Coastal vulnerability mapping due to tsunami using Geographic Information System in Buleleng Regency, Bali Province

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Abstract. Bali is one of the areas vulnerable to disasters because of its geographical position, which is flanked by two earthquake sources in the form of a subduction zone and back-arc thrust zone, which can cause a tsunami in Bali region. This research aims to identify and map the level of coastal vulnerability to the tsunami in Buleleng Regency, Bali Province. The mapping was carried out using Geographic Information System (GIS). This study used secondary data and field data. The parameters used in analyzing the level of tsunami vulnerability were land elevation, slope, land use, distance from the beach, and distance from the river. The level of vulnerability was grouped into five classes, namely very safe (35,466.9 ha), safe (70,485.0 ha), moderately vulnerable (17,645.0 ha), vulnerable (6,903.3 ha), and very vulnerable (438.9 ha) located in the Districts of Gerokgak, Seririt, Buleleng, and Sawan which are close to the river.

Keywords: Buleleng, coastal vulnerability, GIS, mapping, tsunami

1. Introduction
Bali is one area that is declared vulnerable to disasters because of its geographical position, which is flanked by two earthquake sources in the form of the subduction zone in the south of Bali which is the meeting zone of the Indo-Australian plate and Eurasian plate. A back-arc thrust tectonic zone in the north of Bali causes a high seismic activity in Bali [2]. The presence of back-arc thrust in the north of Bali caused many shallow and deep earthquakes in the area, such as happened in 1976 Seririt Earthquake with a magnitude of 6.6 of Richter scale. This is what caused the potential tsunami in the northern region of Bali [3].

Tsunamis are ocean waves generated by disturbances at the bottom of the sea, such as tectonic earthquakes, volcanic eruptions, and underwater avalanches [4, 5]. A tsunami is a catastrophic disaster that has occurred several times in Bali, e.g. in 1815 and 1917 [6, 7, 8]. The earthquakes that generate tsunamis are difficult to be predicted the time and intensity of the event. Tsunami events are relatively rare but cause many losses and damage in the area affected. The right strategy is needed to reduce the damage and losses caused by this event. Mapping potentially tsunami-vulnerable areas is one of the mitigation strategies that can be used as a future reference in developing preparedness strategies [9].

Coastal vulnerability mapping of the tsunami can be done through multi-criteria spatial analysis in the Geographic Information System. This vulnerability map can assist in making priorities related to the decision-making process using geo-referenced data [10]. This study uses five parameters determining coastal vulnerability to the tsunami: land elevation, land slope, distance from the shoreline, distance from the river, and land use. The results of this study are expected to be inputs and considerations for
stakeholders in decision-making related to the disaster mitigation framework in Buleleng Regency in the future.

2. Materials and Methods

2.1. Time and research location
The research began from a field survey conducted on January 2, 2021, in the coastal area of the Buleleng Regency. The next stage was data processing from February 2021 to March 2021 at the Mapping and Spatial Modeling Laboratory, Department of Marine Science and Technology, Faculty of Fisheries and Marine Sciences, IPB University. The research site map can be seen in Figure 1.

![Figure 1. Research site map in Buleleng Regency.](image)

2.2. Data and tools
The sources and information about the data used can be seen in Table 1.

| No | Parameter                  | Data     | Data Sources                                                                 | Resolution          |
|----|---------------------------|----------|------------------------------------------------------------------------------|---------------------|
| 1  | Elevation                 | DEMNAS   | Indonesia Geospatial Information Agency (http://tides.big.go.id/DEMNAS)       | 0.27-arcsecond (± 8 meter) |
| 2  | Slope                     | DEMNAS   | Indonesia Geospatial Information Agency (http://tides.big.go.id/DEMNAS)       | 0.27-arcsecond (± 8 meter) |
| 3  | Distance from shoreline   | Topographic Map | Indonesia Geospatial Information Agency (http://tanahair.indonesia.go.id) | -                   |
| 4  | Distance from river       | Topographic Map | Indonesia Geospatial Information Agency (http://tanahair.indonesia.go.id) | -                   |
| 5  | Land use                  | Topographic Map | Indonesia Geospatial Information Agency (http://tanahair.indonesia.go.id) | 1:25000             |
| 6  | Bathymetry                | BATNAS   | Indonesia Geospatial Information Agency (https://tanahair.indonesia.go.id/demnas/#/batnas) | 6-arcsecond         |

* Only to display depth contours (Isodepth)

Tools used include ASUS L8H42HF Core i5 Laptop hardware equipped with ArcGIS 10.5, Microsoft Excel 2016, and Microsoft Word 2016. Tools used during field surveys include the Garmin 64s Global Positioning System (GPS), stationery, and cameras. Materials used include data Digital Elevation Model.
(DEM) National, National Bathymetry (BATNAS), Indonesia Topographic Map (RBI), and earthquake history data.

2.3. Data Processing and Analysis
Tsunami vulnerability analysis is determined by using the overlay method of several parameters. The parameters used to determine tsunami vulnerability are land elevation, slope, distance from the shoreline, distance from the river, and land use. Based on these parameters, the matrix for determining tsunami vulnerability is compiled, as shown in Table 2.

Table 2. Matrix of coastal vulnerability parameters against tsunami disaster.

| No | Parameter | **Weighted (%) | Criterion | **Score |
|----|-----------|---------------|-----------|---------|
| 1  | Land elevation (m) [11] | 25 | <10 | 5 |
|    |           |               | >10 – 25 | 4 |
|    |           |               | 25 – 50 | 3 |
|    |           |               | 50 – 100 | 2 |
|    |           |               | >100 | 1 |
| 2  | Slope (%) [12] | 20 | 0 – 2 | 5 |
|    |           |               | 2 – 5 | 4 |
|    |           |               | 5 – 15 | 3 |
|    |           |               | 15 – 40 | 2 |
|    |           |               | >40 | 1 |
| 3  | Distance from shoreline (m) [13] | 20 | 556 | 5 |
|    |           |               | >556 | 4 |
|    |           |               | >1400 | 3 |
|    |           |               | >2404 | 2 |
|    |           |               | >3528 | 1 |
| 4  | Distance from river (m) [14] in [11] | 15 | <100 | 5 |
|    |           |               | 100 – 200 | 4 |
|    |           |               | 200 – 300 | 3 |
|    |           |               | 300 – 500 | 2 |
|    |           |               | >500 | 1 |
| 5  | Land use [16, 17] | 20 | Settlements, rice fields, mangroves, swamp forests | 5 |
|    |           |               | Gardens, ponds, lakes | 4 |
|    |           |               | Fields/moors | 3 |
|    |           |               | Shrub, grass, vacant land | 2 |
|    |           |               | Forests, land vegetation, rock and limestone | 1 |

**Weighting and scoring refers to research [17]**

Each parameter is given in different weight and score, determined based on the influence of these parameters on the level of tsunami vulnerability according to the reference material of [17]. The scoring was intended to assess the limiting factor on each parameter assigning weights to each parameter in this study ranged from 15-25% and scores in the range of 1-5. The weighting and scoring of the parameters used can be seen in Table 2. Then, the total score of each class is determined using the formula [18]:

\[
N_t = \sum_{j=1}^{5}(B_j \times S_j)
\]  

(1)

Note:
\[ i = \text{Elevation, slope, distance from the shoreline, distance from river, land use} \]
\[ j = 1, 2, 3, 4, 5 \]
\[ N_i = \text{Total weight} \times \text{score for the-i parameter} \]
\[ B_j = \text{Weight on each criterion} \]
\[ S_j = \text{Score on each criterion} \]

Mathematically, the calculation of vulnerability level by using overlay analysis is described in the following equations:

\[
\text{Vulnerability level} = \left[ (\text{land elevation} \times 0.25) + (\text{land slope} \times 0.2) + (\text{distance from shoreline} \times 0.2) + (\text{distance from river} \times 0.15) + (\text{land use} \times 0.2) \right]
\] (2)

Based on the calculation of the total score, the highest \( (N_{\text{max}_i}) \) and the lowest total score \( (N_{\text{min}_i}) \) are obtained. The highest total score minus the lowest total score divided by the number of vulnerability classes will be obtained the score range value \( (R_s) \). Mathematically, the value of the score range values is expressed in the following formula [12], which shows five classes of tsunami vulnerability, namely very vulnerable \( (R_5) \), vulnerable \( (R_4) \), moderately vulnerable \( (R_3) \), safe \( (R_2) \), and very safe \( (R_1) \).

\[
R_s = \frac{\sum (N_{\text{max}_i} - N_{\text{min}_i})}{n}
\] (3)

Note:
\( R_s = \text{Score range} \)
\( n = \text{Number of classes} \)

Based on the formula calculation, the vulnerability class interval is 0.8, with the highest total score of 5 and the lowest total score of 1. A very safe level \( (R_1) \) is obtained from the lowest total score added to the class interval of 0.80. The safe level \( (R_2) \) is obtained from the \( R_1 \) class interval, 1.80, added 0.80. Likewise, the vulnerability classes \( (R_3), (R_4), \) and \( (R_5) \) as presented in Table 3.

| No | Class | Vulnerability Level       | Class interval |
|----|-------|---------------------------|----------------|
| 1  | R1    | Very Safe                 | 1.00 – 1.80    |
| 2  | R2    | Safe                      | 1.81 – 2.60    |
| 3  | R3    | Moderately Vulnerable     | 2.61 – 3.40    |
| 4  | R4    | Vulnerable                | 3.41 – 4.20    |
| 5  | R5    | Very Vulnerable           | 4.21 – 5.00    |

3. Results and Discussion

3.1. Land elevation

The results of land elevation mapping (Figure 2) showed that Buleleng Regency has a diverse elevation. Areas with a land elevation of <10 meters are generally located in coastal areas in Sawan, Buleleng, Banjar, Seririt, and Gerokgak subdistricts. Areas with land elevation ranging from >10-25 meters are found in coastal areas in Kubutambahan and Tejakula subdistricts. Areas with land elevation ranging from 25-50 meters and 50-100 meters are located throughout the region in Buleleng Regency. Areas with a land elevation of >100 meters are found in most areas of the Buleleng Regency.
The impact of the tsunami on the mainland was heavily affected by land elevation. The lower the elevation of the land, the more vulnerable it will be and result in higher damage. On the contrary, the higher the elevation of the land, the smaller the vulnerability and the less damage caused. The high or low of a land elevation is related to the large volume of tsunami runoff entering the land. The lowlands near the coast have the highest vulnerability against tsunami disasters compared to the highland plains. This height will affect the tsunami inundation area [19, 20].

3.2. Land slope
The results of land slope mapping (Figure 3) showed that Buleleng Regency has a fairly varied slope (0->40%). Land slope with a value of 0-2% falls into the flat category; 2-7% falls into the slope category; 7-15% falls into the wavy category; 15-25% falls into the steep category; 25-45% falls into the very steep category; and >45% belongs to the steep category [15]. Most coastal areas of the Buleleng Regency are dominated by a slope of 0-15%, including Tejakula, Kubutambahan, Sawan, Buleleng, Banjar, Seririt, and Gerokgak subdistricts. The slope value of land by 15->40% dominates in Gerogkak and Seririt subdistricts and tends to be far from the coast.

The slope of the land is related to the range of tsunami to land. The slope of the land that is spreading will make it easier for the tsunami to propagate further ashore to increase tsunami vulnerability. The tsunami event can see in Banda Aceh, tsunami waves can crash as far as 5 km from the shoreline [22, 23]. The increasing slope of the land (on steep to steep beaches) causes the encroachment of the tsunami will not be too far to the mainland because the tsunami will be held back and reflected by coastal cliffs or hills near the beach [5, 24].
3.3. Distance from shoreline
The distance from the shoreline is divided into five classes based on algorithms according to [19] using tsunami run-up history reports, i.e., the run-up of 5-10 meters can reach 556-1400 meters, the run-up of 10-15 meters can reach 1400-2404 meters, and run-up of 15-20 meters can reach 2404-3528 meters (Figure 4). Judging from the parameters of distance from the shoreline, it appears that the coastal areas of Buleleng Regency include Gerokgak, Seririt, Banjar, Buleleng, Sawan, Kubutambahan, and Tejakula subdistricts are located at a distance of 556 meters from the shoreline. Two sub-districts mostly have a >3528 meters from the shoreline, namely Busungbiu and Banjar subdistricts.

In general, the vulnerability and risk of a region to tsunami becomes higher as the proximity of the region to the coastline increases. On the other hand, the vulnerability and risk level will decrease if the region is further away from the coastline [5, 20]. This is because the height of the tsunami waves will be reduced as the distance increases as the waves reach the shoreline [26].

3.4. Distance from river
The coastal area of the Buleleng Regency has seven rivers that flow directly into the sea in Sawan, Buleleng, Seririt, and Gerokgak subdistricts. In Sawan subdistrict, three rivers flow directly into the sea. In Buleleng and Seririt subdistricts, two rivers flow into the sea, while in Gerokgak Subdistrict there is one river that boils into the sea. The distance from the river in Buleleng Regency is divided into five classes as presented in Figure 5.

The existence of rivers and other waterways that flow into the sea is also an important parameter in assessing tsunami vulnerability because it can affect the encroachment of tsunami flows to land [17]. The area near the river has a very high level of vulnerability due to the accumulation of tsunami wave energy and water mass, so that it will cause great damage. This is because tsunamis entering through the river estuary will experience an increase in speed and water level. After all, the same water mass discharge must travel through narrow gaps simultaneously [27]. Tsunami encroachment on the river has a higher speed than the encroachment of tsunamis on land. Moreover, this can sustain and spread wave energy further upstream and can cause damage in areas far from the shoreline, estimated to reach land as far as a kilometer or more, especially if the tsunami enters at high tide [15], [17].
3.5. Landuse/Landcover
Landuse/land cover in Buleleng Regency consists of 12 types of land use, i.e., forests, swamp forests, fields, land vegetation, settlements, developed land, grasslands, rice fields, shrubs, ponds, mangroves, and plantations, which are further classified into five classes (Figure 6). Landuse/land cover is a thorough landuse natural or human intervention under its needs to meet human needs financially [28]. Landuse in coastal areas is generally characterized by dynamic and complex land use (multi-functional) [29].
Landuse classes include settlements, land built, rice fields, mangroves, and swamp forests found on the coast of Buleleng Regency, especially in Sawan, Buleleng, Banjar, and Seririt subdistricts. Landuse classes include plantations found in some coastal areas of Sawan, Tejakula, and Gerokgak subdistricts. Some coastal areas of Kubutambahan and Tejakula subdistricts have landuse classes in the form of fields or moors. Landuse class in the form of forests and land vegetation is seen to dominate in Gerokgak Subdistrict.

Figure 6. Landuse map of Buleleng Regency.

3.6. Tsunami Vulnerability Analysis
The level of tsunami vulnerability in the Buleleng Regency is divided into five classes, namely R1 (very safe), R2 (safe), R3 (moderately vulnerable), R4 (vulnerable), and R5 (very vulnerable). The category of very safe and safe dominates in almost all Buleleng districts that are increasingly away from coastal areas. It is a safe area from tsunami waves. This is because Buleleng has a height >50 to >100 meters, distance from the shoreline >2404 to >3528 meters, then the distance from river >300 to >500 meters, with a slope of 15 to >40%, so that Buleleng set a low level of vulnerability. Mapping the level of tsunami vulnerability in the coastal area of Buleleng Regency is presented in Figure 7.

The category is moderately vulnerable to be seen in areas >556 to >1400 meters from the coastline, has an elevation of 25-50 meters with a land slope in the region predominantly worth 5-15%. In addition, there are no rivers in the area, so the area is modeled as an area with moderate levels of vulnerability. Coastal areas with a medium vulnerable category are seen in the western Gerokgak subdistrict, especially the West Bali National Park area.

Vulnerable areas almost dominate in the coastal areas of Tejakula, Kubutambahan, Sawan, Buleleng, Banjar, Seririt, and Gerokgak subdistricts. The area is at a distance of >556 meters from the coastline with a predominantly land slope worth 2-5% and 5-15%. In addition, the land elevation in the area is worth 10-25 meters.

The very vulnerable category area was found on Sawan, Buleleng, Seririt, and Gerokgak subdistricts close to the river that flows directly into the sea. The area is 556 meters from the coastline, with a slope of the land in the region predominantly worth 0-2 and 2-5%. The field survey results showed that the coastal areas of Buleleng, including Tejakula, Kubutambahan, Sawan, Buleleng, Banjar, Seririt, and Gerokgak subdistricts, are also at land elevations worth <25 meters. In line with statements [25] and [17], higher levels of tsunami vulnerability are found in areas with lower altitudes. Areas with lower
elevations increase tsunami vulnerability, resulting in greater risk, and vice versa. The relevant fact reinforces the Tohoku tsunami in 2011 that some areas close to the coastline but having higher elevations suffered less damage. The existence of rivers or estuaries in Sawan, Buleleng, Seririt, and Gerokgak subdistricts affects tsunami wave runoff that causes tsunami wave runoff to deepen. This condition increases the level of tsunami vulnerability so that it is modeled as a high level of vulnerability.

Figure 7. Map of coastal vulnerability to the tsunami in Buleleng Regency.

The area for each category of vulnerability in Buleleng Regency can be seen in Figure 7. The area with the category is very vulnerable (R5) has an area of 438.9 ha, the category of vulnerable (R4) is 6,903.3 ha, category moderately vulnerable (R3) by 17,645.0 ha, safe category (R2) of 35,466.9 ha, and very safe category (R1) of 70,485.0 ha. The comparison between the categories of very vulnerable and safe vulnerability looks small. However, it remains to be considered. This is because the location is in a densely populated settlement and has many lands built up. Although this area is relatively small, the loss level due to tsunami disasters can be very detrimental. Therefore, areas with vulnerability categories are very vulnerable and vulnerable require adequate mitigation efforts to minimize losses.

4. Conclusion
The level of coastal vulnerability to the tsunami in Buleleng Regency, Bali Province were grouped into five classes of vulnerability that are very safe (70,485.0 ha), safe (35,466.9 ha), moderately vulnerable (17,645.0 ha), vulnerable (6,903.3 ha), and very vulnerable (438.9 ha). The level of coastal vulnerability with a category is very vulnerable found in coastal areas of Gerokgak, Seririt, Buleleng, and Sawan subdistricts close to the river. Coastal areas that fall into the category of vulnerable are in almost all coastal areas of Buleleng Regency, except Busungbiu and Sukasada subdistricts. The category of vulnerability that dominates in Busungbiu and Sukasada is safe by 27.09% and very safe by 53.83% of all Buleleng Regencies.

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