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Analysis of vulnerability level to tsunami on the Bengkulu City coastal using Geographic Information System

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Abstract. Bengkulu City is one of the areas that has a high potential for experience earthquake and tsunami disasters because of its location right above the subduction zone of the Indo-Australian plate with the Eurasian plate. The objective of this study was to identify and map the degree of susceptibility to tsunamis in the coastal regions of Bengkulu City. The tsunami vulnerability map was created used the overlay method used five parameters, namely land elevation, land slope, distance from rivers, distance from the coastline, and land use. This research, which covers 14 sub-district areas was carried out used Geographic Information System (GIS). The level of tsunami vulnerability is divided into five classes, namely very safe with an area of 230.82 ha (1.19%), safe with an area of 4,402.30 ha (22.75%), moderately vulnerable with an area of 8,135.78 ha (42.04%), vulnerable with an area of 5,361.06 ha (27.70%), and very vulnerable with an area of 1,222.38 ha (6.32%). The city of Bengkulu is dominated by the medium vulnerability class so that in general it is classified as not safe enough from the risk of a tsunami disaster.

1 Introduction

Indonesia is located on three main plates in the world, namely the Eurasian Plate, the Indo-Australian Plate and the Pacific Plate, which causes a high potential for earthquakes in Indonesia [1]. One of the impacts caused by the earthquake was a tsunami. Tsunami is a very large sea wave that is triggered by an earthquake on the seabed due to plate thrusting or subduction, movement of faults, volcanic eruptions on the seabed, or collisions with space objects [2]. Earthquake with a magnitude of >7 SR, a depth of the epicenter <100 km, with an normal or reverse fault pattern has the potential to cause a tsunami [3].

One of the areas with a high potential for large earthquakes and tsunamis in Indonesia is Bengkulu City [2]. Based on its geological conditions, the marine waters of Bengkulu City stand directly above the subduction zone of the Eurasian plate with the Indo-Australian plate at a rate of 4-6 cm/year [4]. This causes the city of Bengkulu City is very prone to earthquakes with large magnitudes, which is one of the triggers of tsunamis. There were 8 tsunami incidents recorded in Bengkulu namely on 1770, March 18, 1818, November 24, 1833,

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October 10, 1896, June 25, 1914, September 25, 1931, April 21, 1958, September 12, 2007 [5].

However, the occurrence of tsunami, cannot be accurately anticipated in terms of when and where it will occur. This is because most tsunamis are a result of an earthquake, which cannot be forecasted in terms of timeframe [6]. Hence, it is imperative to implement proactive measures to reduce the consequences of tsunami occurrences in vulnerable regions of Bengkulu City. This includes the development of disaster mitigation documents, such as the creation of hazard maps [7]. Utilizing five parameters influencing tsunami vulnerability namely elevation, land slope, proximity to the coastline, distance from rivers, and land use, this research endeavors to identify and map the tsunami vulnerability levels in the coastal regions of Bengkulu City. This endeavor serves as a preventative mitigation strategy against tsunami hazards. With this map, it can be seen which parts of the area are very vulnerable to tsunamis so that they can minimize the impact and increase prevention such as the construction of giant sea walls or breakwaters [2]. In addition, for areas that are not vulnerable to tsunamis, evacuation routes can be built. A tsunami vulnerability level map may be created by utilizing Geographic Information system (GIS) technology, employing spatial query analysis and overlay analysis with a weighting mechanism [8].

2 Materials and methods

2.1 Time and study area

The research was conducted from December 2022 to June 2023 located in the Bengkulu City area. Data collection and processing was carried out at the Spatial Mapping and Modeling Laboratory, Department of Marine Science and Technology, Faculty of Fisheries and Marine Sciences, IPB University. The study area is shown in Figure 1.

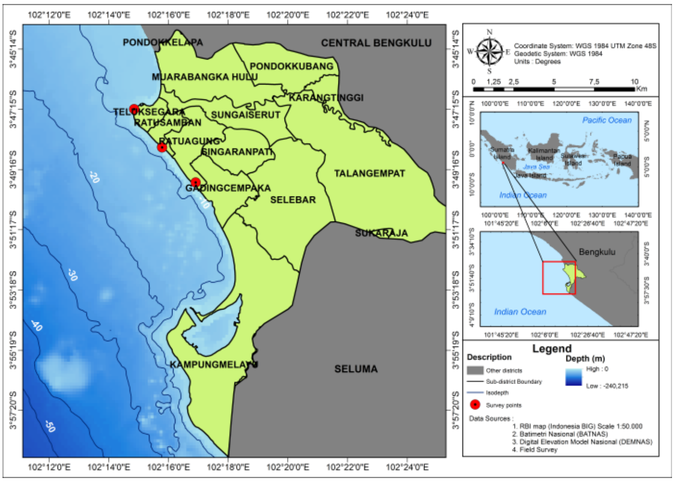

Fig. 1. The study area is on the coast of Bengkulu City, Bengkulu Province

2.2 Data and tools

The sources and information about the data used can be seen in Table 1. The tool used in this research is an Intel Core i5-2410M laptop equipped with GIS software. The materials used are included data Digital Elevation Model (DEMNAS), National Bathymetry (BATNAS), and Indonesia Topographic Map (RBI maps).

Table 1. Sources of Information and Data Acquisition

Parameter	Data	Data Sources	Resolution
Land elevation	DEMNAS	Badan Informasi Geospasial (BIG)	0.27-*arcsec*
Land slope	DEMNAS	BIG	0.27-*arcsec*
Distance from shoreline	Indonesia Rupabumi (RBI) maps	BIG	1:50,000
Distance from river	RBI maps	BIG	1:50,000
Landuse	RBI maps	BIG	1:50,000
Earthquake epicenter point	Earthquake Record Data	*Earthquake Hazard* USGS	-
*Bathymetry	BATNAS	BIG	6-*arcsec*

* Only to display depth contours (Isodepth)

2.3 Data processing and analysis

The stages in data processing are include classification of parameters which are land elevation, land slope, distance from the shoreline, distance from the river, and landuse [8]. The elevation and land slope spatial data is in the form of DEMNAS raster data while the other three spatial data is in the form of RBI data.

Table 2. Matrix of coastal vulnerability parameters against tsunami disaster

Parameter	**Weighted	Criterion	**Score
Land elevation (m) [10]	25%	<10 ≥10 - 25 >25 - 50 >50 - 100 >100-300	5 4 3 2 1
Land slope (%) [11]	20%	0 - 2 2 - 5 5 - 15 15 - 40 >40	5 4 3 2 1
Distance from river (m) [12]	20%	<100 100 – 200 200 – 300 300 – 500 >500	5 4 3 2 1
Distance from shoreline (m) [13]	20%	556 >556 >1400 >2404 >3528	5 4 3 2 1
Landuse [12, 14]	15%	Settlements, rice fields, mangroves, swamp forests Gardens, ponds, lakes Fields/moors Shrubs, grass, vacant land Forests, land vegetation, rock and limestone	5 4 3 2 1

**Weighting and scoring refer to research [8]

For the land slope parameter, the elevation raster data will be converted into land slope raster data with the *slope* function in the form of a percent value. Meanwhile, the distance from the coastline and river parameters were obtained using the *buffer* technique. After that, data from the five parameters used will be classified based on the results of the literature study. Data on the five parameters used will be classified based on the results of the literature study. Furthermore, the tsunami vulnerability analysis is determined by using the overlay method of the five parameters with scores and weights according to their level of influence on the level of tsunami vulnerability in the matrix based on the research of Wemben and Nareswari 2021 [14]. Based on these parameters, the matrix for determining tsunami vulnerability is compiled, as shown in Table 2.

The matrix in Table 2 is determined by the score and weight of each parameter based on the influence of that parameter on the level of tsunami vulnerability based on [14]. Scoring aims to assess the factors that limit each parameter. The weighting for each parameter in this study ranges from 15-25% and a score of 1-5 indicates the level of tsunami vulnerability (very vulnerable, vulnerable, moderately vulnerable, safe and very safe). Then, the total score of each class is determined using the formula [15]:

$$N_i = \sum_{j=1}^{5} B_j x\, S_j \tag{1}$$

Note:
i = land elevation, land slope, distance from the shoreline, distance from river, land use
j = 1,2,3,4,5
Ni = total weight × score for the-i parameter
Bj = weight on each criterion
Sj = score on each criterion

Based on the calculation of the total score, the N value is used to determine the class interval for the level of vulnerability. The calculation for each interval class is obtained from the highest N value (N max) minus the lowest N value (N min) which is divided into five classes. The tsunami vulnerability level class interval is formulated as follows where L: class interval width, n: number of classes [15].

$$L = \frac{\sum_{j=1}^{5}(Bi\ x\ Si)max - (Bi\ x\ Si)min}{n} \tag{2}$$

Based on calculations using the formula above, a class interval width value of 0.67 is obtained with a minimum score of 1.65 and a maximum score of 5. The value of the very safe category vulnerability level (R1) is obtained from the minimum score value of 1.65 added with a class interval width of 0.67. And so on for safe (R2), moderately vulnerable (R3), vulnerable (R4) and very vulnerable (R5) values as presented in Table 3.

Table 3. Tsunami vulnerability class interval

Number	Class	Vulnerability Level	Class Interval
1	R1	Very Safe	1.65 – 2.31
2	R2	Safe	2.32 – 2.98
3	R3	Moderately Vulnerable	2.99 – 3.65
4	R4	Vulnerable	3.66 – 4.32
5	R5	Very Vulnerable	4.33 – 5.00

3 Results and discussion

3.1 Processing of tsunami parameter data

Based on earthquake data from the USGS earthquakes hazard, there were 70 earthquake events centered in the sea in Bengkulu area during the period 1833-2023 with varying earthquake strengths and depths. There were 3 earthquake events at a depth of < 100 km and magnitude > 7 SR which had the potential to cause a tsunami. In the Bengkulu area, 8 tsunami events were recorded in the period 1770-2007 [5].

A tsunami event with the largest earthquake magnitude of 8.2 occurred on November 24 1833, the rising tsunami waves splashed onto the coast destroying the breakwater and surrounding houses [16]. In addition, on September 12 2007, an earthquake with a magnitude of 7.9 occurred at a depth of 10 km and produced a tsunami as high as 3.6 m.

The geographical condition of the Bengkulu City coast is a sandy beach with a sloping beach depth and a relatively shallow depth of 0-1.5 m [17, 18]. The type of beach that tends to be sloping will influence the height of the tsunami that arrives at the beach. One of the coastal morphologies in Bengkulu City is a bay and a river flows into the coast. The bay can increase the size of tsunami waves [19]. The existence of this river estuary can increase the risk of a tsunami disaster [20].

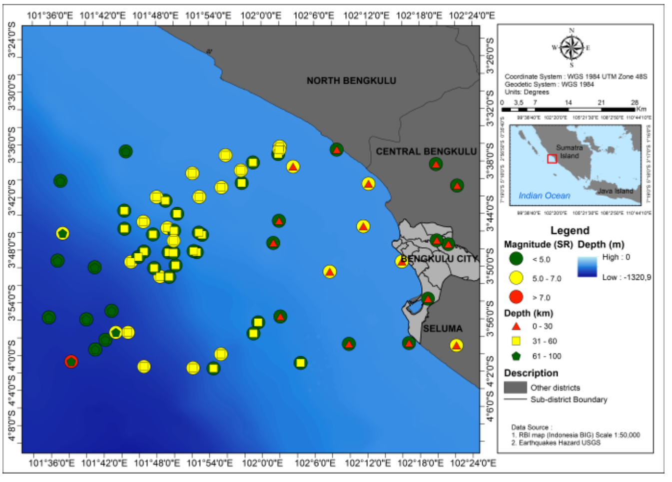

Fig. 2. Location of the earthquake in 1833 – 2023 in Bengkulu City and its surroundings

3.2 Land elevation

Bengkulu City has a relatively low land elevation. Areas with a very vulnerable have an elevation of <10 m, dominated by coastal areas. Meanwhile, areas with a very safe level of vulnerability are only found in Talang Empat Sub-district. The area along the coastline of Bengkulu City is dominated by a elevation of 0-10 m, so it is classified as a high danger zone for tsunami disasters [21]. Meanwhile, areas with land elevation of >15 m are found in the eastern part of Bengkulu City which is away from the coastline.

The lower the land elevation of an area, the greater the level of vulnerability to tsunami hazards [22]. On the other hand, the higher the land elevation of a place, the lower the level of vulnerability to tsunami hazards [2]. The high and low levels of land elevation are related to the size of the volume of tsunami run-off entering the land [23]. Based on the results of data processing, information on the area of land elevation vulnerability classes is obtained which is presented in Table 4.

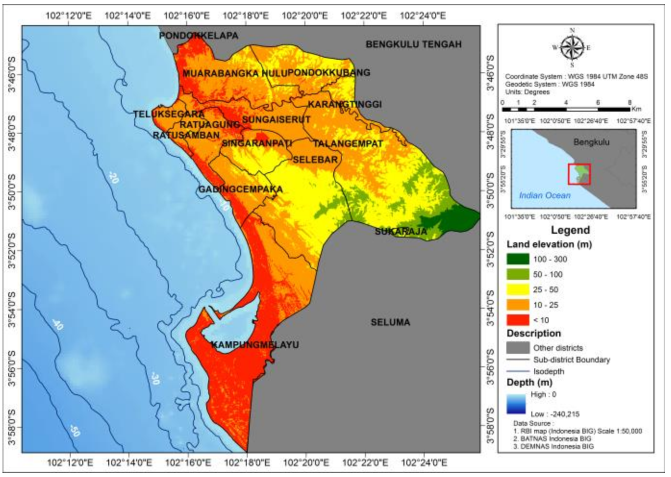

Fig. 3. Distribution of land elevations in Bengkulu City

The city of Bengkulu is dominated by the high land elevation vulnerability class with an area of 9,003.27 ha (45.35%), while the area with the very low vulnerability class has the smallest area, namely 422.58 ha (2.13%). The area of each criterion for land elevation parameters is presented in Table 9.

Table 4. The land elevation area on the coast of Bengkulu City

Number	Vulnerability Level	Area (Ha)	Percentage (%)
1	Very Vulnerable	4,453.37	22.43
2	Vulnerable	9,003.27	45.35
3	Moderately Vulnerable	4,829.32	24.32
4	Safe	1,145.33	5.77
5	Very Safe	422.58	2.13

3.3 Land slope

The coastal area of Bengkulu City is dominated by a land slope of 0-2% to 5-15%. Coastal areas with a land slope of 0-2% are found in the Sub-districts of Kampung Melayu, Muara Bangkahulu, and Sungai Serut. Areas with land slopes of 15 to >40% are found in most areas of Bengkulu City which are far from the coast. The coast of Bengkulu City is dominated by flat and sloping areas, while land slopes >25% (very steep) or areas with very low danger zones will only be in the eastern part of Bengkulu City [21].

The steeper the land, the lower the tsunami wave height will be [10]. On the other hand, flat and sloping land will have high tsunami waves. On steep beaches, the tsunami will not go very far inland because it is blocked and will be reflected back by the coastal cliffs. Meanwhile, on sloping beaches, tsunamis can hit freely several kilometers inland [24]. Based on the results of data processing, information on the area of the land slope vulnerability class area is obtained which is presented in Table 5.

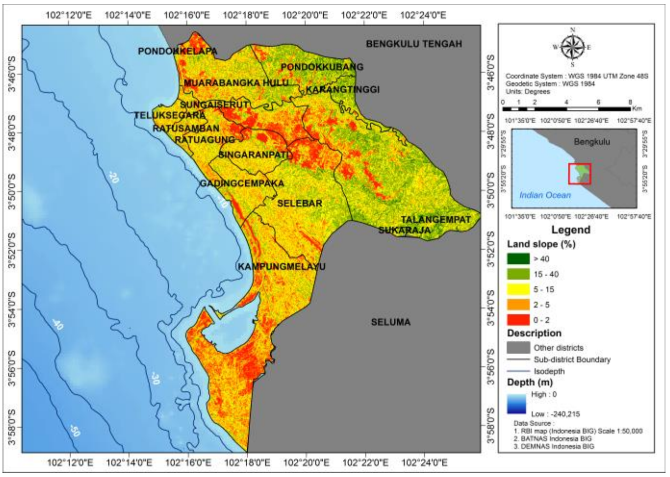

Fig. 4. Distribution of land slopes in Bengkulu City

The city of Bengkulu is dominated by the moderate land slope vulnerability class with an area of 8,155.60 ha (41.30%), while the area with the very low vulnerability class has the smallest area, namely 242.92 ha (1.23%). The area of each criterion for land slope parameters is presented in Table 9.

Table 5. The land slope area on the coast of Bengkulu City

Number	Vulnerability Level	Area (Ha)	Percentage (%)
1	Very Vulnerable	2,753.,43	13.94
2	Vulnerable	4,287.98	21.72
3	Moderately Vulnerable	8,155.60	41.30
4	Safe	4,306.02	21.81
5	Very Safe	242.92	1.23

3.4 Distance from shoreline

Areas with a very high level of vulnerability have a distance of no more than 556 m from the coastline, namely the coastal parts of the sub-districts of Kampung Melayu, Gading Cempaka, Ratu Agung, Ratu Samban, Teluk Segara, Muara Bangkahulu, and Sungai Serut. Meanwhile, areas with a very low level of vulnerability are sub-districts that are far from the coast, such as Talang Empat and Karang Tinggi sub-districts.

An area will become more vulnerable to tsunamis as the area gets closer to the coastline. On the other hand, the level of vulnerability will decrease as the area moves further away from the coastline. Thus, areas with a distance of < 1400 m from the coastline are classified as vulnerable while areas > 2404 m from the coastline are classified as not vulnerable [25, 26]. This is because the height of the tsunami wave will decrease with increasing distance when the wave reaches the coastline [2]. Based on the results of data processing, it shows the extent of the vulnerability class area, distance from the coastline, which is presented in Table 6.

Bengkulu City is dominated by areas with a very low vulnerability class with an area of 10,776.10 ha (54.38%). Meanwhile, areas with a low vulnerability class have the smallest area at 1,940.67 ha (9.79%). The area of each criterion for the distance parameter from the coastline is presented in Table 9.

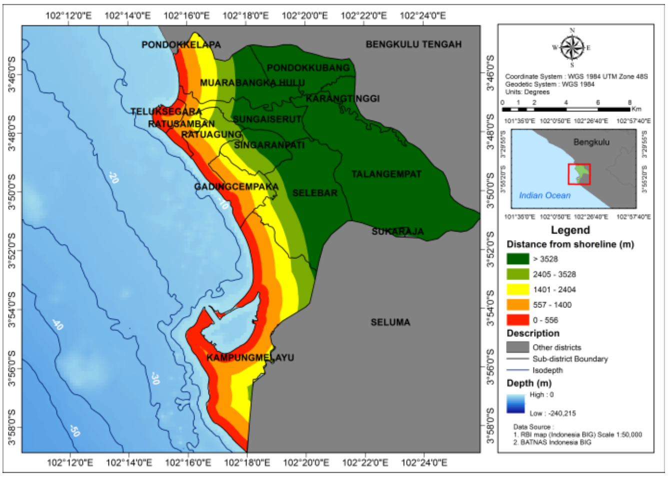

Fig. 5. Distance from the shoreline of Bengkulu City

Table 6. The distance from the coastline area of Bengkulu City

Number	Vulnerability Level	Area (Ha)	Percentage (%)
1	Very Vulnerable	2,148.97	10.84
2	Vulnerable	2,526.52	12.75
3	Moderately Vulnerable	2,424.85	12.24
4	Safe	1,940.67	9.79
5	Very Safe	10,776.10	54.38

3.5 Distance from river

Areas with very high vulnerability are <100 m from the river, while areas with very low vulnerability are >500 m from the river [12]. In the Bengkulu City area there are 3 quite large rivers, namely the Hitam River, Serut River, and Jenggalu River. The Hitam River flows into the beach in Muara Bangkahulu sub-district. The Serut River flows at the edge of the beach in Sungai Serut sub-district, while the Jenggalu River flows at the edge of the beach in Kampung Melayu sub-district.

Rivers that flows into the coast will result in an increase in the amount of water in the river during a tsunami so that the water in the river will overflow to the surface. This is because, when a tsunami passes through a narrow area such as a river, there will be an increase in speed and water level because the same water mass discharge must spread through a relatively narrow gap at the same time [27]. The results of data processing showing the area of vulnerability distance from the river to the tsunami disaster are presented in Table 7.

Bengkulu City is dominated by areas with a very high vulnerability class with an area of 9,394.16 ha (47.26%), while areas with a low vulnerability class have the smallest area at 1,904.06 ha (9.58%). The area of each criterion for the distance parameter from the river line is presented in Table 9.

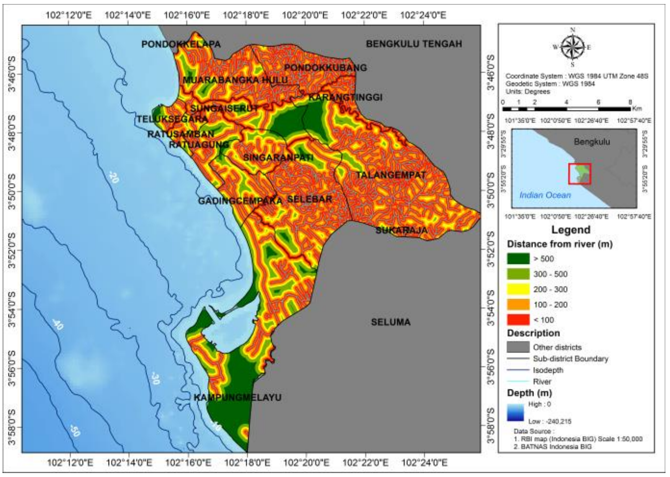

Fig. 6. Distance from the river of Bengkulu City

Table 7. The distance from the river area of Bengkulu City

Number	Vulnerability Level	Area (Ha)	Percentage (%)
1	Very Vulnerable	9,394.16	47.26
2	Vulnerable	4552.09	22.90
3	Moderately Vulnerable	2,075.63	10.44
4	Safe	1,904.06	9.58
5	Very Safe	1952.48	9.82

3.6 Landuse

The city of Bengkulu is dominated by a high level of vulnerability, namely land use for gardens, lakes and ponds. Areas with a very high vulnerability class are dominated by the coastal areas of Bengkulu City with dense settlements, namely Teluk Segara, Sungai Serut, Ratu Samban, Ratu Agung, and Gading Cempaka sub-districts. In general, the distribution of land cover on the coast of Bengkulu City consists of residential areas and beachside tourist areas dominated by pine trees and low shrubs [2].

The level of tsunami vulnerability for each type of land use is different because each land use has a different level of reduction when hit by tsunami waves. Land use types such as settlements, irrigated rice fields and land vegetation (gardens) have a low level of reduction in exposure to tsunami waves so they are more vulnerable [28]. Based on the results of data processing, it shows the area of land use vulnerability classes presented in Table 8.

The city of Bengkulu is dominated by the high vulnerability class, namely gardens, lakes and ponds with an area of 12,223.91 ha (62.65%), while the area with the medium vulnerability class, namely moorland or fields, has the smallest area, namely 418.55 ha (2, 15%). The area of each criterion for land use parameters is presented in Table 9.

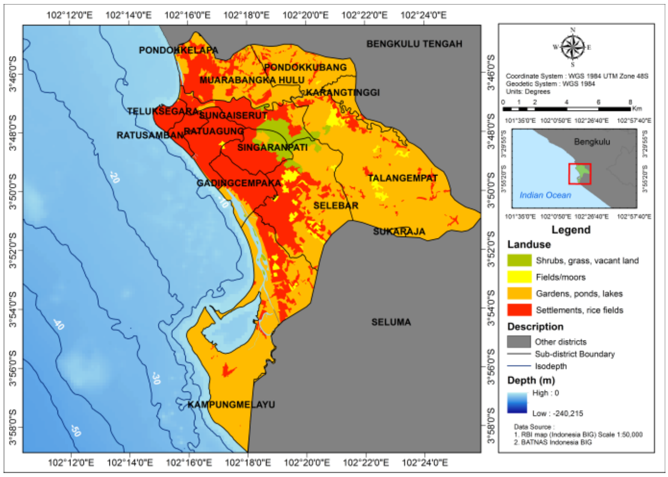

Fig. 7. Land use of Bengkulu City

Table 8. Area of land use on the coast of Bengkulu City

Number	Vulnerability Level	Area (Ha)	Percentage (%)
1	Very Vulnerable	6,207.53	31.81
2	Vulnerable	12,223.91	62.65
3	Moderately Vulnerable	418.55	2.15
4	Safe	662.59	3.40

3.7 Tsunami vulnerability analysis

The mapping results (Figure 8) show that areas with low and very low levels of vulnerability are dominated by Sukaraja and Talang Empat sub-districts, which are located far from coastal areas, have steep land slopes and dominate the eastern part of Bengkulu City, so they are considered to be areas with low risk or safe from tsunami disasters. The medium vulnerability category is seen to dominate almost all areas of Bengkulu City spread across all sub-districts. The medium vulnerability category is seen to dominate almost all areas of Bengkulu City which are spread across all sub-districts. This is because areas with low elevation are dominantly located on the coast so that non-coastal areas tend to have elevations that are not low. It is also supported by the steep land slope in the eastern part of Bengkulu City and the distance away from the coastline. Areas in the moderate class are not safe enough from the risk of tsunami disaster.

Dark green color on the map indicates that the area is a very low vulnerability area, green color indicates that the area is a low vulnerability area, yellow color indicates that the area is a medium vulnerability area, orange color indicates that the area is a high vulnerability area, while red color indicates that the area is a very high vulnerability area. Areas with a high vulnerability category almost dominate all sub-districts located on the coast, namely Gading Cempaka, Pondok Kelapa, Ratu Agung, Ratu Samban and Teluk Segara sub-districts. This area is classified as unsafe against tsunamis and has the potential to suffer significant damage. The parameters that most affect this area are elevation, land slope and distance from the coastline because it is a coastal area with a short distance from the coastline with an elevation of 10-25 m which is low and a land slope of 2-5% which is quite gentle. Areas that fall into the highly vulnerable category are located on the coast of Kampung Melayu, Muara

Bangkuhulu and Sungai Serut sub-districts. Elevation parameters, distance from the coastline and rivers and landuse are the most influential in this area because it is directly adjacent to the coastline with low elevation, dominant landuse of dense settlements and has a river that empties into the sea.

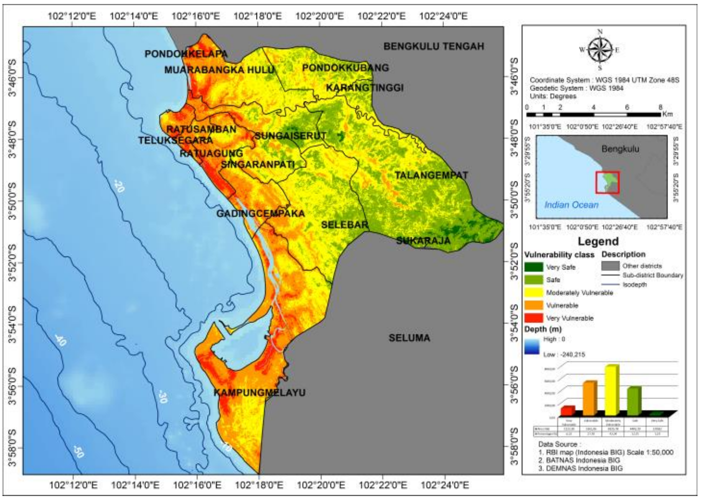

Fig. 8. Distribution of tsunami vulnerability levels in Bengkulu City

The level of influence of a parameter is determined based on the score of each classification and the weight of each parameter on its level of influence on tsunami vulnerability. The greater the weight, the greater the influence of the parameter on the tsunami. The area for each criterion for each sub-district is presented in Figure 9. The very high vulnerability class is generally found in areas along the coast of Bengkulu City and directly adjacent to the coastline. Coastal areas have a higher level of tsunami danger than areas located inland far from the coast [29]. The area and percentage for each class of tsunami vulnerability on the coast of Bengkulu City are presented in Table 9.

Table 9. The area of the vulnerability level on the coast of Bengkulu City

Number	Vulnerability Level	Area (Ha)	Percentage (%)
1	Very Vulnerable	1,222.38	6.32
2	Vulnerable	5,361.06	27.70
3	Moderately Vulnerable	8,135.78	42.04
4	Safe	4,402.30	22.75
5	Very Safe	230.82	1.19

Land use in areas prone to the risk of tsunami disasters is dominated by gardens, fields and relatively dense settlements [30]. In Bengkulu City, the coastal area has tourist locations, residential areas and ports [17]. Densely populated areas are in Rawa Makmur Village, Kandang Kampung Melayu, Pondok Kelapa, Pondok Besi, and others [31]. Based on the condition of the beaches, the beaches of Bengkulu City are classified as sandy beaches with a fairly gentle depth. There are several river estuaries that could increase the danger of a tsunami. Apart from that, along the coast of Bengkulu City there are no hills or barriers that can withstand the tsunami [21]. So that tsunami waves will reach settlements in the coastal areas of Bengkulu City more quickly. Apart from that, Bengkulu City has bays in the administrative areas of Segara Bay and Sepang Bay. The presence of the bay will cause the height of the tsunami waves to increase or increase by 1.5-2 times with a strengthening of the tsunami waves in the percentage of 50% - 200% [31]. This can happen because a tsunami that hits the bay area will narrow it and cause an increase in water mass and the energy of a tsunami wave [32].

Areas in the very vulnerable category (R5) have an area of 1,222.38 ha (6.32%), the vulnerable category (R4) is 5,361.06 ha (27.70%), the moderately vulnerable category (R3) is 8,135.78 ha (42.04%), the safe category (R2) was 4,402.30 ha (22.75%), and the very safe category (R1) was 230.82 ha (1.19%). The area of each sub-district of Bengkulu City in terms of level of vulnerability is presented in Figure 9. Each sub-district identified shows a different level of tsunami risk. So adequate mitigation efforts are needed so that losses can be minimized, such as creating disaster mitigation documents, such as tsunami risk maps, evacuation route maps, as well as outreach to the public through the media [33].

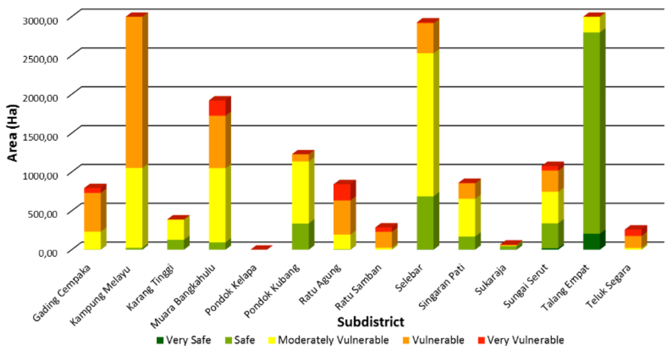

Fig. 9. Comparison of the area of each sub-district of Bengkulu City regarding the level of tsunami vulnerability

4 Conclusion and recommendation

The level of coastal vulnerability to tsunamis in Bengkulu City is divided into five vulnerability classes, namely very safe (230.82 ha), safe (4,402.30 ha), moderately vulnerable (8,135.78 ha), vulnerable (5,361.06 ha), and very vulnerable (1,222.38 ha). The city of Bengkulu, predominantly characterized by a medium vulnerability class, is generally classified as not sufficiently safe from the risk of tsunami disasters including Karang Tinggi, Pondok Kubang, Selebar and Singara Pati sub-districts with high elevation. It is also supported by the steep land slope in the eastern part of Bengkulu City and the distance away from the coastline. In contrast, the coastal areas are primarily dominated by high and very high vulnerability classes, rendering them particularly unsafe from the threat of tsunami disasters. The level of coastal vulnerability in the highly vulnerable category is found in coastal areas that are directly adjacent to the coastline, have rivers that drain into the sea, and low elevation. The vulnerability category that dominates in the Sukaraja District and Talang Empat District is safe at 22.75% and very safe at 1.19% of the entire Bengkulu City. Other parameters such as shoreline shape, bathymetry, run-up height, and distance to the earthquake source are needed in this research to map more comprehensive tsunami risk areas.

References

1. D.P. Utomo, B. Purba, *Proceedings of the National Seminar on Science Information Riset (SENARIS)* (2019)

2. S.H. Santius, Settlement. J., **10,** 2 (2015)
3. [BMKG] Badan Meteorologi, Klimatologi dan Geofisika. Tsunami (2017)
4. Winardi, R. Gatot, Sugiantoro, L. Ninok, D. Adrianus. Jogja Earthquake, Indonesia and the World (Gramedia, Jakarta ID, 2006)
5. [BMKG] Badan Meteorologi, Klimatologi dan Geofisika. Indonesian Tsunami Catalog 416-2018 (2019)
6. T.P. Tarigan, P. Subardjo, D. Nugroho, J. Ocean., **4**, 4 (2015)
7. U. Kultsum, A. Muhari, Z Fuad, *Proceedings of the National Congress of Sciene* (2016)
8. P.A. Burrough. Principles of Geographical Information Systems for Land Resource Assessment Palaeosols, Their Recognition and Interpretation (Clarendon Press, Oxford UK, 1986)
9. B. Wemben, A. Nareswari, J. Soc. Sci., **8**, 6 (2021)
10. E. Sengaji, B. Nababan, E. J. Mar. Sci. Tech., **1**, 1 (2009)
11. I. Faiqoh, J. Lumban-Gaol, M.L. Marisa, Inter. J. Remote. Sens. Earth. Sci., **10**, 2 (2013)
12. S. Firmansyah. Pangandaran Beach Vulnerability Index Due to the Tsunami Disaster (IPB univ, Bogor ID, 2012)
13. A.B. Sambah, F. Miura, J. Geogr. Inf. Syst., **6**, 1 (2014)
14. A. Pratiwi. Spatial Analysis of the Vulnerability of the West Coast Region of Banten Province to the Tsunami Disaster Using Geographic Information Systems (IPB univ, Bogor ID, 2017)
15. A.A. Muzaki. Spatial analysis of coral reef quality as a basis for determining marine conservation areas using the cell based modeling method in Karang Lebar and Karang Congkak Seribu Islands, DKI Jakarta (IPB univ, Bogor ID, 2008)
16. H. Latief, N.T. Puspito, F. Imamura, J Nat Disaster., **22**, 1 (2000)
17. M.A.P. Saputri. The influence of coastal characteristics on tsunami risk on the coast of Bengkulu City (Bengkulu univ, Bengkulu ID, 2020)
18. P.D. Apriliansyah, Y. Johan, P.P. Renta, J. Enggano., **3**, 2 (2018)
19. S.D. Anugrah , B. Sunardi, *Proceedings of the Int Conf Suistanable Build Environ* (2012)
20. F. Saputri. The influence of the slope and shape of the coast on the height of the tsunami in Cilacap (Pamulang press, Tangerang ID, 2018)
21. H.T. Fachri, Y. Malik, H. Murtianto , J. Geogr. Educ., **10**, 2 (2022)
22. O. Oktariadi. J. Indones. Geol., **4**, 2 (2009)
23. N.P.A.R. Suhita, V.P. Siregar, J. Lumban-Gaol IOP. Conf. Ser.: Earth. Environ. Sci., **944** (2021)
24. P. Subarjo, A. Raden., Trop. Mar J., **18**, 2 (2015)
25. T.P.T. Sinaga, A. Nugroho, Y.W. Lee, Y. Suh, KSCE. J. Civ. Eng., **15**, 3 (2011)
26. S. Diposaptono and Budiman. Tsunami (Popular scientific books, Bogor ID, 2005)
27. G. Pedersen, S. Glimsdal, Open. Oceanogr. J., **4** (2010)
28. A.N.H. Putra. Tsunami disaster risk level and its spatial variations (case study of Padang City, West Sumatra) (Indonesia univ, Depok ID, 2009)
29. H.S. Naryanto, J. Disaster. Risk. Reduct. Technol., **3**, 1 (2019)

30. Z.M.A. Bustomi, T.H. Ramadhan, H. Cahyadi, D. Muslim, *Proceedings of the III National Seminar of Sciene Faculty of Geological Engineering, Padjadjaran University*, Sumedang (2017)
31. B. Harlianto, Suwarsono, Supiyati, *Proceedings of the II National Seminar of Coastal and Watershed Management*, 159–166 (2016)
32. R Triatmadja. Tsunamis: Occurrence, Propagation, Damage, and Mitigation (Gajah Mada univ, Yogyakarta ID, 2010)
33. Y. Mudin, I.W.J. Pramana, Sabhan, Gravity., **14**, 2 (2015)