Rising Seas Threaten Bandar Lampung: Analyzing Tidal Flood Disaster Potential

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Abstract. Tidal flood is a phenomenon of sea level rise with a water level elevation that is higher than the coastline. Sea level rise and land subsidence are several factors that can cause the phenomenon of tidal flood. This study aims to predict the effect of the trend of sea level rise based on tidal data of 18.6 years and land subsidence on the level of tidal flood threat along the Bandar Lampung coastal area. Tidal data obtained from numerical model predictions are used to determine water level elevation and spatial approach using Geographic Information Systems (GIS) with Landsat-8 satellite image data processed to get the area of tidal flood inundation caused by sea level rise. The result indicates that the trend of sea level rise along the Bandar Lampung coastal area was 0.024 mm/year. The outcome shows that tidal inundation of short-term in 2027 is about 25.337 ha along the Bandar Lampung coastal area and for the long-term prediction in 2072 is 122.8 ha. From this result, the threat levels from 2022, short-term, and long-term predictions are predominantly in the low-threat level, but the inundation area increases every year.

Keywords: tidal flood, sea level rise, Bandar Lampung, tidal inundation, GIS.

1 Introduction

The coastal area is a region where interactions between the land and the sea occur, mutually influencing each other [9]. As a result, coastal areas experience dynamic changes due to natural responses and human activities. Supporting factors in the dynamics of coastal areas include climate, hydro-oceanography, sediment supply, sea level changes, and human activities [9]. Coastal areas are highly vulnerable to natural disasters, including tidal floods. Tidal floods usually occur during full moon or during the period of a full moon. During this time, the gravitational pull of the moon on Earth is very strong, causing the movement of seawater towards the coast to be stronger than usual. Tidal flooding is a phenomenon where seawater overflows onto the land in areas along the coast that are lower than the average sea level (mean sea level) due to the tidal flow process. Therefore, observations of tides can be used as a benchmark to assess the potential for tidal flooding.

Tidal flooding can result in damage to buildings, infrastructure, and disrupt the activities of coastal communities. Observations of the potential for tidal flooding need to be conducted in coastal areas to minimize the impacts. There are two causes of tidal flooding: rising sea levels and land subsidence [2]. The rise in sea levels can be

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attributed to global warming, which leads to increasing the tidal ranges. Meanwhile, land subsidence occurs due to changes in land use and inadequate drainage systems. Bandar Lampung is the capital city of Lampung province. Besides serving as the centre for governmental, social, political, educational, and cultural activities, it is also the economic hub of the Lampung region. According to the Lampung Disaster Risk Assessment in 2019 [4], several locations in Bandar Lampung, such as the districts of Bumiwaras, Panjang, Teluk Betung Timur, and Teluk Betung Selatan, were classified as having a moderate threat level for flood disasters. This could be further assessed when considering sea level rise. The research objectives are predicting the rise in sea levels along the coast, predicting the distribution of tidal flood inundation due to sea level rise (SLR) in short-term and long-term, and producing the map of potential tidal flood threats along the coast of Bandar Lampung city. Administratively, Bandar Lampung City shares borders with several regions: Lampung Selatan Regency to the North, Teluk Lampung to the South, Pesawaran Regency to the West, and Lampung Selatan Regency to the East. Bandar Lampung City comprises four coastal districts: Teluk Betung Timur District, Teluk Betung Selatan District, Bumiwaras District, and Panjang District. These four areas are the locations for this research. The hypothesis of this research is that the coastal areas of Bandar Lampung experience a rise in sea levels, yet the threat level of tidal floods remains in low category.

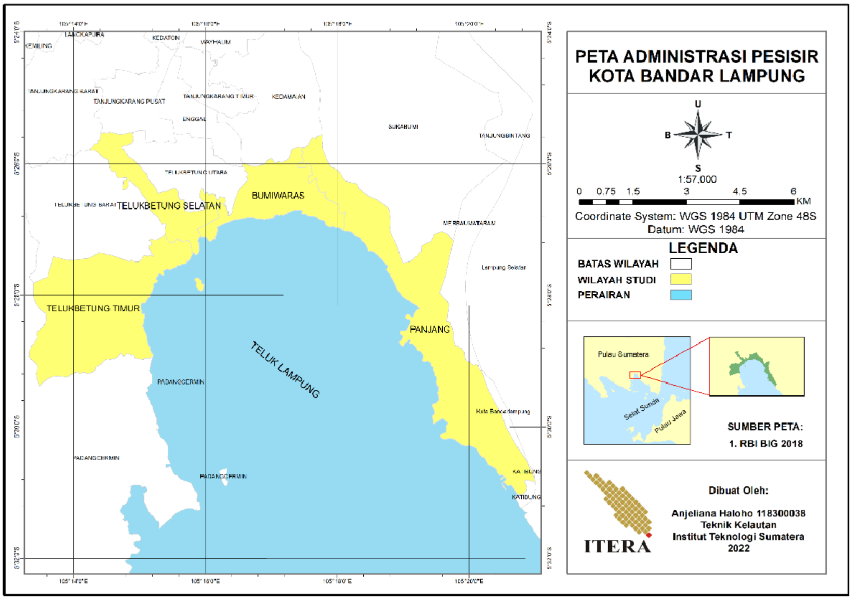

Fig. 1. Location of this research.

2 Methodology

In this research, both primary and secondary data will be utilized. Primary data includes tidal data and field surveys, including interviews aimed at understanding the land use conditions in the research area and gathering information about the phenomenon of sea level rise and its impact on coastal inundation. The collection of primary data is carried out through documentation and validation of the study location's conditions. Secondary data is obtained by downloading from websites that provide the necessary data from government agencies and other sources. The secondary data in this research includes tidal data, DEM (Digital Elevation Model) imagery, and RBI (Spatial Plan and Environmental Plan) map at a 1:50,000 scale. After having all the raw data, it was processed until having the useful data. Tidal data must be validated between primary and secondary data to prove the accuracy of data. Then, the area of tidal flooding threat is obtained for further analysis. The complete flowchart of the research methodology is shown in Fig. 2.

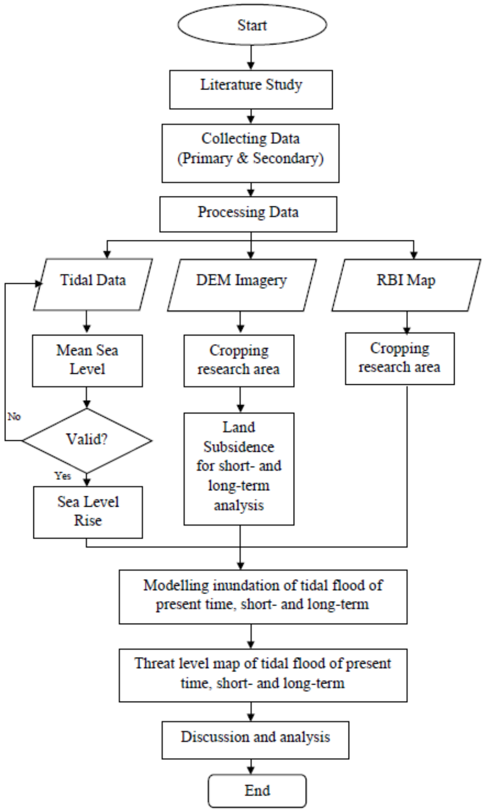

Fig. 2. Flowchart of study.

3 Characteristics of Bandar Lampung City

In this research, there are three characteristics of locations that used for analysis, such as elevation of coastal area, land use and slope gradient, and sea level rise of Bandar Lampung coastal area.

3.1 Elevation of coastal area

The data on land elevation was obtained through the processing of DEM (Digital Elevation Model) data using ArcGIS software. The range of elevations of Bandar Lampung coastal area is from -1.91 to 380.8 meters (Fig. 3).

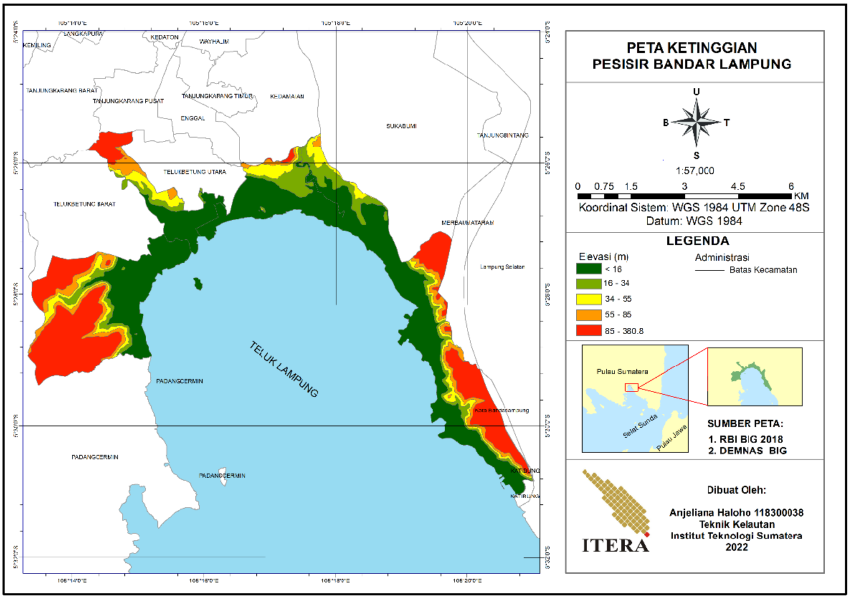

Fig. 3. Elevations map of Bandar Lampung coastal area.

The elevation below 16 meters (green colour) in four districts is the threating area. The total threating area are 288.26 ha, 605.63 ha, 144.75 ha, and 340.40 ha for Bumiwaras, Panjang, Teluk Betung Selatan, and Teluk Betung Timur, respectively.

3.2 Land use and slope gradient.

Land use classification is classified into 7 classes. The total area of each classification is 137.6 ha for bodies of water, 2.7 ha for ponds/paddy fields, 474.9 ha for forests, 255 ha for vacant land, 24.6 ha for mangroves, 1064.9 ha for residential/built-up areas, and 1060.3 ha for shrubs/brush. The land cover map for the coastal areas of Bandar Lampung City is presented in Fig. 4.

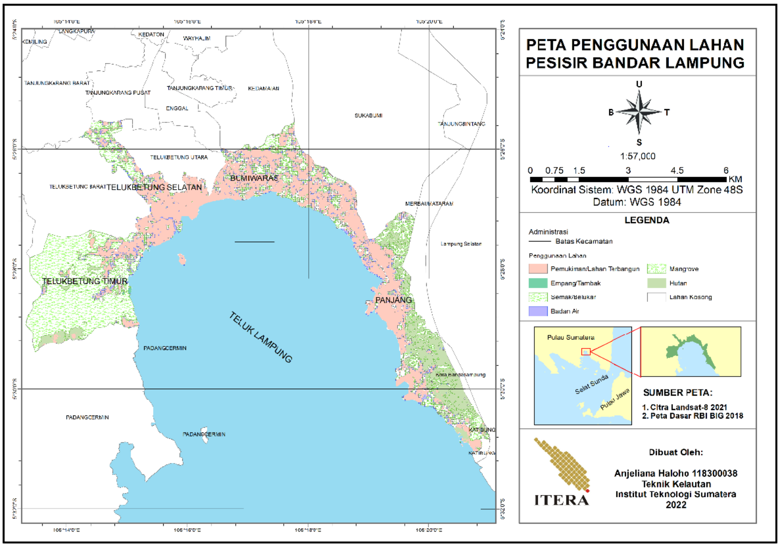

Fig. 4. Land use of Bandar Lampung coastal areas.

3.3 Sea Level Rise (SLR)

The tidal data prediction was obtained from Mike21 for a period of 18.6 years, from 2003 to 2021. It was then processed to obtain the amplitude and constant phase difference values of tidal harmonics using the least square method. The least square method is based on determining the water level model that minimizes the squared error against observed water levels. Based on calculations using the least square method, the tidal data yielded primary tidal constants, including So, M2, S2, N2, K2, K1, O1, P1, M4, and MS4. These harmonic constants are used to determine the tidal type and Mean Sea Level (MSL) value. The results show in Table 1.

Table 1. Harmonic constants.

Constants	Amplitude (m)	Fase (^{0})
So	0.9424	0.000
M2	0.2106	354.991
S2	0.1315	68.529
N2	0.0353	317.258
K2	0.0426	184.549
K1	0.0876	280.341
O1	0.0279	202.646
P1	0.0294	329.775
M4	0.0001	65.006
MS4	0.0010	33.291

After obtaining the amplitude and phase values for each tidal component, the tidal type at the research location can be determined. In this study, the tidal type is determined based on the Formzahl value. The Formzahl value equation is [7],

$$F= K1+O1M2+S2 \quad (1)$$

The results indicate that the Formzahl value in the coastal areas of Bandar Lampung City is 0.3517, indicating a mixed semidiurnal tidal type with a value of $0.25 < F < 1.50$. This means that there are two high tides and two low tides occurring daily, but occasionally, there might be one high tide and one low tide [5].

Then, the tidal data of Mike21 and BIG (Geospatial Information Agency) data of 8 years between 2014 to 2021 [1] was validated. The validation of Mike21 and BIG data using Mean Relative Error (MRE), and the result indicates that the accuracy is 89%. Therefore, the mean sea level in Bandar Lampung coastal area is used from Mike21 data.

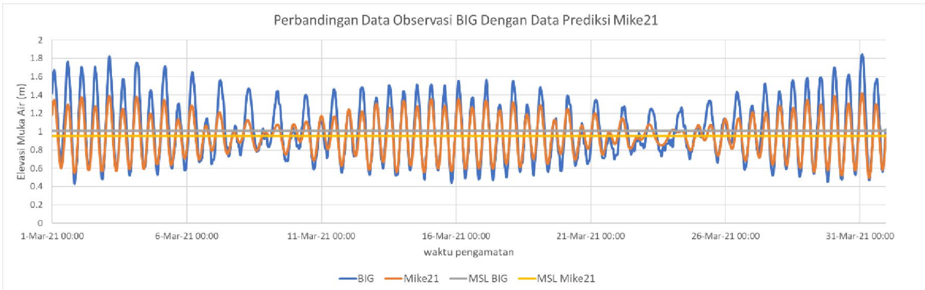

Fig. 5. Comparison Graph between Mike21 and BIG tidal data.

The mean sea level equation from linear regression is [6],

$$Y=ax+b \quad (2)$$

The mean sea level value obtained is 0.94 meters. This mean sea level value is then used as a basis to predict sea level rise for the year 2027 and the year 2072. To determine the annual trend values of SLR, the equation used is [6],

$$Trend\ per\ year= Ymax-Yminobservation\ years \quad (3)$$

Then, the predictions of SLR can be obtained with this formula [6],

$$SLRp=SLRr \times (Yp-Yb) \quad (4)$$

Where,

SLRp : Prediction of sea level rise
SLRr : Annual sea level rise
Y_p : Prediction year
Y_b : Basic year

The nominal of each data was input to those equations, and the line equation is,

$$y=(2\times 10-5)x+0.9437 \quad (5)$$

Thus, the trend of SLR is 0.024 mm/year in Bandar Lampung coastal area. The prediction of SLR in each year for this study is concluded in Table 2.

Table 2. Prediction of sea level rise.

No	Prediction Year	SLR (mm)
1	2022	0.024
2	2027	0.12
3	2072	1.2

4 Modelling of Tidal Flood Inundation

In 2022, field observations were conducted by interviewing local residents at several research points, including Kp. Harapan Jaya in Panjang District, Gudang Lelang in Bumiwaras District, Pulau Pasaran, and Keteguhen in Teluk Betung Timur District. From the interviews, it was revealed that tidal floods occur during the full moon. Therefore, the sea level is at its maximum or higher than usual. Information about the height of tidal flood inundation and the distance of the inundation area was obtained from the interviews. Subsequently, manual measurements were conducted based on the information regarding the distance of the inundation area. Measurements were made from the highest high tide line to the farthest distance of inundation from the coastline. The results are presented in the table 3.

Table 3. Inundation height based on interviews.

Location	Inundation height (m)	Distance from coastline (m)
Kp. Harapan Jaya, Panjang District	0.4 – 0.8	5 – 15
Gudang Lelang, Bumiwaras District	0.3 – 0.8	15 – 128
Pulau Pasaran and Keteguhen in Teluk Betung Timur District	0.1 – 0.3	30

The interview results obtained were then used as verification for the inundation model that will be created based on the highest tide parameter resulted from the processing of the Mike21 tidal data. In the inundation model for March 2022, with a highest tide value of 1.49 meters, an area of 24.7 hectares was found to be inundated, spread across the entire of Bandar Lampung coastal area, with inundation heights ranging from 0.05 to 2.5 meters, and at distances ranging from 2 to 228 meters from the coastline. The map of inundation of tidal flood is shown in Fig. 6. The area of inundation of tidal flooding is in blue color. The area of inundation in each district is concluded in Table 4.

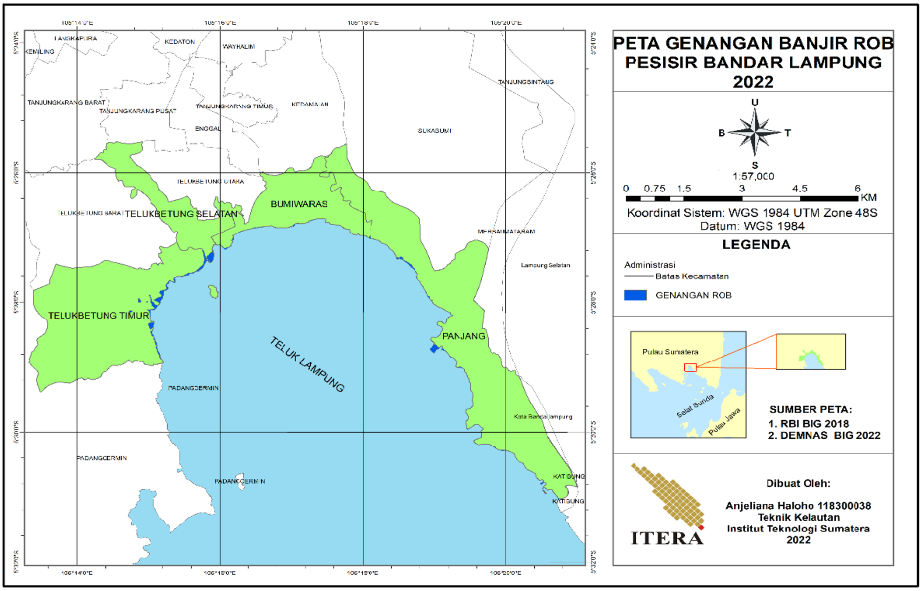

Fig. 6. Map of inundation of tidal flooding in Bandar Lampung coastal area.

Table 4. Area of inundated tidal flood in each district.

District	Area of inundated (ha)	Distance from coastline (m)
Bumiwaras	1.2	2 – 33
Panjang	5.8	5 – 58
Teluk Betung Selatan	3.6	8 – 158
Teluk Betung Timur	14.1	3 - 228

5 Threat levels of Tidal Flood

From the obtained inundation results, the inundation heights are also determined to classify the inundation threat levels. Based on BNPB Regulation No. 2 of 2012 [3], flood heights are classified into three classes, as shown in the following Table 5.

Table 5. Threat levels of tidal flood [3].

No	Threat Level	Inundation height (m)
1	Low	< 0.75
2	Moderate	0.75 – 1.5
3	High	> 1.5

From the inundation model, the area for each level—low, moderate, and high—was determined to be 18.391 ha (82.8%), 2.380 ha (10.7%), and 1.446 ha (6.5%), respectively. Based on the percentages obtained, the flood threat in the coastal areas of Bandar Lampung City is dominantly classified as low. On the threat map, the low-level is symbolized with green color, the moderate-level with yellow color, and the high-level with red color. The threat map of tidal flood is shown in Fig. 7.

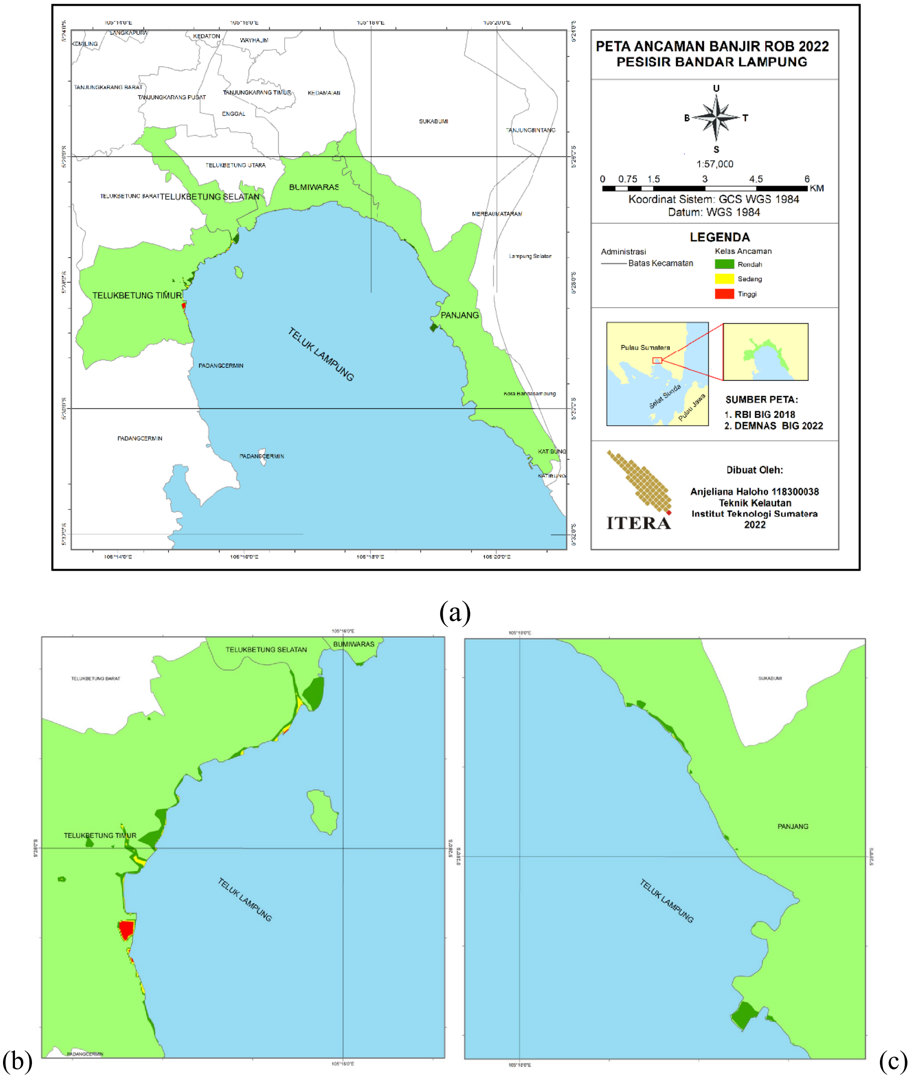

Fig. 7. (a) Threat map of tidal flood, (b) Threat map of tidal flood in detail for Teluk Betung Timur, Teluk Betung Selatan, and Bumiwaras district, (c) Threat map of tidal flood in detail for Panjang district.

6 Tidal Flood Prediction for Short-Term (2022 – 2027) and Long-Term (2022 – 2027)

This study was also conducted to predict the threat levels in the short-term and long-term using the previously employed method. In the short term, an additional criterion was added when modelling tidal flood inundation, which is the land subsidence criterion. According to the research [8], the value of land subsidence with Small Baseline Subset Differential SAR Interferograms in the coastal areas of Bandar Lampung City is in the range of 0.005 to 0.025 m per year. The prediction of land subsidence was obtained from DEMNAS data, and the predictions for 2027 and 2072 are as follows in Table 6.

Table 6. Prediction of land subsidence.

No	Prediction Year	Land subsidence (m)
1	2022	0.005
2	2027	0.025
3	2072	0.25

6.1 Threat levels of tidal flood prediction in short-term (2022 – 2027)

After modelling the inundation of tidal flood for short-term period, the threat map of tidal flood is conducted based on Table 5. The threat map is shown in Fig. 8. and the area of each level is described in Table 7.

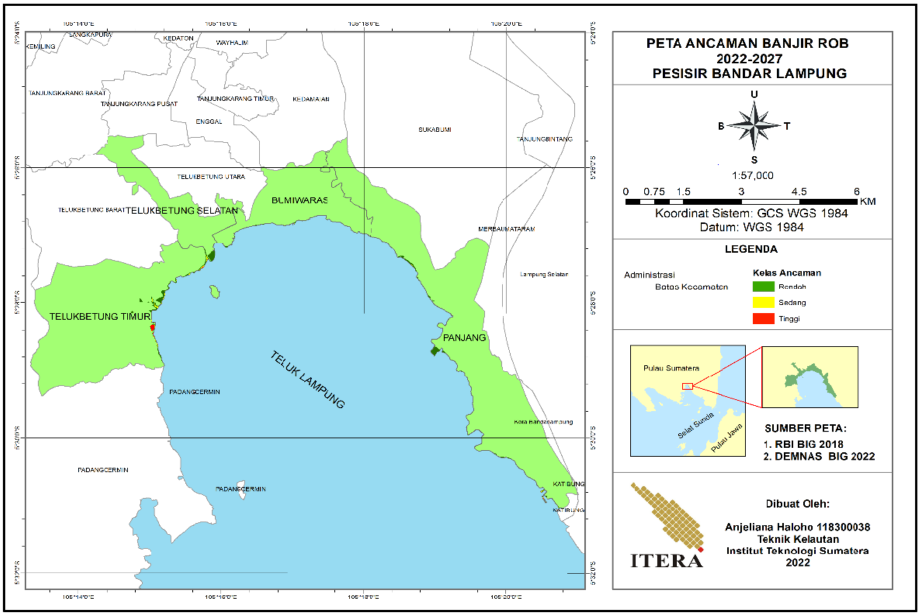

Fig. 8. Threat map of Tidal Flood for short-term period (2022-2027).

Table 7. Area of inundated tidal flood in each district for short-term (2022-2027).

Threat Level	District	Area of inundated (ha)	Distance from coastline (m)
Low	Bumiwaras	0.6	5 – 38
	Panjang	6.7	4 – 22
	Teluk Betung Selatan	3.8	9 – 173
	Teluk Betung Timur	9.6	4 – 116
Moderate	Bumiwaras	0.005	11
	Panjang	0.5	10
	Teluk Betung Selatan	0.1	
	Teluk Betung Timur	2.4	17 – 109
High	Bumiwaras	0	
	Panjang	0.015	
	Teluk Betung Selatan	0.017	
	Teluk Betung Timur	1.6	**4** – 20

6.2 Threat levels of tidal flood prediction in long-term (2022 – 2072)

The method of obtaining the threat map of tidal flood for long-term is conducted with land subsidence based on Table 6. The map depicting the threat assessment can be observed in Fig. 9., and the respective area sizes for each threat level are detailed in Table 8.

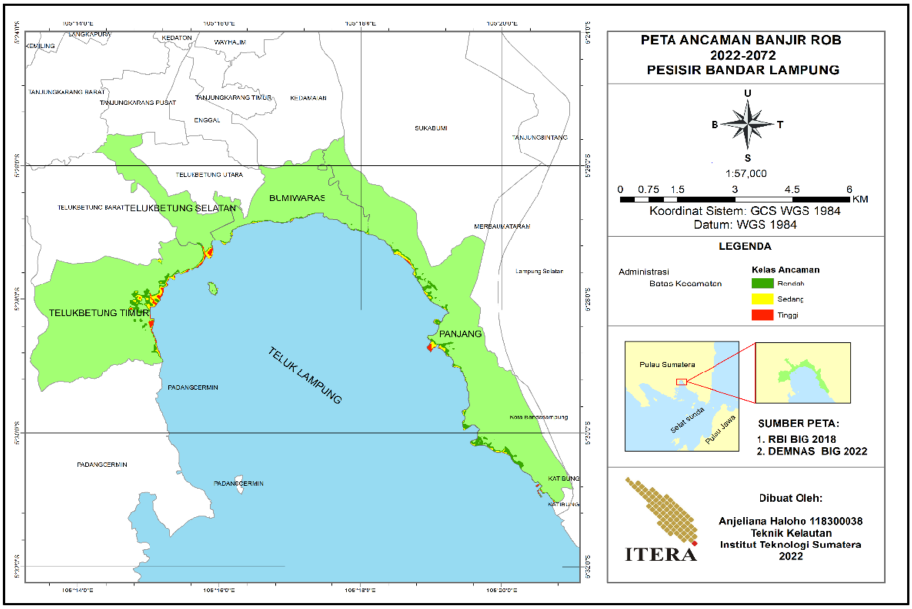

Fig. 9. Threat map of Tidal Flood for long-term period (2022-2072).

Table 8. Area of inundated tidal flood in each district for long-term (2022-2072).

Threat Level	District	Area of inundated (ha)	Distance from coastline (m)
Low	Bumiwaras	5.2	15 – 145
	Panjang	39.2	13 – 433
	Teluk Betung Selatan	1.5	185
	Teluk Betung Timur	31.7	35 – 706
Moderate	Bumiwaras	1.8	6 – 60
	Panjang	11.6	4 – 125
	Teluk Betung Selatan	2.3	2 – 304
	Teluk Betung Timur	14.9	91 – 579
High	Bumiwaras	0.1	9 – 12
	Panjang	3.4	10 – 39
	Teluk Betung Selatan	2.3	4 – 142
	Teluk Betung Timur	8.8	11 - 380

7 Conclusion

This study concludes that using the 18.6 years tidal data (2003-2021) and processing with least square method revealed that the Bandar Lampung coastal area have mixed semidiurnal tidal type with a Formzahl value of 0.3517. The MSL (Mean Sea Level) value was calculated to determine the prediction of sea level rise, which was obtained from the linear regression calculation of tides from 2003 to 2021, resulting in an increase of 0.024 mm per year. For the short-term prediction of 5 years (2027), it is estimated that there will be a sea level rise of 0.12 mm and land subsidence of 0.025 m, resulting in 25.337 hectares of coastal area in Bandar Lampung being inundated, with water levels ranging from 0.05 to 2.59 meters. For the long-term prediction (2072), there is an estimated sea level rise of 1.2 mm and land subsidence of 0.25 m, leading to 122.8 hectares of coastal area in Bandar Lampung being inundated, with water levels ranging from 0.002 to 3.781 meters. The threat levels from 2022, short-term, and long-term predictions are predominantly in the low-threat level, but the inundation area increases every year.

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