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Analysis of Inundation Area as the Impact of Sea Level Rise in Padang City, West Sumatera

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ABSTRACT

Coastal areas have a high potential for natural resources, but the intensity of their utilization often leads to physical environmental changes. One of the significant impacts is land subsidence and sea level rise, which trigger tidal flooding (rob floods). This study aims to determine the rate of sea level rise from 2014 to 2023 using tidal data analysis and to predict inundation areas for 2033, 2043, and 2053. This study was carried out in July 2024 in the coastal region of Padang City, West Sumatra Province. The research method is a survey, with a remote sensing approach and direct field observation (ground checks) to verify the accuracy of the spatial data. The study results indicate that Padang City exhibits a mixed tide, predominantly semidiurnal, with a Formzahl value of 0,41. The sea level is rising at a rate of 1,56 cm per year. The value was applied to predict sea level rise for 2033, 2043, and 2053, resulting in estimated increases of 0,156 m, 0,312 m, and 0.468 m, respectively. Subsequently, the projected sea level heights were analyzed to determine the extent of inundated areas for each respective year, and the results show that the inundated areas would reach 150,81 hectares, 161,51 hectares, and 172,37 hectares. This trend suggests that, as time progresses, the extent of areas affected by tidal flooding (rob) will continue to expand, potentially disrupting economic activities, damaging infrastructure, and impacting the social fabric of coastal communities.

Keywords: Padang City, Sea Level Rise, Tidal Flooding, Tides

1. INTRODUCTION

Coastal areas possess substantial and strategic resource potential across economic, social, and ecological dimensions. Without sustainable approaches, the intensive use and management of coastal regions often result in substantial physical environmental alterations. These physical changes can trigger various natural hazards in coastal areas, including tidal flooding (*Rob*). This phenomenon occurs due to land subsidence and sea-level rise, which have become significant issues in many coastal areas (Cahyaningtyas, 2018).

Tidal flooding (*rob*) is a natural phenomenon in which seawater inundates land areas during high tide. Such intrusion may occur via rivers, drainage systems, or underground flow paths. From a natural perspective, tidal flooding may result from extreme tidal fluctuations (Nafisah et al., 2017). However, anthropogenic factors also play a significant role, including intensive groundwater extraction and accelerated development, which substantially drive land subsidence. In addition, sea level rise due to global warming further intensifies and extends tidal flooding across various coastal areas (Hadi, 2019). The impacts of tidal flooding include infrastructure damage and disruptions to the economic and social activities of communities living in affected areas (Hakim et al., 2023).

Padang City is a coastal region geographically situated along the direct boundary with the Indian Ocean. This condition puts the area at high risk of sea-level rise. Furthermore, the dense population and intense economic activity in Padang City's coastal zone exacerbate its susceptibility to tidal flooding (Damayanti, 2016). The tidal flood that occurred on June 7, 2016, stands as a tangible example, during which several coastal areas of Padang City were submerged to depths of 20-80 cm, with sea waves reaching up to 6 m in height.

As part of mitigation efforts, mapping tidal flood-prone areas is essential to inform effective, evidence-based policy decisions. Such mapping efforts can be facilitated by leveraging developments in geospatial technology, primarily through the implementation of Geographic information Systems (GIS).

Geographic information Systems (GIS) can integrate diverse spatial and non-spatial datasets and conduct precise analyses of factors contributing to tidal flooding events (Zevri, 2022). With its strengths in spatial analysis, GIS can model trend patterns and estimate the extent of affected areas with greater precision (Nurdiawan & Harumi, 2018).

Based on this background, this study aims to analyze the potential tidal inundation resulting from sea level rise in the coastal area of Padang City. The research was conducted using a spatial approach, utilizing tidal and remote sensing data and analyzing them in ArcGIS. Parameters, including land elevation, slope, and land use, were examined to assess the spatial extent and distribution of tidal inundation. It is expected that the findings of this research will provide a scientific foundation for disaster risk reduction, the development of climate change adaptation strategies, and sustainable spatial planning in Padang City's coastal region.

2. RESEARCH METHOD

Time and Place

This research was conducted in June 2024 in the coastal area of Padang City, West Sumatra Province (Figure 1). The data analysis was conducted at the Physical Oceanography Laboratory, Department of Marine Science, Faculty of Fisheries and Marine, Universitas Riau.

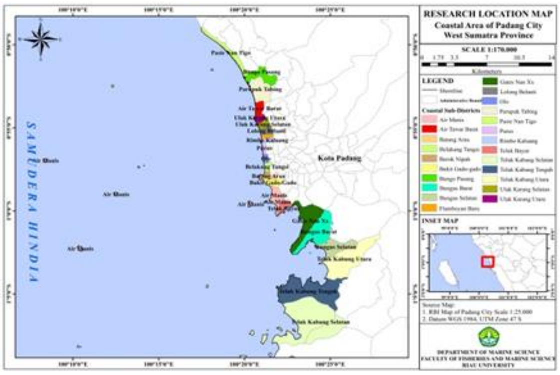


Figure 1. Research location

Method

The research used a survey methodology, incorporating remote sensing techniques and on-site field verification (ground checks) to ensure the accuracy of the spatial data. It was conducted in several phases, including a literature review, the collection of primary and secondary data, and the processing of data to analyze flood-prone areas resulting from tidal events.

Procedures

Tidal

Tidal observations were conducted manually over 15 days at 1-hour intervals. The observation site was selected using the area sampling method to represent a broader geographic area (Utami et al., 2017). The harmonic constants' main components include M2, S2, K2, N2, K1, O1, P1, M4, and MS4. These components are used to determine the tidal type by calculating the Formzahl (F) value using the formula proposed by Rampengan (2013).

$$F=\frac{(K1 + O1)}{(M2 + S2)}$$

Based on monthly Mean Sea Level (MSL) calculations from 2014 to 2023 (processed from data on the IOC-Sea Level Monitoring website), a linear regression analysis was conducted to identify the trend of sea-level rise. The regression equation used (Khasanah et al., 2017):

$$Y=a+bx$$

After the monthly trend was obtained, the annual rate of increase was calculated using the formula (Cahyadi et al., 2016):

$$\text{Annual Trend} = \frac{Y_{maks} - Y_{min}}{\text{Observation Period (in Years)}}$$

Land Use

Land-use mapping was carried out using Landsat-8 satellite imagery. Supervised classification was performed using the maximum likelihood method. The classification accuracy was evaluated using a confusion matrix. According to Jensen (2015), the following metrics can determine the accuracy of the assessment values:

$$\text{Overall Accuracy} = \frac{D}{N} \times 100\%$$

Description:

D = Number of correctly classified pixels

N = Total number of sample pixels."

$$\text{Producer's accuracy} = \frac{X_{ii}}{X_{i+}} \times 100\%$$

Description:

X_{ii} = total number of correctly classified cells in the class (diagonal cell value)

x_{i+} = total number of cells in the row (i.e., reference or actual class total)

$$\text{User's accuracy} = \frac{X_{ii}}{X_{I+}} \times 100\%$$

X_{ii} = Total number of correctly classified cells in the class
X_{i+} = Total number of cells in the row

$$\text{Kappa Accuracy} = \frac{(TS \times TCS) - \sum(\text{Column count} \times \text{amount on line})}{TS^2 - \sum(\text{Column count} \times \text{amount on line})}$$

Description:
TS = Total number of samples
TCS = Total number of correctly classified samples across all classes

Land Elevation

Land elevation data were derived from a Digital Elevation Model (DEM) obtained from the Geospatial Information Agency (BIG) website. The dataset was processed in ArcGIS using cropping, georeferencing, and reclassification to determine land elevation within the study area.

Slope Gradient

The slope gradient was derived from Digital Elevation Model (DEM) data from the Geospatial information Agency (BIG) using ArcGIS. The analytical process involved cropping, georeferencing, applying the 'slope' tool, and reclassifying slope gradients into designated classes based on field conditions.

Distance from the Coast

The distance from the Coast was processed using ArcGIS software. The analysis stages included digitizing the coastline, creating multiple ring buffers, and reclassifying using spatial analysis tools to categorize proximity zones relative to the coastline.

Distance from the River

River distance processing was conducted in ArcGIS. All rivers within the study area were digitised, creating multiple ring buffers, and reclassified using spatial analysis to group areas by proximity to the rivers.

Data Analysis

The analysis of sea level rise was conducted using 10-year tidal data (2014–2023) obtained from the IOC-Sea Level Monitoring website. The dataset was analyzed using the Admiralty method to derive monthly Mean Sea Level (MSL) values. Subsequently, a linear regression analysis was conducted to obtain the average annual rate of sea level rise. The results of this regression were used to predict future sea level heights using the following equation:

Predicted Year n = Trend per year × Year to be predicted (n)

Areas potentially inundated due to sea-level rise were analyzed using a mathematical logic (logical operator) approach in ArcGIS, specifically the Raster Calculator. This analysis combines two types of data: Sea Level Rise (SLR) values and DEM data (elevation and slope). The logical expression used in the raster function is as follows:

Inundated Area = "DEM" ≤ SLR

The results of the raster analysis were then reclassified using conditional logic to categorize areas into inundated and non-inundated zones by applying the Con function:

Inundated Area = Con (Data < Criteria, True, False)

The next step was to convert the raster output into polygon data to obtain the extent of the affected area. The resulting polygon data were overlaid with land-use data to analyze the distribution of inundation across different land cover types within the study area.

3. RESULT AND DISCUSSION

Land Use

The analysis of both primary and secondary data resulted in the classification of land use in Padang City's coastal zone into five classes. The respective area of each class is shown in Table 1.

Table 1. Land use classes

No	Land use class	Description
1.	Badan Air	Rivers, Ponds, Water Inundation
2.	Agriculture	Fields, Plantations, Rice Fields
3.	Forest	Dryland Forest, Wetland Forest, Grassland, Shrubland
4.	Settlement	Built-up Area (houses, buildings)
5.	Open Land	Vacant Land

The classification was conducted by interpreting 2024 Landsat imagery using the supervised maximum likelihood classification (MLC) method. This method was chosen for its ability to achieve high classification accuracy based on the statistical distribution of pixel spectral values (Ardiansyah et al., 2017). To assess the accuracy of the classification results, validation was conducted using a confusion matrix, comparing the classified imagery with field sample points and additional reference sources, such as Google Earth. The accuracy assessment results are presented in Table 2.

Table 2. Classification accuracy results

Class	UA (%)	PA (%)	OA (%)	KA
BA	100	83,33		
PT	85,96	98		
HT	97,53	92,94	92,35	0,88
PM	94,44	77,27		
LT	77,78	100		

Based on Table 2, the overall accuracy value of 92.35% and the kappa coefficient of 0,88 indicate that the classification results are highly accurate and valid. According to satellite image classification guidelines developed by LAPAN, as cited in Asma (2018), a classification result is considered valid if the Confusion Matrix calculation yields an accuracy above 75%. The classified land use areas are presented in Table 3.

Table 3. Land use classification area

No	Land Use	Area (ha)
1.	Settlement	1527,80
2.	Agriculture	3246,06
3.	Water Bodies	127,19
4.	Open Land	60,35
5.	Forest	4925,04
Total		9886,44

Based on land-use area results, the coastal region of Padang City is predominantly forested, particularly in the southern part, such as Bungus Teluk Kabung District, which serves as a conservation zone and buffer for the coastal ecosystem. The land use map is shown in Figure 2.

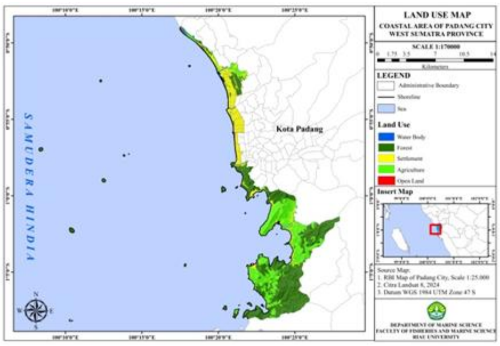


Figure 2. Land use map

Land Elevation

The coastal region of Padang City features a varied topography, with elevations ranging from 0 to 942 meters above sea level (masl). The classification and area of each elevation class are presented in Table 4.

Table 4. Land area by elevation

No	Elevation (mdpl)	Category	Areas (ha)
1.	0-10 m	Very Lowland	3.272,37
2.	10-50 m	Lowland	932,09
3.	50-100 m	Moderate Elevation	915,72
4.	100-200 m	Highland	1.555,47
5.	> 200 m	Hills/ Mountains	3.156,04
Total			9.831,69

Based on the elevation analysis, approximately 33.28% of the coastal area lies within the zone less than 10 meters above sea level, categorized as very lowland. This condition indicates that a significant portion of the study area is highly vulnerable to inundation, particularly in the northern region, which is the lowest coastal-elevation zone. In contrast, the highest elevations are found in the southern part, which is predominantly hilly and mountainous (Figure 3).

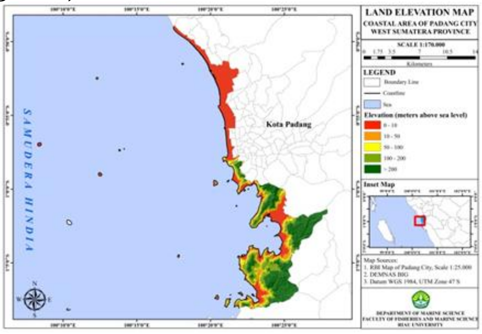


Figure 3. Land elevation map

Slope Gradient

The coastal slope of Padang City was classified into five slope classes according to the Guidelines for Land Rehabilitation and Soil Conservation (1986), as cited in Utomo (2019). The classification and area of each slope class are presented in Table 5.

Table 5. Slope gradient area

No	Slope %)	Category	Area (ha)
1	0-8	Flat	5224,03
2	8-15	Gently Sloping	3178,18
3	15-25	Moderately Steep	1314,77
4	25-44	Vert Steep	111,65
5	> 45	Very Steep	2,63
Total			9831,26

Flat slope gradients predominantly characterize the coastal area of Padang City. Based on the analysis, more than 50% of the coastal region falls into the flat category with a slope range of 0–8%, indicating that water flow in this area tends to be slow and easily retained on the surface. This condition suggests a high potential for flooding, as flat terrain promotes water accumulation. Therefore, the gentler the slope of an area, the higher the risk of flooding, whereas steeper slopes are generally less prone to inundation. The slope gradient map is presented in Figure 4.

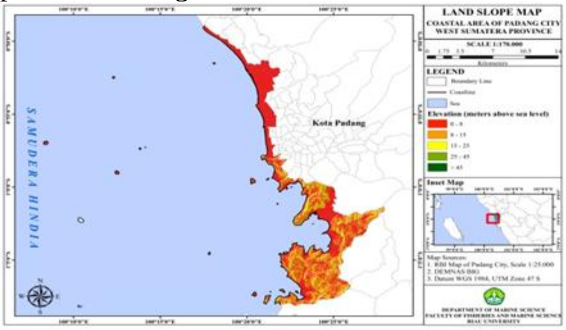


Figure 4. Slope gradient map

Distance from the Coast

The distance from the coastline in the coastal area of Padang City was analyzed using RBI maps in ArcGIS by generating perpendicular lines extending 1,000 meters inland from the shoreline through spatial analysis tools. The coastal distance was classified into five classes. The area of each distance class is presented in Table 6.

Table 6. Area by distance from the coast

No	Distance from the coast (m)	Area (ha)
1	0-250 m	1874,7
2	250-500 m	1386,98
3	500-750 m	1042,72
4	750-1000 m	863,25
5	> 1000 m	4692,67
Total		9860,32

The coastal distance parameter for Padang City shows that the smallest area lies within the 750–1,000 m zone from the shoreline, covering 863.25 ha, or 8.75% of the total area. In contrast, the area located more than 1,000 m from the Coast is the largest, comprising 4,692.67 ha or 47.59% of the total analyzed coastal zone. Areas less than 200 m from the shoreline are considered highly vulnerable to tidal flooding, whereas those located more than 800–1,000 m inland tend to be relatively safer. This finding is consistent with Kultsum's (2017) study, which found that the closer a region is to the coastline, the higher its vulnerability to tidal inundation. The distance-from-coast map is presented in Figure 5.

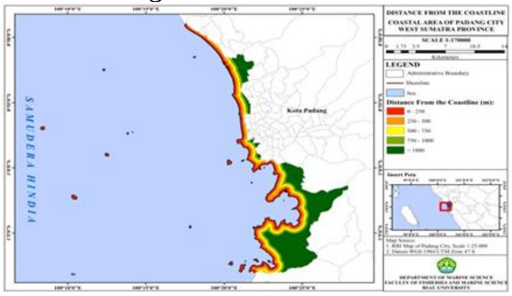


Figure 5. Distance from the Coast Map

Distance from the River

The distance from rivers in the coastal area of Padang City was analyzed using spatial river data in ArcGIS, focusing on major rivers through spatial analysis tools. The distance from rivers was classified into five classes. The classification and area of each distance class are presented in Table 7.

Table 7. Area by distance from the river

No	Distance from the river (m)	Area (ha)
1	0-100 m	1172,41
2	100-200 m	928,10
3	200-300 m	846,99
4	300-400 m	791,61
5	> 400 m	6121,49
Total		9860,61

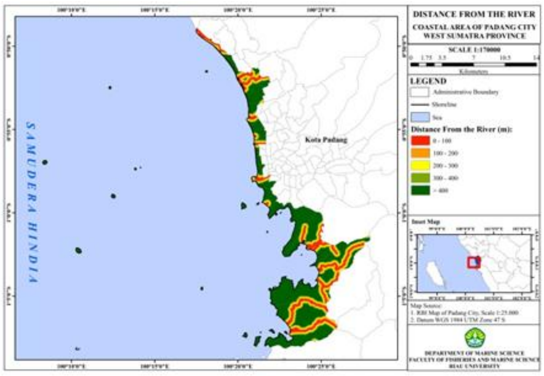


Figure 6. Distance from the river map

The river distance parameter in the coastal area of Padang City indicates that areas located more than 400 m from rivers have the greatest coverage (6,121.40 hectares, or 62.08%). Still, their risk of tidal inundation is relatively low. Conversely, areas within 0–100 m from rivers, although smaller (1,172.41 ha or 11.89%), face the highest risk due to their proximity to river channels and the potential for water overflow. This zone should be prioritized for mitigation efforts. However, according to Ramdhany et al. (2021), river distance significantly influences the overall vulnerability to tidal flooding (Figure 6).

Sea Level Rise

Tidal measurements were conducted directly at one-hour intervals over 15 days and analyzed using the Admiralty method. The analysis yielded a Formzahl value of 0.41, indicating a mixed tide prevailing semidiurnal type, characterized by two high tides and two low tides each day, with unequal heights and durations. The tidal graph is shown in Figure 7.

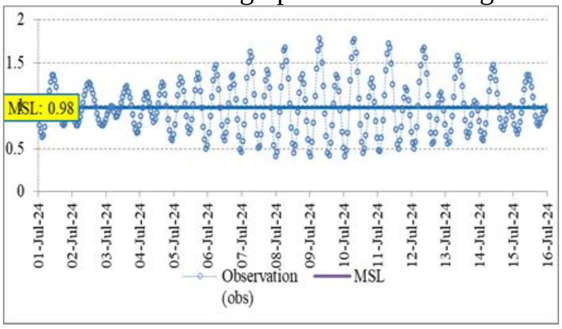


Figure 7. Tidal graph of Padang City

The sea level rise rate was calculated from tidal data for the 2014–2023 period, obtained from the Padang City Tidal Station via the IOC Sea Level Monitoring website. The data were analyzed using the Admiralty method to obtain monthly mean sea level (MSL) values, as shown in Figure 8.

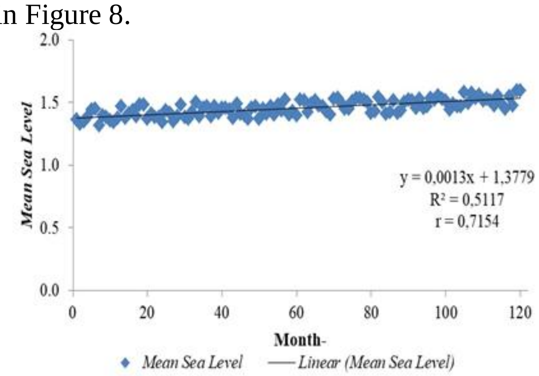


Figure 8. Monthly Mean Sea Level (MSL)

The annual MSL values show a consistent increase, rising from 137.5 cm in 2014 to 152.6 cm in 2023 (Figure 9). Based on tidal data from 2014 to 2023, the average sea level rise rate in Padang City is 1.56 cm per year. This value predicted sea level height for 2033, 2043, and 2053. Tidal data spanning ten years or more yields more accurate results. The longer the data period, the higher the accuracy of sea level rise predictions (Table 8).

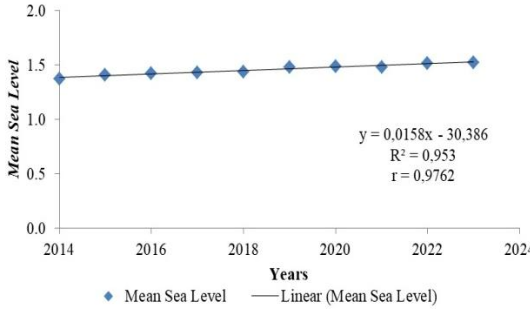


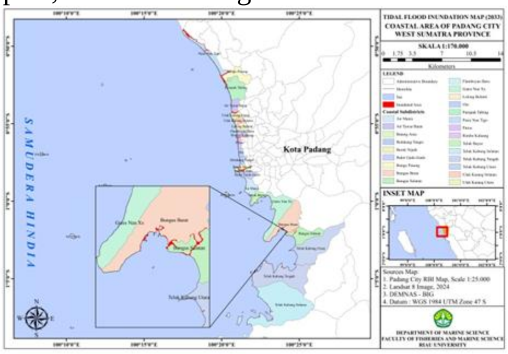
Figure 9. Annual Mean Sea Level (MSL)

Table 8. Predicted sea level rise

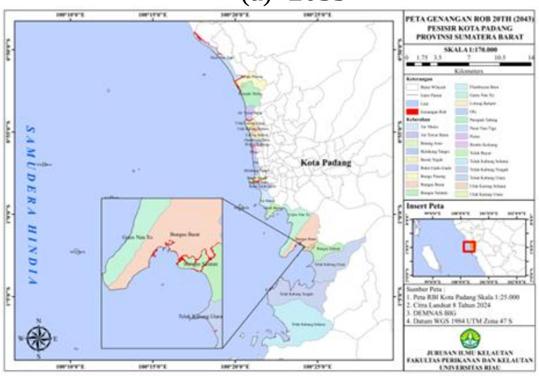
Year	Sea Level Rise (m)
2023	0,0156
10th(2033)	0,156
20th(2043)	0,312
30th(2053)	0,468

Predicted Tidal Flood Inundation Distribution in 2033, 2043, and 2053

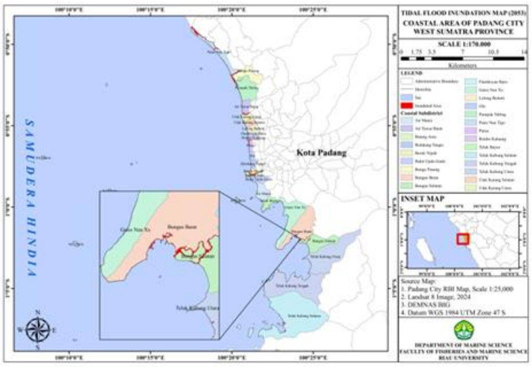
The predicted tidal inundation distribution due to sea level rise in 2033, 2043, and 2053 indicates that the coastal area of Padang City will be inundated by 150.81 hectares, 161.51 ha, and 172.37 ha, respectively. The inundation areas are distributed across several sub-districts with varying levels of impact, as shown in Figure 10.



(a) 2033



(b) 2043



(c) 2053

Figure 10. Tidal Flood Inundation Distribution Map for 2033, 2043, and 2053

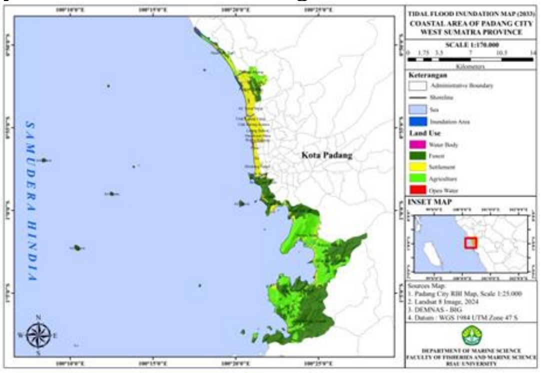
Tidal flooding in the coastal area of Padang City affects various land uses, with varying levels of impact depending on each area's topography and local conditions. The effects of inundation on land-use types are presented in Table 9

Table 9. Distribution of tidal flood inundation by land use

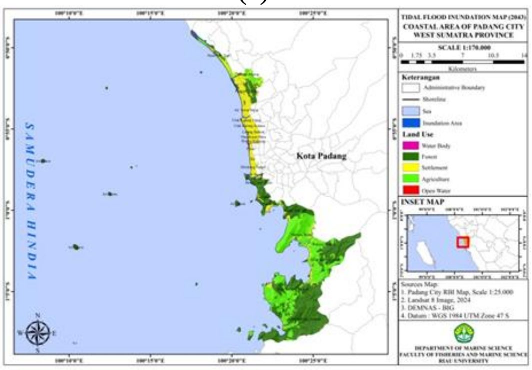
No	Class	2033 (ha)	2043 (ha)	2053 (ha)
1	Water Bodies	89.52	93.00	94.45
2	Forest	27.69	29.88	31.94
3	Open Land	6.50	7.26	7.93
4	Settlement	10.98	12.36	14.36
5	Agriculture	16.13	19.02	23.69
Total		150.81	161.51	172.37

The affected areas predominantly comprise built-up land, rice fields, water bodies, and non-agricultural vegetation. Land use changes in coastal regions, including urbanization and excessive groundwater extraction also contribute to the increased risk of tidal inundation. This is primarily due to over-extraction of groundwater and structural loads from existing buildings. Excessive water use and low soil permeability can lead to land subsidence (Ulfani et al., 2024).

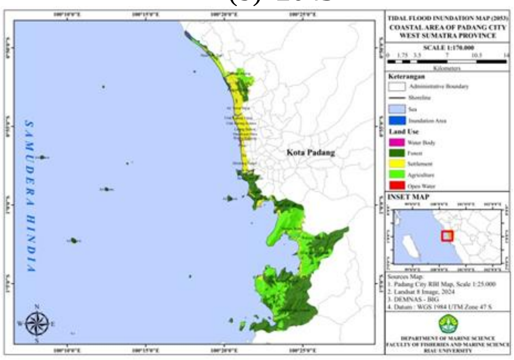
Land subsidence is often caused by land-use practices that disregard environmental carrying capacity and ecological balance. This condition exacerbates the impacts of sea level rise, particularly in coastal areas. Therefore, mitigation and adaptation measures are crucial to minimize the associated risks. Mitigation efforts can be implemented by developing protective infrastructure, such as dikes, dams, road elevation, and mangrove reforestation, which serve as natural barriers against coastal abrasion (Syahputra, 2016). Meanwhile, adaptation strategies may include strengthening regulations and promoting accommodative spatial planning, such as improving drainage systems in residential areas. Additionally, physical protection measures, such as the construction of sea walls in areas directly adjacent to settlements and main roads, are necessary to resist seawater overflow (Isdianto et al., 2014). The distribution map of inundation by land use is shown in Figure 11.



(a) 2033



(b) 2043



(c) 2053

Figure 11. Tidal flood inundation map in relation to land use

4. CONCLUSION

Based on the research, it can be concluded that Padang City has a mixed tide prevailing semidiurnal type, with a Formzahl value of 0.41. Analysis of tidal data using linear regression from 2014–2023 indicates a sea-level rise rate of 1.56 cm per year in Padang City. The projected tidal inundation for 2033, 2043, and 2053 shows corresponding sea-level rises of 0.156 m, 0.312 m, and 0.468 m, with inundated areas covering 150.55 ha, 161.25 ha, and 172.11 ha, respectively.

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