Coastal vulnerability index aftermath tsunami in Palu Bay, Indonesia

Z Imran\textsuperscript{1,2,*}, S W Sugiar\textsuperscript{t} and A N Muhammad\textsuperscript{3}

\textsuperscript{1}Department of Aquatic Resources Management, Faculty of Fisheries and Marine Sciences, IPB University, Bogor, 16680, Indonesia
\textsuperscript{2}SEAMEO BIOTROP, Jl. Raya Tajur, Bogor, West Java, 16134, Indonesia

*Corresponding author: zulhamsyah.imran@biotrop.org

Abstract. A significant impact of the disaster has influenced a rapid growth of economics for the Palu City 2030 framework. Discovering coastal vulnerability index value is needed to measure tsunami affecting the vulnerability risk and evaluate development plan in 2010-2030. This paper used spatial analysis to estimate coastal vulnerability index (CVI) before and aftermath of the earthquake and tsunami. An assessment of CVI was carried out using seven physical parameters and integrated with the Analytical Hierarchy Process (AHP) to build into five categorized. The result has shown that there was an increased vulnerability risk from moderate to very high rank, where the total amount of area under pressure was 12.8 km\textsuperscript{2} (56.53\%) and rose to 14,367 km\textsuperscript{2} (63.72\%) after the tsunami hit. A coastal area of Ulujati-Mantikulore could be categorized into the very low risk-moderate class; meanwhile, along the region of West Palu, East Palu, North Palu, and Tawaili were indicated into the high-very high-risk class of vulnerability. This paper finding shows that it is needed a decision of policymaker on making a mid/long-term plan, and it should prioritize a precision disaster-based calculation to minimize the loss and damage by the disaster in the future.

1. Introduction

Indonesia, as an archipelagic state consisting of 17,508 islands with a coastline of 81,000 km length and around 140 million people or 60\% of the Indonesian population living in coastal areas [1]. The majority of Indonesia’s coastal zone is highly influenced by climate change, disasters, and anthropogenic factors. It can be affected by the population living in this fragile area. As known that the earthquake and tsunami can cause enormous damage and loss on the coastal ecosystem and its natural resources. Indonesia was one of the areas which are highly vulnerable by earthquakes, and tsunami hit [2].

A tsunami can significantly make changes to the coastal physical parameters, which are divided into seven types, namely geomorphology, elevation, slope, sea-level rise, shoreline change rate, mean tidal range, and significant wave height [3]. The devastating impact of a tsunami will be increasing the vulnerability value of the physical parameters in the coastal area. The physical parameters are highly affected, and they will be increased risk level by hazardous when shoreline change rate is shifted to be the worse condition. It can be changed by the accretion and abrasion processes at the shoreline, which will lead to shifting the coastal bathymetry [4].

The coastal area of Palu City, Central Sulawesi, is a semi-enclosed bay, and it is classified as a vulnerable area to earthquake and tsunami disasters. The natural disaster of the Sulawesi earthquake...
and tsunami in Indonesia on September 28, 2018, killed at least 2000 and leave damage from faults with a length of more than 150 km is one of the examples of how vulnerable the area is [5]. The impact of the Palu tsunami also caused a significant retreat of the coastline and liquefaction, causing severe damage almost as long as the coasts of Palu [6]. The tsunami caused the physical parameters of the coast of Palu to be changed. This change in the value of coastal physical parameters will increase the value of the coastal vulnerability index. The increased value of this index must be watched out for, or it will threaten the potential and even claimed lives. These research aims are to discover the changes of CVI value on how tsunami affecting the physical parameters then elevates the vulnerability risk, and to evaluate Palu’s medium-term spatial development plan in 2010-2030.

2. Methods of the study

2.1. Study site and time
Palu Bay is a semi-closed water area. The mouth part in the north meets the Makassar Strait with a width of about 9 km. The length of the coastline is around 100 km; therefore, the shape of the formation extends to the ratio between the width, and the length of the bay is around 1:11, with the total area 206,935,000 m² (207 km²) and the sea depth of 0 - 800 m. The water and land area of Palu Bay are 189.00 km² and 2,158.62, respectively. These areas are located in Palu City and Donggala District. As known that Palu Bay is structured by beaches and seas, estuaries, deltas, mangroves, coral reefs, seagrass beds as well as various species of fish or marine life [7]. This study was selected representative area as it can be seen in Figure 1, namely Ulujati, West Palu, East Palu, Mantikulore, North Palu, and Tawaili Sub District. This research was carried out from November 2018 to August 2019.

![Study site focusing on red colour in area affected by tsunami in Palu Bay](image)

Figure 1. Site study area in Palu Bay, Indonesia.

2.2. Open sea data
This research used primary and secondary data and information. Type of ecosystem and the state of shoreline damage were collected using observation and ground throating method. The secondary data were gathering using the acquisition of altimetry, extracting variables, grid processing, and projections data. This study was also explored using open source data from various agencies, such as National
Geospatial Information Agency (BIG), The United States Geological Survey (USGS), National DEM (DEMNAS), and Aviso+ to support the secondary data. The process of obtaining data was carried out using an online system approach by accessing the sites of each data provider/agency. The satellite image data was used to analyze the parameters of coastline changes. These data were obtained through the USGS website, namely https://glovis.usgs.gov/app. Geomorphological, elevation, slope, and tidal parameters were collected through the DEMNAS, the Indonesian Earth Plan (RBI) Coverage Map, and tidal prediction sites provided by the National Geospatial Information Agency (BIG). Finally, the parameters of significant wave height and sea-level rise were obtained through the provider of Aviso+ altimetry data, which could be accessed through the aviso.altimetry.fr/en/home.html site. The resolution, quality, and coordinate data systems were needed to be considered in the acquisition of data from different places with the number of parameters available.

2.3. Spatial Multi-Criteria Evaluation (SMCA)

The qualitative assessment of coastal vulnerability was conducted through Spatial Multi-Criteria Analysis (SMCA) that was used to support the quantitative assessment as a useful complementary method in both qualitative and quantitative risk analysis and zoning. Moreover, SMCA can facilitate the participatory processes which are intended to choose sustainable risk mitigation measures, and it can also support decision-makers who face making evaluations of projects or policies based on multiple criteria in identifying priority areas to reduce the risk for an action plan document [8-11].

Spatial Multi-Criteria Analysis can be used to process, combine, and transforms several geographical data (input) into a resultant decision (output) [12]. This research followed four steps to arrange the thematic map, namely: 1) structuring the problem, 2) arranging the standard of judgment value for the maps parameter according to explicit criteria formulation, 3) establishing the importance of each criterion respect to other criteria and the problem, and 4) aggregating a procedure. At the end of the process was the additional sensitivity analysis to examine the robustness of the outcome.

2.4. CVI approach

The relationship among the spatial information and data analysis was used to calculate the coastal vulnerability (CVI) in this research. The criteria and benchmarks of physical parameters were determined based on a study from [3] and [13]. In this study, the coastal vulnerability index was divided into three groups, namely low, moderate, and high. The weighting of physical parameters is based on a study [3]. The CVI is determined based on seven parameters, namely geomorphology, shoreline change rate, elevation, slope, mean sea level rise, mean tidal ride, and mean significant wave height. Quantitative assessment of coastal vulnerability was carried out through weighting to provide a range of values for each parameter due to the criteria of the CVI using the Analytical Hierarchy Process (AHP) [14]. These parameters were used to calculate the value of the CVI using the equation followed:

$$CVI = \sqrt{\left( \frac{p1 \times p2 \times p3 \times p4 \times p5 \times p6 \times p7}{7} \right)}$$

Where:

CVI = Coastal Vulnerability Index
p1 = geomorphology
p2 = shoreline change rate
p3 = elevation
p4 = slope
p5 = mean sea level rise
p6 = mean tidal ride
p7 = mean significant wave height
Determining variables scores and calculating CVI was modified and adapted from USGS research that it was suggested by [13] as it can be seen in Table 1. The spatial analysis process was used to process, integrate, and calculate the CVI to identify the state of Palu Bay’s coastal area vulnerability in both before and after disasters.

Table 1. Modified determination of scores for CVI.

| Parameters                  | Very Low | Low          | Moderate       | High                        | Very High                  |
|-----------------------------|----------|--------------|----------------|-----------------------------|----------------------------|
| Geomorphology (p1)          | Rocky,   | Medium cliffs| Low cliffs,    | Beaches (pebbles),          | Barrier beaches,            |
|                             | cliffs,   |              | glacial drift, | estuary,                    | beaches (sand),            |
|                             | coasts,   |              | salt,          | lagoon,                     | mudflats,                  |
|                             | fjords,   |              | mangrove       | alluvial plains             | delta                      |
| Shoreline change rate (p2)  | >2.0      | 1.0 - 2.0    | +1.0 – (-1.0)  | -1.0 – (-2.0)               | < 2.0                      |
| Elevation (p3)              | >30       | 20.1 - 30.0  | 10.1 - 20.0    | 5.1 - 10.1                  | 0 - 5.0                    |
| Slope (p4)                  | >1.9%     | 1.3% - 1.9%  | 0.9% - 1.3%    | 0.6% - 0.9%                 | < 0.6                      |
| Mean sea-level rise (p5)    | < -1.0    | -1.0 - 0.99  | 1.0 - 2.0      | 2.1 - 4.0                   | > 4.0                      |
| Mean tidal rise (p6)        | < 1.0     | 1.0 - 1.9    | 2.0 - 4.0      | 4.1 - 6.0                   | > 6.0                      |
| Mean significant wave height (p7) | 0 - 2.9 | 3.0 - 4.9    | 5.0 - 5.9      | 6.0 - 6.9                   | ≥7.0                       |

3. Result and Discussion

3.1. Result
The coastal vulnerability analysis revealed that it was a significant difference in the CVI when it was compared before and after the tsunami disaster. The CVI of Palu Bay was divided into low, moderate, and high vulnerability categories and it was 9.9 km² (43.53%), 8.1 km² (35.30%), and 4.8 km² (21.18%) respectively before the tsunami hit Palu Bay as it can be seen in Figure 2. Table 2 figures out more detail information on CVI in Palu Bay.

![Figure 2. The CVI of Palu Bay before the tsunami.](image-url)
Table 2. The area and percentage of CVI in Palu Bay before the tsunami.

| Sub District | CVI Categories | Area (km$^2$) | Percentage (%) |
|--------------|----------------|---------------|----------------|
| Ulujati      | Very Low       | 1.836         | 26.94          |
| West Palu    |                | 0.023         | 1.27           |
| East Palu    |                | 0.009         | 0.50           |
| Mantikulore  | Low            | 0.506         | 8.69           |
| North Palu   |                | 0.561         | 9.13           |
| Taiwan      |                | 0.427         | 10.21          |

| Ulujati      |                  | 2.475         | 36.31          |
| West Palu    |                  | 0.180         | 9.87           |
| East Palu    | Low              | 0.261         | 14.41          |
| Mantikulore  |                | 1.932         | 33.19          |
| North Palu   |                  | 1.640         | 26.69          |
| Taiwan      |                  | 0.858         | 20.52          |

| Ulujati      | Moderate         | 1.585         | 23.26          |
| West Palu    |                  | 0.939         | 51.57          |
| East Palu    | High             | 1.149         | 63.42          |
| Mantikulore  |                | 2.208         | 37.92          |
| North Palu   |                  | 2.543         | 41.38          |
| Taiwan      |                  | 1.528         | 36.54          |

| Ulujati      |                  | 0.836         | 12.26          |
| West Palu    |                  | 0.612         | 33.60          |
| East Palu    | High             | 0.350         | 19.33          |
| Mantikulore  |                | 1.014         | 17.42          |
| North Palu   |                  | 1.355         | 22.04          |
| Taiwan      |                  | 1.259         | 30.11          |

| Ulujati      | Very High        | 0.083         | 1.22           |
| West Palu    |                  | 0.067         | 3.69           |
| East Palu    |                  | 0.042         | 2.34           |
| Mantikulore  | High             | 0.162         | 2.78           |
| North Palu   |                  | 0.047         | 0.76           |
| Taiwan      |                  | 0.110         | 2.62           |

The CVI was almost a similar distribution within Palu Bay's aftermath tsunami. However, this index was indicated an increase, and it tends to be led by a high-class category of vulnerability, as
shown in Figure 3. The total area of low vulnerability class was around 8.2 km$^2$ (36.33%), followed by 8.1 km$^2$ (36.13%) and 6.2 km$^2$ (27.54%) in the moderate vulnerability and the high vulnerability class respectively. The categories of the CVI in Palu Bay can be seen in Table 3.

Table 3. The area and percentage of CVI Palu Bay aftermath tsunami.

| Region  | Vulnerability Index | Area (km$^2$) | Percentage (%) |
|---------|---------------------|---------------|----------------|
| Ulujati | Very Low            | 1.564         | 25.26          |
| West Palu |                   | 0.005       | 0.38           |
| East Palu |                   | 0.007       | 0.70           |
| Mantikulore |              | 0.248       | 5.09           |
| North Palu |                  | 0.519       | 9.79           |
| Tawaili |                     | 0.359       | 9.25           |
| Ulujati | Low                | 2.458         | 39.71          |
| West Palu |                   | 0.116        | 8.68           |
| East Palu |                   | 0.075        | 7.98           |
| Mantikulore |              | 0.983       | 20.21          |
| North Palu |                  | 1.065       | 20.08          |
| Tawaili |                     | 0.782       | 20.13          |
| Ulujati | Moderate           | 1.293        | 20.88          |
| West Palu |                   | 0.428        | 31.94          |
| East Palu |                   | 0.431        | 45.75          |
| Mantikulore |              | 1.944       | 39.96          |
| North Palu |                  | 2.440       | 46.03          |
| Tawaili |                     | 1.631       | 41.99          |
| Ulujati | High               | 0.776        | 12.53          |
| West Palu |                   | 0.680        | 50.72          |
| East Palu |                   | 0.385        | 40.89          |
| Mantikulore |              | 1.460       | 30.01          |
| North Palu |                  | 1.214       | 22.89          |
| Tawaili |                     | 1.011       | 2.01           |
| Ulujati | Very High          | 0.100        | 1.61           |
| West Palu |                   | 0.111        | 8.27           |
| East Palu |                   | 0.044        | 4.68           |
| Mantikulore |              | 0.230       | 4.72           |
| North Palu |                  | 0.064       | 1.22           |
| Tawaili |                     | 0.102       | 2.62           |
3.2. Discussion

This research found that there was a different class of The CVI each sub-district in Palu Bay. The low vulnerability class was distributed across the coastal area of the Ulujati Sub District; however, the high vulnerability class was located across the coastal area in Palu Sub District, and it is going up around 6.36%. The overall result showed that the CVI of the Palu Bay comparison between before and aftermath tsunami in Figure 4. This figure presented that one hand, the low category of CVI was decreasing, and another hand, the high one was increasing in the same area of sub-district located in Palu Bay.

An increasing of CVI was noticeably caused by the geomorphology parameter as the determinant factor in this case. As known that Palu Bay geomorphology was formed by irregular and weak topography and also a flood area [15]. The existing geomorphology was worsened by the condition of land cover, which was dominated by infrastructure, such as building and settlement that these distributed within the coastal areas of Palu Bay. Thus, the slightly different and worse impact of the tsunami in Palu Bay was caused by triggering liquefied gravity flows and underwater landslides. Another factor was slope and shoreline in Palu Bay. These couple factors were in the lower level, and it can be caused by several conditions, as we mentioned above. Those factors caused a change rate of
parameter and gave a significant impact on the increasing of CVI in Palu Bay. As the formulation of CVI deals with the identification slope and shoreline as key variables representing significant driving processes influencing the coastal vulnerability and the coastal evolution in general [6].

The percentage difference in high-risk vulnerability class was the greatest, whereas the percentage of class in very high risk vulnerable was the smallest difference between before and the aftermath. The increase in CVI value needs to be looked out because a decision making in setting the right management program in a coastal area that has the highest level of a vulnerability was very crucial, such as to address socio-economic aspects (for example number of people affected, infrastructure potentially damaged and economic costs) [16].

4. Conclusion
This research is trying to reveal that the CVI in the coastal area of Palu Bay is just based on general physical parameters, namely geomorphological parameters, and it is needed to conduct deep research in the future. It can be concluded that the determined irregular and weak topography is very vulnerable. It is indicated and determined by the rate of change in coastline before and after the tsunami. Those factors are dominated at a vulnerable level, elevation with moderate vulnerability, slope with not very vulnerable level, tides with moderate levels of vulnerability, sea-level rise with a very vulnerable level of vulnerability, and wave height at a level of not very vulnerable. The level of vulnerability of the Palu City Sub District is generally in moderate vulnerability before and after the tsunami. Before the tsunami, the vulnerability index is dominated by the level of not being vulnerable to moderate. After the tsunami, the vulnerability index is dominated by the level of not being vulnerable to moderate. After the tsunami, the vulnerability index is dominated by the level of not being vulnerable to moderate.

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