered a large earthquake that caused the tsunami. According to [1] the Australian plate subducts with a depth of 100-20 km below the island of Java and 600 km in the North of Java. The consequences of the plate result in high seismicity with more than 20 active volcanoes in this zone. The Banten Province region, especially Pendeglang Regency has the potential to be affected by the tsunami considering that the southern part of Java is an active subduction zone. It has been recorded that an earthquake has occurred 4 times with the magnitude of the earthquake magnitude reaching 6 SR in a period of 7 years (2008 - 2014), where three of them are in the subduction zone.
Earthquake events with the centre in the southern region of Java and Sumatra, recorded once occurred on November 22, 2008 with the epicentre at 4.44º South Latitude and 101.15º East Longitude, the earthquake which was at a depth of 23 km occurred at 142 km southwest of Bengkulu. Furthermore, on July 6, 2013, the Mentawai Islands shook with a strength of 6.4 SR and was centered in an area 149 km southeast of the Mentawai Islands, West Sumatra. At 23.47 WIB on June 13, 2013 an earthquake with a magnitude of 6.5 SR (6.7 SR according to USGS) was centered at 348 km from the city of Bandung with a depth of 11 km. Whereas the last one happened in the Kebumen area with an earthquake measuring 6.1 SR on January 25, 2014 and located at the coordinates of 8.004º South and 109.238º East with a depth of 83 km.

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 future events [2]. The study aims were to map the tsunami vulnerability parameters in the coastal area of Pandeglang Regency, to assess the distribution of vulnerability area of the coastal area of Pandeglang Regency, and to analyze the potential impact of tsunami hazards in the coastal areas of Pandeglang Regency regarding the land use. The previous study was applied numerical modeling to assess the potential affected area hit by tsunami waves. This research introduces an additional approach in order to support the previous work using the application of geographical dataset in the term of spatial analysis.

2. Method

2.1. Study area

This research was conducted in the coastal area of Pandeglang Regency, through the processing of satellite image data related to the Digital Elevation Model (DEM). Pandeglang Regency is one of eight regencies/cities in Banten Province which is on the western part of Java Island with an area of 2,747 km² or 29.98% of the total area of Banten Province. The coastline reaches 307 km, and geographically located between 6º21’-7º10’ South Latitude and 104º48’-106º11’ Longitude. Study area as shown on figure 1.

Figure 1. Map of the study area, coastal area of Banten Regency, the part of Indian Ocean and Sunda Strait
2.2. Data and Method

Mapping and analysis of the distribution of tsunami vulnerability area require several supporting parameters. In this study, the physical parameter of tsunami vulnerability was applied. These parameters were determined based on the results of the literature review and scientific publications related to research on tsunami vulnerability. The assumption of the selection of parameters used in this study was the availability of data acquisition and calculation was visible to be done.

The physical parameters for creating tsunami vulnerability map used and analyzed in this study consisted of the following parameters:

2.2.1. Topographic Elevation. The topographic elevation is the main requirement for assessing tsunami vulnerability. The research applied the Digital Elevation Model (DEM) of the Shuttle Radar Topography Mission (SRTM) to obtain the topographic elevation of the study area. The DEM resolution used was 90 meters which were then carried out downscale to a 30-meter grid using bilinear interpolation. The elevations obtained from SRTM processing were reclassified according to the value or tsunami vulnerability range in the five vulnerability classes as presented in Table 1.

Table 1. The physical vulnerability value range for elevation, slope, and land use [3–7]

| Vulnerability class | Elevation (m) | Slope (%) | Coastsline distance (m) | Land use | Coastal type |
|---------------------|--------------|-----------|------------------------|---------|--------------|
| High                | <5           | 0-2       | <556                   | Urban   | V bay        |
| Slightly high       | 5-10         | 2-6       | 556-1400               | Agriculture | U bay        |
| Moderate            | 10-15        | 6-13      | 1400-2404              | Bare soil | Cape         |
| Slightly low        | 15-20        | 13-20     | 2404-3528              | Water   | Straight     |
| Low                 | >20          | >20       | >3528                  | Forest  | Neutral      |

2.2.2. Slope Topography. The topographic slope was calculated using the algorithm of Burrough and McDonnell [8], with the slope formula $\sqrt{(\partial z / \partial x)^2 + (\partial z / \partial y)^2}$, where $\partial z / \partial x$ is the angle for the eastward, and $\partial z / \partial y$ is the angle for the north-south direction. Tsunami run-ups can be severe depending on the area of the relatively flat topography because tsunamis can flow more easily to flat areas, but can be resisted or turned by hills bordering the coast [6]. Tsunami vulnerability based on slope data was created using the classification of vulnerability class as described in Table 1.

2.2.3. Land Use. Land use is one parameter that is assumed to affect the level of vulnerability. In other words, different classes of vulnerability are affected by different land uses. Tsunami vulnerability based on land use data was created using the classification of vulnerability class as described in Table 1. The impact of the tsunami disaster on each type of land use is different. This is because every land use has a certain level of reduction when hit by a tsunami wave.

2.2.4. Coastline Distance. The distance of coastal areas was divided into five classes of vulnerability to tsunami hazards. This parameter describes the distance from the coastline of the study area towards the land as much as five-ring radiiuses. The distance from the coastline is associated with the possibility of tsunami coverage. In general, vulnerability is higher with the area closer to the coastline. To clarify coastal proximity, the calculation was applied Equation (1) [4].

$$\log X_{max} = \log 1400 + \frac{4}{3} \log (Y_0 / 10)$$  \hspace{1cm} (1)

2.2.5. Coastal Type. The coastal profile can also affect the height of the tsunami and speed up towards the land. Beaches with indentations may have a higher vulnerability than beaches without curves because wave energy tends to concentrate on the bay [7]. In this study, the shape of the coast in the study area was divided as described in Table 1. Some of the bays in Pandeglang Regency are Carita Bay, Lada Bay, LegonTundo Bay, LegonCaritaan Bay. Each of these bays has a different shape, where there are U-shaped and V-shaped tones, while some of the cape found in Pandeglang are Ketapang.
Cape, Panda Cape, Kuntianak Cape, Cawar Cape. In addition to the bay and cape there are also coastal areas with straight coastal morphometry.

3. Result and discussion

3.1. Multi-criteria analysis and vulnerability mapping

Based on the overall parameters that have been generated and explained above (elevation, slope, coastal type, land use, and distance from the coastline to the mainland, the next analysis was the analysis of overlaying through a cell-based or grid-based approach. All parameters that will be analyzed for vulnerability are changed first into grid format or raster type data consisting of pixels. Due to the overlay process is an overlay of all raster type data, the weight values of each parameter need to be given. In this study, the weight (in percent) of each parameter was given based on a literature review and research results on the physical tsunami vulnerability studies published by Sambah and Miura [9]. The weight of each parameter is an elevation with a weight of 39.76%, a slope of 24.80%, a land-use of 10.52%, a coastal type of 6.66%, and a distance from the coastline to the mainland with a weight of 18.25%.

An example of a conditional function for tsunami vulnerability modeling based on elevation parameters is grid_vulnerability = IFF ((1 = "very low") AND (2 = "low") AND (3 = "medium") AND (4 = "high"), true, false). Modeling with this conditional function is also performed on other parameters (slope, coastal type, land use, and distance from coastline to land), with the same command language. The next overlay was the overlaying process of all raster data from the elevation, slope, coastal type, land use, and distance from the coastline to the mainland through the geospatial arithmetic model. This model follows the algorithm as follow:

\[(\text{elevation} \times 0.3976) + (\text{slope} \times 0.2480) + (\text{coastline distance} \times 0.1825) + (\text{land-use} \times 0.1052) + (\text{coastal type} \times 0.0666).\]

3.2. Tsunami vulnerability analysis

This study maps spatially the level of tsunami vulnerability in Pandeglang District, which later can be used as one of the inputs in the tsunami disaster mitigation program in Pandeglang District. Spatial analysis in raster data is a basis for cell-based spatial modeling. This cell has a certain value, so it will be easier in terms of spatial analysis by prioritizing the main parameters.

The high tsunami vulnerability areas spread in five western coastal sub-districts, namely Labuan Subdistrict, Pagelaran District, Patia Sub-District, Sukaresmi Sub-District, Sobang District. Areas of high vulnerability are obtained mostly on the west coast. Medium, low and very low vulnerability areas are located along with the central, western, and southern parts of Pandeglang Regency. Very low vulnerability area was 5,214 ha from the total area of Pandeglang Regency and the very high vulnerability area was 179.64 ha of the total area. The most extensive area was a region with very low vulnerability, around 40.10% of the area of Pandeglang Regency. Furthermore, 25.53% of the region was a region with moderate vulnerability and 1.38% was a region with a very high vulnerability class which is identified along the coast and was mostly found at the west coast of Pandeglang Regency.

In the spatial mapping of tsunami vulnerability areas, it can be seen that in the middle area of Pandeglang Regency described a moderate vulnerability. This is caused by the effect of the slope parameters, wherein the sub-districts of Ciput to Cikedal District have a high slope. This area was still mapped as a low-risk area. The results obtained from this overlay concluded that there were three areas that had high vulnerabilities, namely: Pagelaran, Sukarasmi and Panimbang, and two regions with moderate vulnerability (Cigeulis and Sumur). Tsunami vulnerability map based on each parameter as illustrated in figure 2, while tsunami vulnerability map as the resulting form cell-based modeling as shown in figure 3.
Figure 2. Tsunami vulnerability map in the coastal area of Banten based on the parameter of: [a] elevation; [b] slope; [c] coastline distance; [d] coastal type.
3.3. Landuse

In the analysis of land, there are two types of data known as land use and land cover. The terminology of land use and land cover is sometimes confusing and considered the same. But basically land use and land cover are different things. Land cover is a natural appearance of the earth such as vegetation, snow, forests and so on. Whereas land use is the appearance of the earth as a result of human activities such as rice fields, fields, buildings and so on. Landuse mapping in this study was conducted using spatial land use data collected from the Regional Development Planning Agency of Pandeglang Regency. Based on the data obtained, it is known that the type of land use found in the Pandeglang Regency consists of several land uses, namely shrubs/bushes, ponds, buildings, forests, swamp forests, plantations, settlements, swamps, bare land, irrigated rice fields, and fields.

Some validation processes were carried out using high-resolution imagery such as Google Earth imagery and field validation of several lands uses at the research site to ensure the correct land use type. The type of land use in the region of Pandeglang regency was dominated by the fields, gardens, forests, shrubs, and settlements. The impact of the tsunami disaster on each land use was different due to every land use has a certain level of reduction when it was hit by a tsunami wave, for example the level of vulnerability to land use for irrigated rice fields was important because it was an economic source of the surrounding community. If the irrigated fields are affected, the area of the paddy field will be filled with seawater and the area of land mixed with salt water which will be affected by the soil. A tsunami disaster could change the land use type.

3.4. The Impact of tsunami vulnerability to land use

In the very low vulnerability class, the built area has a percentage of 0.01% affected with an area of 12.67 km², fields with a percentage of 21.58% with a land area of 18,595.98 km², and forests with a percentage of 78.40% with the area is 67,550.05 km². Low-class vulnerability class described forest with a percentage of 61.51% (681.67 km²) and bare land with a percentage of 26.49% (293.56 km²). The middle class on tsunami vulnerability showed bare soil with a percentage of 1.02%, freshwater with a percentage of 0.91%, shrubs/bushes with a percentage of 22.63%, rained rice fields have a percentage of 5.10%, settlements have a percentage of 7.74%, and gardens have a percentage of
6.60%. Whereas for high class of tsunami vulnerability described three affected land use type areas, such as ponds with a percentage of 0.37% (169.44 km$^2$), and swamps with a percentage of 0.45% (205.39 km$^2$) and the last were irrigated rice fields with a percentage of 99.18%.

| No | Land use               | Very High Areas (Km$^2$) | High Percentage of Vulnerability Area | Middle Percentage of Vulnerability Area | Low Percentage of Vulnerability Area | Very Low Percentage of Vulnerability Area |
|----|------------------------|--------------------------|---------------------------------------|----------------------------------------|-------------------------------------|-------------------------------------------|
| 1  | Water body             | 0                        | 133.038                               | 12.00                                  | 0                                   | 0                                         |
| 2  | Coastal                | 0                        | 1495.03                               | 1.02                                   | 0                                   | 0                                         |
| 3  | River                  | 0                        | 1338.33                               | 0.91                                   | 0                                   | 0                                         |
| 4  | Shrubs / Bushes        | 0                        | 33122.23                              | 22.63                                  | 0                                   | 0                                         |
| 5  | Pond                   | 0                        | 0                                     | 0                                      | 0                                   | 169.44                                   |
| 6  | Building               | 12.67                    | 0.01                                  | 0                                      | 0                                   | 0                                         |
| 7  | Swamp Forest           | 0                        | 681.67                                | 61.51                                  | 0                                   | 0                                         |
| 8  | Swamp                  | 0                        | 0                                     | 0                                      | 0                                   | 0                                         |
| 9  | Grass                  | 0                        | 293.56                                | 26.49                                  | 0                                   | 0                                         |
| 10 | Rainfed rice fields    | 0                        | 7459.89                               | 5.10                                   | 0                                   | 0                                         |
| 11 | Field                  | 18595.98                 | 21.58                                 | 0                                      | 0                                   | 0                                         |
| 12 | Settlement             | 0                        | 11328.37                              | 7.74                                   | 0                                   | 0                                         |
| 13 | Forest                 | 67550.05                 | 78.40                                 | 0                                      | 0                                   | 0                                         |
| 14 | Plantation / Plantation| 0                        | 91632.57                              | 62.60                                  | 0                                   | 0                                         |
| 15 | Irrigated Rice Fields  | 0.000                    | 0                                     | 0                                      | 0                                   | 45308.12                                 |
|    | Total                  | 86158.70                 | 1108.28                               | 146376.42                              | 0                                   | 45682.95                                 |

4. Conclusions

It can be concluded that the elevation, slope, coastal type, land use, and the coastline distance were topographic physical parameters that can be used to identify the tsunami vulnerability of the Pandeglang District. Based on the analysis, it can be seen that plantation area was the area with the widest area included in the category of tsunami vulnerability, while the very high of tsunami vulnerability class was the irrigated rice field area, covering an area of 45,308.12 ha. Areas of very high vulnerability were found in the western coastal areas of the sub-districts Labuan Pagelaran, Patia, Sukaresmi, and Panimbang.

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