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Flood Tidal Risk Modeling On The Coast Of West Sulawesi Using Geographic Information Systems To Support Climate Change Adaptation Planning

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Abstract

Coastal flooding or tidal inundation (*banjir rob*) is one of the visible impacts of climate change that increasingly affects coastal regions in Indonesia, including West Sulawesi Province. The rise of sea level, land-use changes, and mangrove degradation have intensified the vulnerability of coastal areas to tidal flooding. This study aims to model the risk of tidal flooding along the coast of West Sulawesi using Geographic Information Systems (GIS) and to formulate climate change adaptation strategies through spatial and SWOT analyses. The research utilized spatial datasets including elevation, slope, distance from the coastline and rivers, land use, and mangrove density. The analysis was conducted using a scoring, weighting, and overlay approach to generate a tidal flood vulnerability map, which was validated using actual flood event data from 2021–2025. The results indicate that low-lying coastal zones below 5 meters above sea level with sparse mangrove cover particularly in Polewali Mandar, Majene, and Mamuju Regencies are highly vulnerable to tidal flooding. Spatial prediction suggests a significant increase in inundation areas by 2075 in line with projected sea-level rise. Based on SWOT analysis, the recommended adaptation strategy is an offensive (S-O) approach, emphasizing the utilization of coastal ecosystem potential and conservation policies to promote mangrove-based ecotourism, strengthen community adaptive capacity, and enhance collaboration among government, academia, and local communities. The findings are expected to provide a scientific foundation for climate change mitigation and adaptation planning in the coastal regions of West Sulawesi toward sustainable coastal development.

Keywords: Tidal Flooding, Climate Change, GIS, SWOT, West Sulawesi

1. INTRODUCTION

Tidal flooding is a hydrometeorological hazard that has been occurring with increasing frequency in Indonesia's coastal regions, driven by a combination of sea level rise and global climate change. This phenomenon exerts widespread impacts across social, economic, and ecological domains, particularly affecting fisheries operations, human settlements, and coastal infrastructure. The continuous rise in sea level is likely to expand inundation extents and exacerbate the vulnerability of coastal areas to tidal flooding [1].

West Sulawesi Province exhibits high vulnerability to tidal flooding. The regencies of Polewali Mandar, Majene, Mamuju, Central Mamuju, and Pasangkayu are frequently affected, particularly during spring tides and extreme weather events. The period from 2021 to 2025 has witnessed infrastructure damage, disruption of fisheries activities, and a decline in the economic productivity of coastal communities, highlighting the need for data-driven adaptation and mitigation efforts. Geographic Information Systems (GIS) can be utilized to map tidal flood-prone areas by integrating various environmental parameters such as topography, tidal patterns, land use, distance from rivers, and mangrove ecosystem conditions [2], [3]. This approach enables accurate spatial analysis as well as long-term projections based on global climate change scenarios.

Several previous studies have employed GIS to map tidal flood risks in North Jakarta, Demak, and Padang [4], [5]. However, these studies generally focus on physical aspects without considering the role of mangrove ecosystems as natural buffers. Mangroves function to attenuate waves and absorb the energy of ocean currents,

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so their degradation can increase the risk of inundation [6]. Therefore, integrating mangrove variables into tidal flood risk modeling represents an innovative and relevant approach for the coastal areas of West Sulawesi.

In addition to spatial modeling, adaptation strategies are necessary to ensure that the research findings can be implemented practically. A SWOT analysis (Strengths, Weaknesses, Opportunities, Threats) is employed to formulate climate change adaptation strategies based on local potentials and regional conditions.

Despite the growing application of GIS in tidal-flood mapping, most existing studies in Indonesia have concentrated on the densely populated coasts of Java and Sumatra such as North Jakarta, Demak, Semarang, and Padang while the coastal zone of eastern Indonesia, particularly West Sulawesi, remains largely unmapped. Furthermore, previous tidal-flood models have generally relied on physical parameters alone (elevation, slope, distance from coastline and rivers) and rarely incorporated the condition of coastal ecosystems, especially mangrove density, as a determinant of vulnerability. Few studies have also translated spatial vulnerability outputs into structured, implementable adaptation strategies. This study addresses these gaps by (1) providing the first comprehensive tidal-flood vulnerability model covering the entire coast of West Sulawesi across five regencies; (2) integrating mangrove density as a natural-protection parameter within a weighted-overlay multi-criteria framework adapted from the Coastal Vulnerability Index; and (3) coupling temporal vulnerability projections for 2035 and 2075 with a SWOT-based analysis to formulate climate-change adaptation strategies. The scientific contribution of this integration lies in bridging spatial risk assessment and ecosystem-based adaptation planning, thereby generating outputs that are directly usable for coastal spatial planning and policy in the region.

This study aims to model tidal flood risks in the coastal areas of West Sulawesi using GIS and to formulate climate change adaptation strategies through spatial and SWOT analyses. The research findings are expected to provide a scientific basis for climate change mitigation and adaptation planning in coastal regions, while also supporting sustainable coastal development in Indonesia.

2. METHODS

2.1. Research Location

The study was conducted along the coastal areas of West Sulawesi Province, encompassing five regencies: Pasangkayu, Central Mamuju, Mamuju, Majene, and Polewali Mandar. This location was selected due to its high vulnerability to tidal flooding.

2.2. Materials and Equipment

The equipment used included field devices (camera, GPS, and drone) for documentation and mapping, as well as laboratory tools (computer, ArcGIS, and Er-Mapper) for spatial analysis. The research materials comprised Digital Elevation Model (DEM) data, land use, coastline data, mangrove conditions, stationery, and questionnaires as supporting data.

2.3. Types and Sources of Data

The data used in this study consisted of:

1. Primary data, obtained through field observations and interviews with local communities and relevant institutions.
2. Secondary data, including spatial data from BIG (Geospatial Information Agency), DEMNAS (National Digital Elevation Model), and RBI maps, as well as related scientific literature.

2.4. Data Collection Method

This study employed a quantitative approach through survey and mapping methods. This technique is suitable for studies covering extensive coastal areas within a limited research timeframe.

2.5. Research Procedure

The study was carried out through five main stages:

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1. Preliminary Stage

   This stage included site surveys, literature review, and preparation of research tools and materials.

2. Data Collection

   This involved the collection of spatial data (DEMNAS, RBI maps, tidal data, land use, and mangrove condition) as well as supporting interviews.

3. Data Analysis

   Tidal flood risk modeling was conducted using Geographic Information Systems (GIS) through the stages of scoring, weighting, and overlaying parameters such as topography, tidal range, land use, distance from the coast and rivers, slope gradient, and mangrove density. The total risk value was calculated using the following formula:

The scoring and weighting of parameters in this study follow the concept of the Coastal Vulnerability Index (CVI) developed by Gornitz [7] and described by Climate-ADAPT [8]. This method applies a semi-quantitative scoring approach (a scale of 1-5) to represent the vulnerability level of each parameter to sea-level rise, where 1 denotes very low and 5 denotes very high vulnerability. The variables were modified from the original CVI parameters and adapted to the coastal conditions of West Sulawesi namely elevation, distance from the coastline, land use, mangrove density, distance from rivers, and slope; such modification is commonly performed in GIS-based studies to improve local suitability [9]. Weighting was carried out using a weighted-overlay approach within GIS multi-criteria analysis, in which each parameter is assigned a weight according to its degree of influence on tidal-flood inundation. Parameters with direct influence, such as elevation and distance from the coastline, were assigned higher weights than the others. The parameter weights are presented in Table A, and the scoring classifications are presented in Tables 2-7.

Table 1. Parameter weights in the tidal-flood risk analysis

No	Parameter	Weight (%)	Description
1	Elevation	25	Primary factor controlling inundation
2	Distance from coastline	20	Proximity to the source of tidal water
3	Land use	10	Level of exposure of the area
4	Mangrove density	20	Natural coastal protection function
5	Distance from river	15	Seawater entry pathway via rivers
6	Slope	10	Influence on inundation accumulation

Source : Weights developed by the author (2025) based on the vulnerability parameters of Gornitz [7]

Table 2. Elevation scoring classification

Class	Elevation (m asl)	Score	Description
1	0–20 m	5	Very high
2	21–50 m	4	High
3	51–100 m	3	Moderate
4	101–300 m	2	Low
5	>300 m	1	Very low

Table 3. Distance-from-coastline scoring

Class	Distance	Score	Description
1	0–250 m	5	Very high
2	250–500 m	4	High
3	500–750 m	3	Moderate
4	750–1000 m	2	Low
5	>1000 m	1	Very low

Source : [10]

Table 4. Land-use scoring

No	Land-use type	Score	Description
1	Brackish pond (tambak)	5	Very high
2	Dryland farming (tegalan)	4	High
3	Paddy field	3	Moderate
4	Shrub/plantation	2	Low
5	Forest	1	Very low

Source : [11]

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Table 5. Mangrove Density scoring

Class	Mangrove condition	Score	Description
1	Very sparse	5	Very high
2	Sparse	4	High
3	Moderate	3	Moderate
4	Dense	2	Low
5	Very dense	1	Very low

Source : Primary data 2025 modified from Keputusan Menteri Negara Lingkungan Hidup No. 201/2004 [12]

Table 6. Distance-from-river scoring

Class	Distance	Score	Description
1	0–100 m	5	Very high
2	100–200 m	4	High
3	200–300 m	3	Moderate
4	300–500 m	2	Low
5	>500 m	1	Very low

Source : *[10]*

Table 7. Slope scoring

Class	Slope (%)	Score	Description
1	0–8	5	Very high
2	8–15	4	High
3	15–25	3	Moderate
4	25–45	2	Low
5	>45	1	Very low

Source : [10]

The complete GIS workflow applied in this study is illustrated in Figure 1. The analysis began with the acquisition of spatial input data, followed by the extraction of six vulnerability parameters. Each parameter was reclassified and scored on a semi-quantitative scale (1-5) and then combined through a weighted-overlay operation using the assigned weights. The overlay produced a composite vulnerability surface that was classified into five levels, from very low to very high. Sea-level-rise projections for 2035 and 2075 were generated using the Raster Calculator, and the resulting maps were validated against historical tidal-flood events. Finally, a SWOT (IFAS-EFAS) analysis was performed to translate the vulnerability outputs into climate-change adaptation strategies.

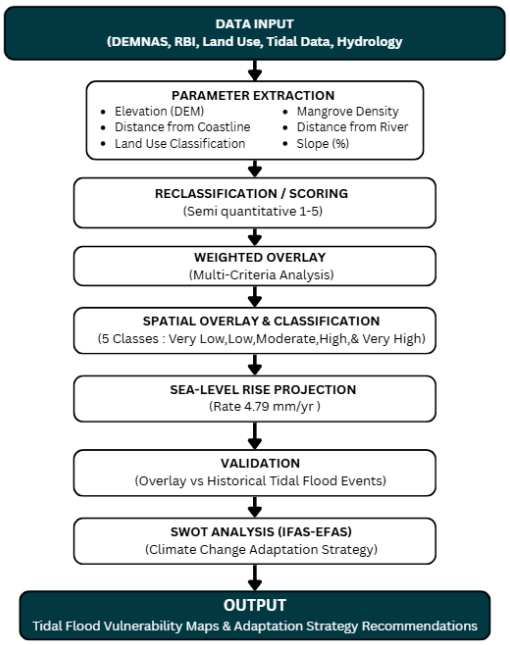


Figure 1. GIS workflow for tidal-flood vulnerability modeling and climate-change adaptation strategy formulation

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$$\sum(\text{score} \times \text{weight}) = \text{hazard level score} \quad (1)$$

The results were classified into five levels of threat: very low, low, moderate, high, and very high. Future inundation predictions were conducted under two scenarios (10 and 50 years ahead) using the logical function:

$$Innudated\ area = DEM < SLR \quad (2)$$

where SLR represents the projected sea level rise. The analysis was performed using the Raster Calculator to determine the affected zones, which were then presented in the form of thematic maps of tidal flood vulnerability.

For the future tidal-flood inundation scenarios, sea-level rise was assumed to occur at a constant rate of 4.79 mm/year (0.479 cm/year). This rate is treated as a modeling assumption rather than a verified local observation. Using 2024 as the reference year, linear extrapolation yields estimated sea-level increases of approximately +5.27 cm by 2035 and +24.43 cm by 2075. These values were incorporated into the elevation parameter using the Raster Calculator to simulate potential future inundation extents. This simplified scenario does not incorporate emission-specific or nonlinear sea-level-rise pathways, as discussed in the limitations section.

4. Climate Change Adaptation Strategies

SWOT analysis (Strengths, Weaknesses, Opportunities, Threats) was employed to formulate adaptation strategies for tidal flooding. Each SWOT factor was assigned a weight (0-1) and a score (1-4) according to its level of influence on sustainable coastal development [13].

5. Data Validation

Validation was carried out by comparing the modeled vulnerability maps with actual tidal flood events that occurred during 2021-2025. The level of agreement was presented in the form of tables or graphs to demonstrate the accuracy of the modeling results.

3. RESULTS AND DISCUSSION

3.1. Tidal Flood Vulnerability Parameters

3.1.1. Elevation Parameter

Land elevation directly influences tidal flood vulnerability. Analysis of the Digital Elevation Model (DEM) indicates that the coastal areas of West Sulawesi are predominantly situated at 0-50 meters above sea level, particularly in the regencies of Polewali Mandar, Majene, Mamuju, and Pasangkayu.

Flat regions such as Campalagian, Wonomulyo, Simboro, Rangas, and Budong - Budong serving as centers of settlements and ports are at high risk of seawater inundation.

Approximately 60-70% of the coastline lies below 50 meters above sea level, making low elevation a key factor determining tidal flood vulnerability [14], particularly in the regencies of Polewali Mandar, Majene, Mamuju, and Pasangkayu, especially in areas directly facing the Makassar Strait.

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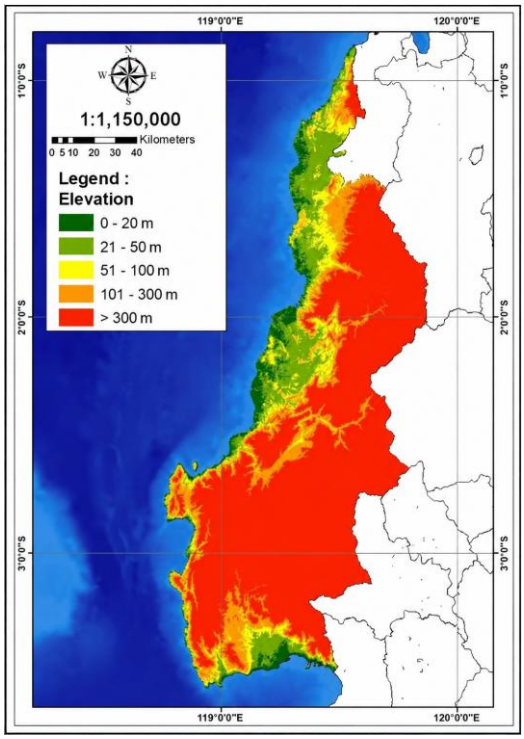


Figure 2. Elevation Parameter of West Sulawesi Province.

3.1.2. Land Use Parameter

Land use influences the level of tidal flood vulnerability in coastal areas [14]. Spatial analysis results indicate that the central to hilly regions of West Sulawesi are dominated by forests and plantations, while the coastal areas are predominantly occupied by rice fields, fishponds, shrubs, and drylands. The rice field and fishpond areas in Campalagian, Balanipa, Simboro, Rangas, and Budong-Budong are at high risk due to their low-lying locations near the coast. In contrast, forests and plantations in the hilly regions exhibit low vulnerability. However, the conversion of forests into intensive plantations in coastal zones increases the potential for inundation as a result of the reduction of natural protective vegetation.

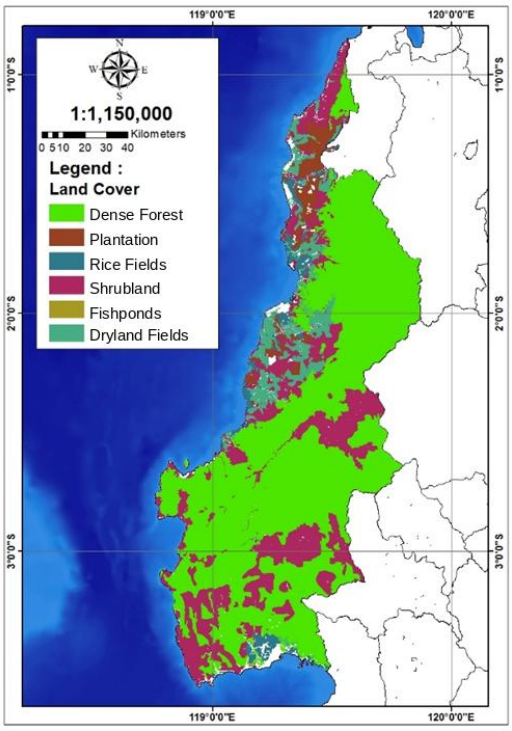


Figure 3. Land Use Parameter of West Sulawesi Province.

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3.1.3. Mangrove Presence Parameter

Mangrove ecosystems along the coast of West Sulawesi are distributed across all coastal regencies, with density levels ranging from very sparse to very dense. Based on the interpretation of Landsat 9 imagery from 2020 and 2025, as well as Google Earth imagery, mangroves are predominantly found in areas directly facing the Makassar Strait, particularly at river mouths and sheltered bays.

Mamuju Regency has the widest distribution of mangroves, with dense stands predominantly found at the mouth of the Mamuju River and around Karampuang Island [15]. Majene is dominated by medium to sparse mangrove density due to the conversion of mangrove areas into fishponds and settlements, while Central Mamuju maintains dense mangrove cover in its natural zones. Pasangkayu exhibits a relatively even distribution of mangroves, although many areas have medium to sparse density, whereas Polewali Mandar has narrow and fragmented mangrove patches, particularly in the Binuang area.

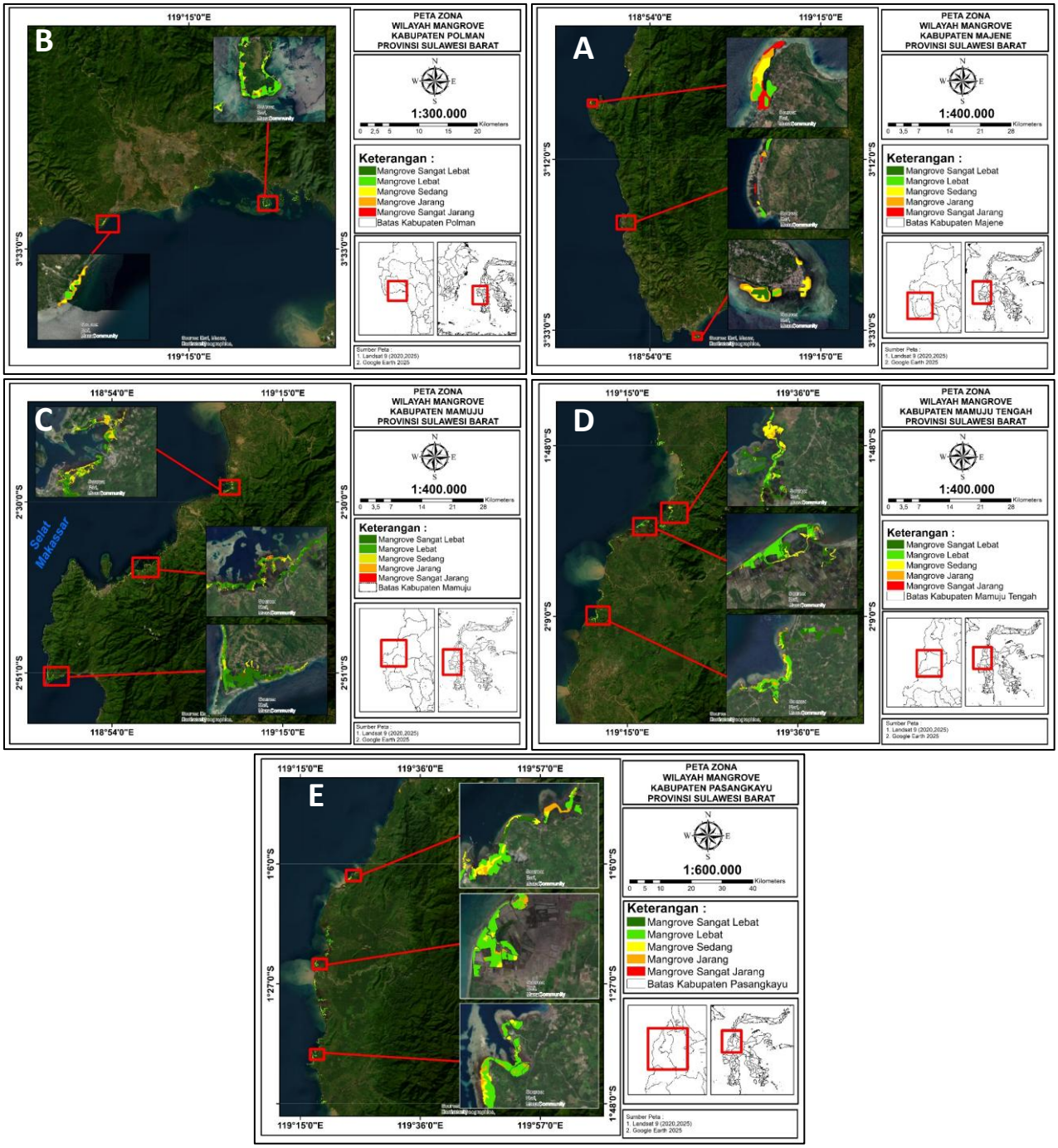


Figure 4. Mangrove Presence Parameter (A=Polman, B=Majene, C=Mamuju, D=Mateng, E=Pasangkayu).

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3.1.4. Distance from the Coastline Parameter

The distance from the coastline is a key factor influencing the level of tidal flood vulnerability. In general, the closer an area is to the shoreline, the higher its potential for inundation caused by tidal surges or sea level rise [16]. Spatial analysis results indicate that all coastal regencies in West Sulawesi Polewali Mandar, Majene, Mamuju, Central Mamuju, and Pasangkayu have high vulnerability zones within 0-500 meters from the coastline.

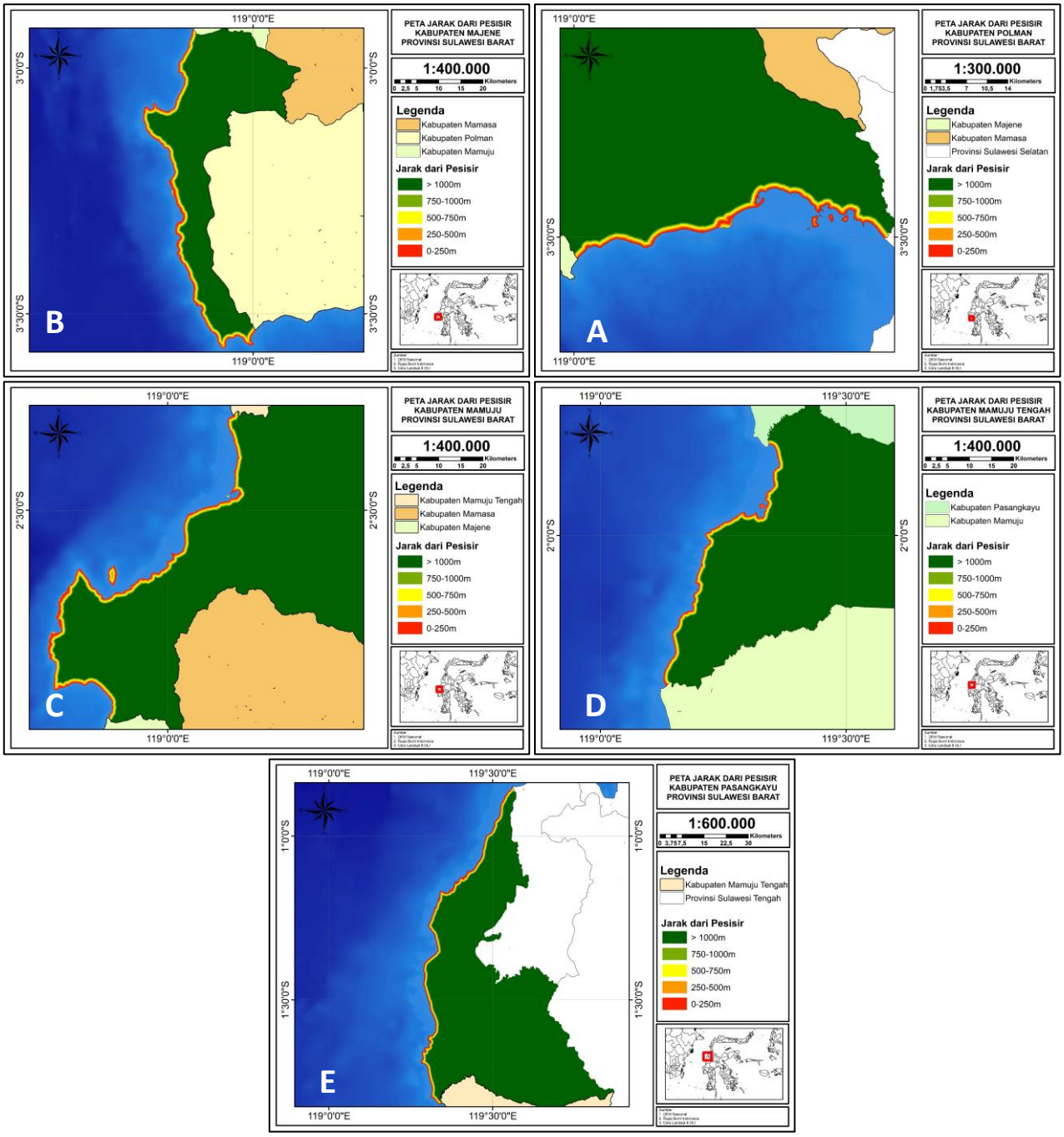


Figure 5. Distance from Coast Parameter (A=Polman, B=Majene, C=Mamuju, D=Mateng, E=Pasangkayu).

3.1.5. Distance from River Parameter

The distance from rivers plays an important role in determining the level of tidal flood vulnerability in the coastal areas of West Sulawesi. Areas located near river channels are at higher risk of inundation, particularly when increased river discharge coincides with high tide conditions [17]. Overlay analysis results show that all

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coastal regencies Polewali Mandar, Majene, Mamuju, Central Mamuju, and Pasangkayu exhibit a similar pattern, where high-risk zones follow the main river channels down to their estuaries.

In Polewali Mandar, high-risk areas are concentrated at the estuaries of the Mandar and Limbong Rivers, which are close to the coastal settlements of Polewali and Binuang. Majene exhibits high risk in East Banggae and Pamboang due to steep and short river flows toward the coast. In Mamuju, high vulnerability levels are found along the Karema and Kalukku watersheds, which discharge into the western coastline. Central Mamuju shows a similar pattern in the Pangale and Budong-Budong areas, while in Pasangkayu, the downstream regions of the Lariang and Dungkait Rivers are prone to inundation due to the combination of high tides and estuarine sedimentation.

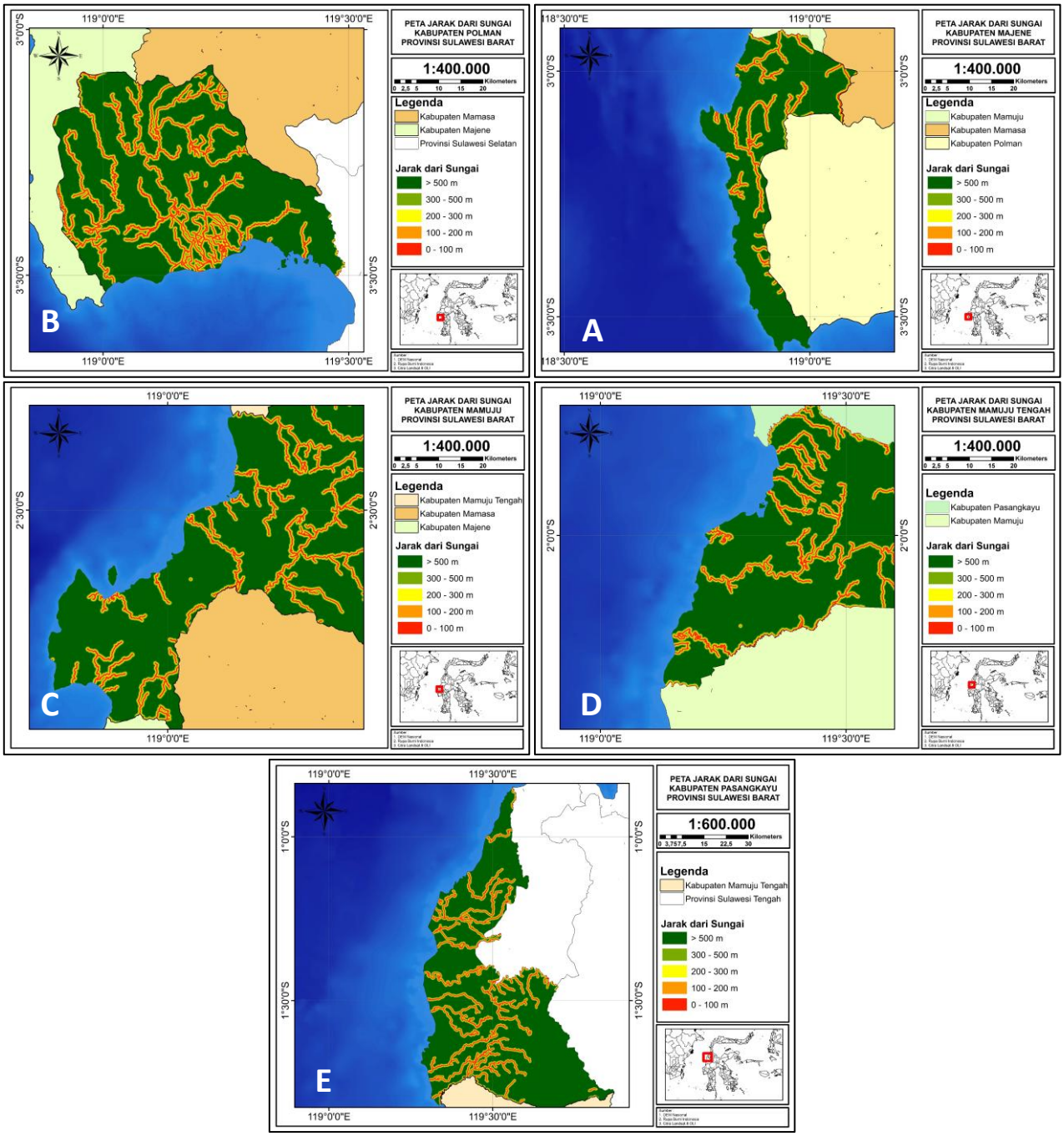


Figure 6. Distance from River Parameter (A=Polman, B=Majene, C=Mamuju, D=Mateng, E=Pasangkayu).

3.1.6. Slope Parameter

Land slope influences the level of tidal flood vulnerability, as it affects surface runoff velocity and the potential for water accumulation [18]. Areas with gentle slopes have a higher risk due to the accumulation of

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seawater that cannot easily drain to lower elevations. Overlay analysis of slope maps in the five coastal regencies of West Sulawesi indicates that most areas fall within the 0–8% slope class (flat to gently sloping), which extends along the coast—particularly in southern Polewali Mandar, the western coast of Majene, and the coastal zones of Mamuju and Central Mamuju facing the Makassar Strait. Meanwhile, slopes greater than 25% (steep to very steep) are generally found in the hilly regions of the central to northern areas. Spatially, flat to gently sloping terrains represent high vulnerability zones to tidal flooding, as they allow seawater to penetrate farther inland, whereas moderately to steeply sloping regions tend to be safer due to their natural drainage capacity [19].

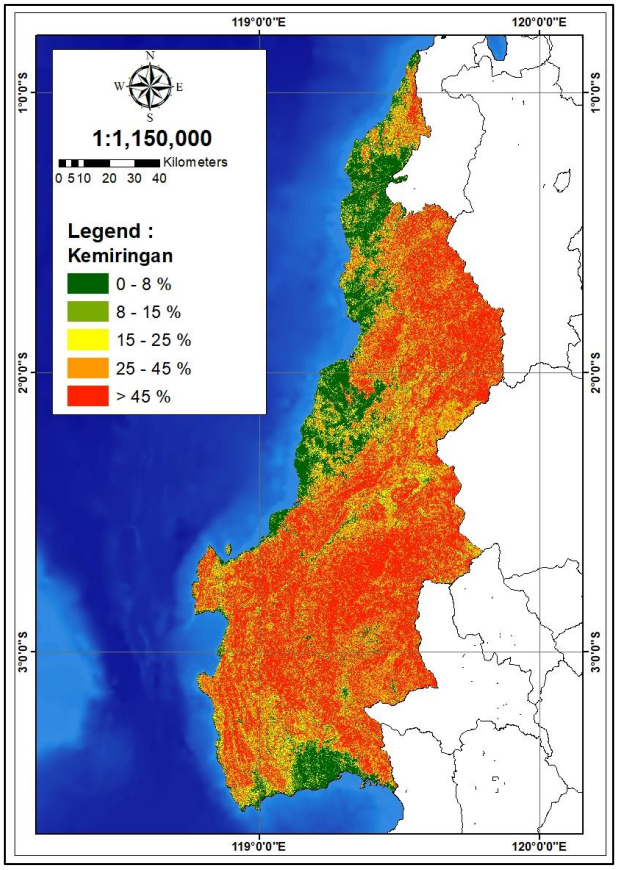


Figure 7. Slope Parameter

3.2. Tidal Flood Vulnerability

3.2.1 Polewali Mandar Regency

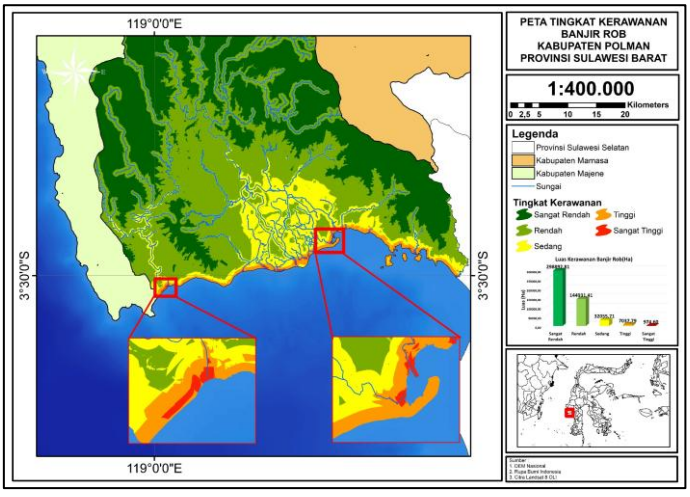


Figure 8. Tidal Flood Vulnerability Map of Polewali Mandar Regency.

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Spatial analysis results indicate that Polewali Mandar Regency exhibits varying levels of tidal flood vulnerability, ranging from very low to very high. Very high and high vulnerability zones are concentrated along the coasts of Binuang, Campalagian, and Mapilli, which are low-lying areas (0–5 meters above sea level) located near major river estuaries. The areas classified as very high vulnerability cover approximately 974.60 hectares, while high vulnerability zones encompass about 7,037.79 hectares, predominantly consisting of dense settlements, fishponds, and open lands near the shoreline. Moderate vulnerability zones cover around 32,055.71 hectares along the central coast, which are relatively protected by mangrove vegetation and slightly higher topography. Meanwhile, low to very low vulnerability areas are found in the central and northern regions, consisting mainly of agricultural land and hilly areas above 10 meters in elevation.

3.2.2 Majene Regency

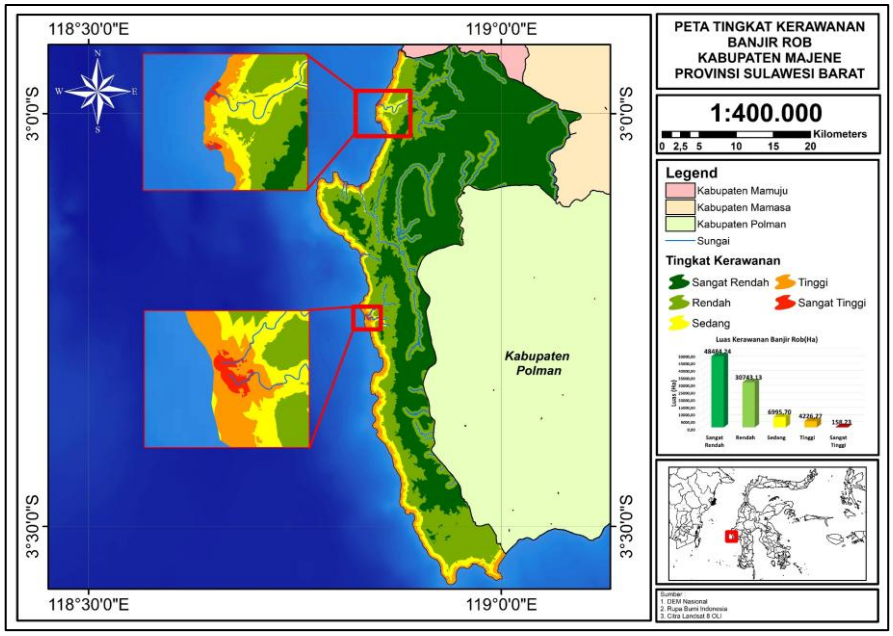


Figure 9. Tidal Flood Vulnerability Map of Majene Regency.

Spatial analysis indicates that the level of tidal flood vulnerability in Majene Regency varies from very low to very high. The very high vulnerability zones are concentrated along the coasts of East Banggae and Pamboang, covering an area of approximately 158.23 hectares. These areas have flat topography (0–5 meters above sea level), are located near river estuaries, and are dominated by fishponds and dense settlements. Such conditions increase the potential for inundation during high tides or when high tides coincide with heavy rainfall.

The high flood risk zone covers an area of 4,226.67 ha, distributed along the southern to northern coastal areas, including Sendana, where human activities such as coastal development and mangrove conversion exacerbate tidal flood exposure. The reduction of mangrove cover decreases the natural capacity of the coastline to attenuate wave energy. Meanwhile, the moderate-risk zone, covering 6,995.70 ha, is located in the transitional area between coastal and hilly regions. The low and very low categories, with areas of 30,743.13 ha and 43,484.24 ha respectively, are generally found in regions with elevations above 10 meters and steep slopes in the central to eastern parts of Majene.

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3.2.3 Mamuju Regency

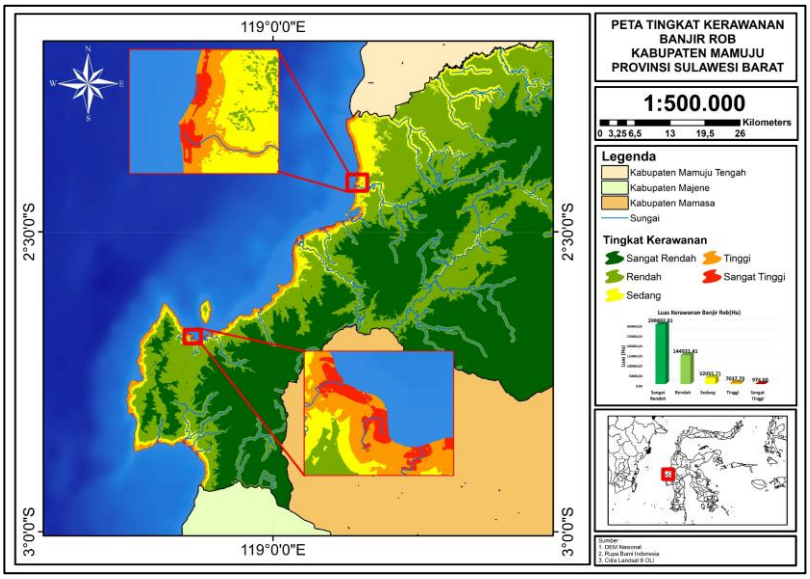


Figure 10. Tidal Flood Vulnerability Map of Mamuju Regency.

Spatial analysis indicates that tidal flood vulnerability in Mamuju Regency varies from very low to very high. The very high vulnerability zone, covering an area of 974.60 ha, is located along the coasts of Mamuju and Kalukku Districts. This zone consists of alluvial lowlands (<5 m above sea level) near the shoreline and the estuaries of the Karema and Kalukku Rivers, dominated by dense settlements and coastal economic activities.

The high tidal flood vulnerability zone, covering an area of 7,037.79 ha, is distributed along the central to northern coast, including parts of Simboro District. This area is influenced by low slopes, loss of protective vegetation, and maximum tidal events driven by sea level rise. The moderate vulnerability zone, covering 32,055.71 ha, lies in transitional coastal–hilly areas, while the low and very low vulnerability zones, covering 144,911.41 ha and 238,982.81 ha respectively, are located in the eastern and southeastern parts of Mamuju, which are higher and more undulating

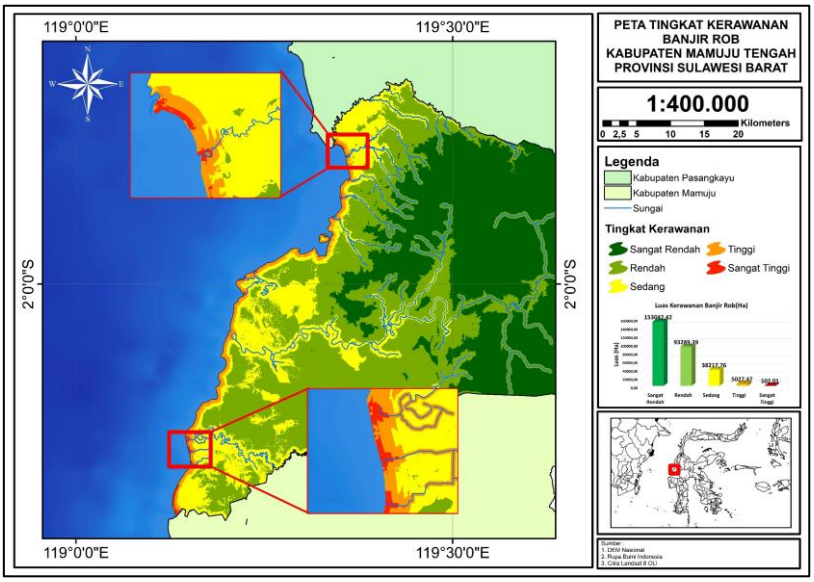


Figure 11. Tidal Flood Vulnerability Map of Central Mamuju Regency.

3.2.4 Central Mamuju Regency

Spatial analysis in Central Mamuju Regency indicates that tidal flood vulnerability is predominantly classified as very low to moderate, with increasing risk along the western coast bordering the Makassar Strait.

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The very high vulnerability zone (502.01 ha) is located in the coastal areas of Topoyo and Budong-Budong, near river mouths and fishponds, while the high vulnerability zone (5,027.47 ha) extends along the western to southwestern coast. The moderate zone (38,217.76 ha) occupies the coastal–hilly transition areas, whereas the low and very low zones, covering 93,289.39 ha and 153,947.42 ha respectively, are found in the eastern and southeastern regions with elevations above 10 meters above sea level. Mangrove logging has further reduced the area's natural capacity to resist tidal inundation.

3.2.5 Pasangkayu Regency

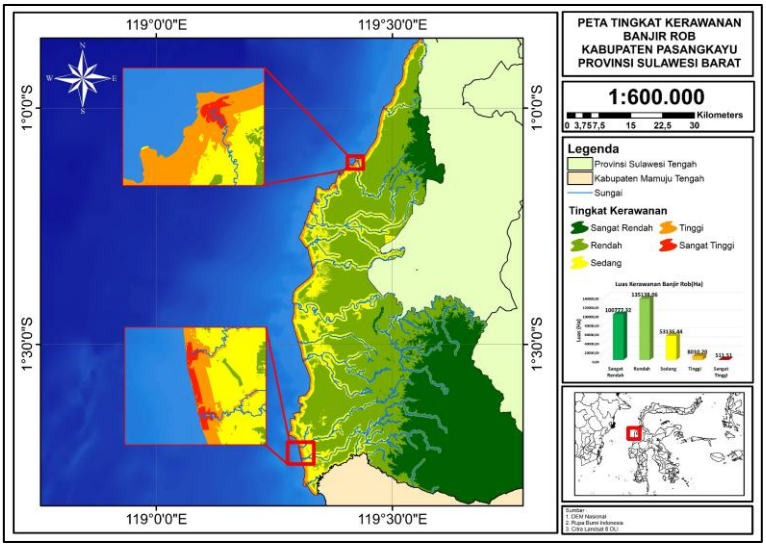


Figure 12. Tidal Flood Vulnerability Map of Pasangkayu Regency.

Spatial analysis in Pasangkayu Regency shows that tidal flood vulnerability is predominantly classified as very low to low, with high to very high zones distributed along the western and southwestern coasts. The very high vulnerability zone (511.51 ha) is located in Sarjo and western Pasangkayu, near river mouths facing the Makassar Strait. The high vulnerability zone (8,010.20 ha) extends along the Bambalamotu–Sarudu coast, while the moderate zone (53,136.44 ha) lies 1-3 km inland from the shoreline. The low and very low zones, covering 100,777.32 ha and 135,138.06 ha respectively, are found in the central to eastern parts of the regency, which are characterized by undulating topography and greater distance from the coast.

3.3. Predicted Tidal Flood Vulnerability

3.3.1 Tidal Flood Vulnerability in 2035

Spatial modeling results indicate that the entire coastal zone of West Sulawesi Province is potentially exposed to tidal flooding by 2035, with varying levels of vulnerability across regencies. The affected areas are generally located at elevations below 5 meters above sea level, encompassing settlements, fishponds, and coastal agricultural lands.

In Polewali Mandar, the most vulnerable zones are found along the coasts of Binuang, Wonomulyo, and Campalagian, which are characterized by flat terrain and extensive aquaculture areas. In Majene, inundation is projected to expand in Banggae and Pamboang, particularly in densely populated areas experiencing land subsidence.

Mamuju is predicted to face high risk in Simboro and Kalukku, especially around river mouths and gently sloping sandy beaches. In Mamuju Tengah, flood potential is identified in Pangale and Topoyo, driven by land conversion into open areas. Meanwhile, in Pasangkayu, inundation is projected in Pasangkayu, Bambalamotu, and Sarudu, which have long, low-lying coastlines.

Overall, coastal vulnerability in western Sulawesi Barat is projected to increase by 2035, necessitating adaptation strategies such as mangrove rehabilitation, elevation of coastal infrastructure, and sustainable coastal spatial planning

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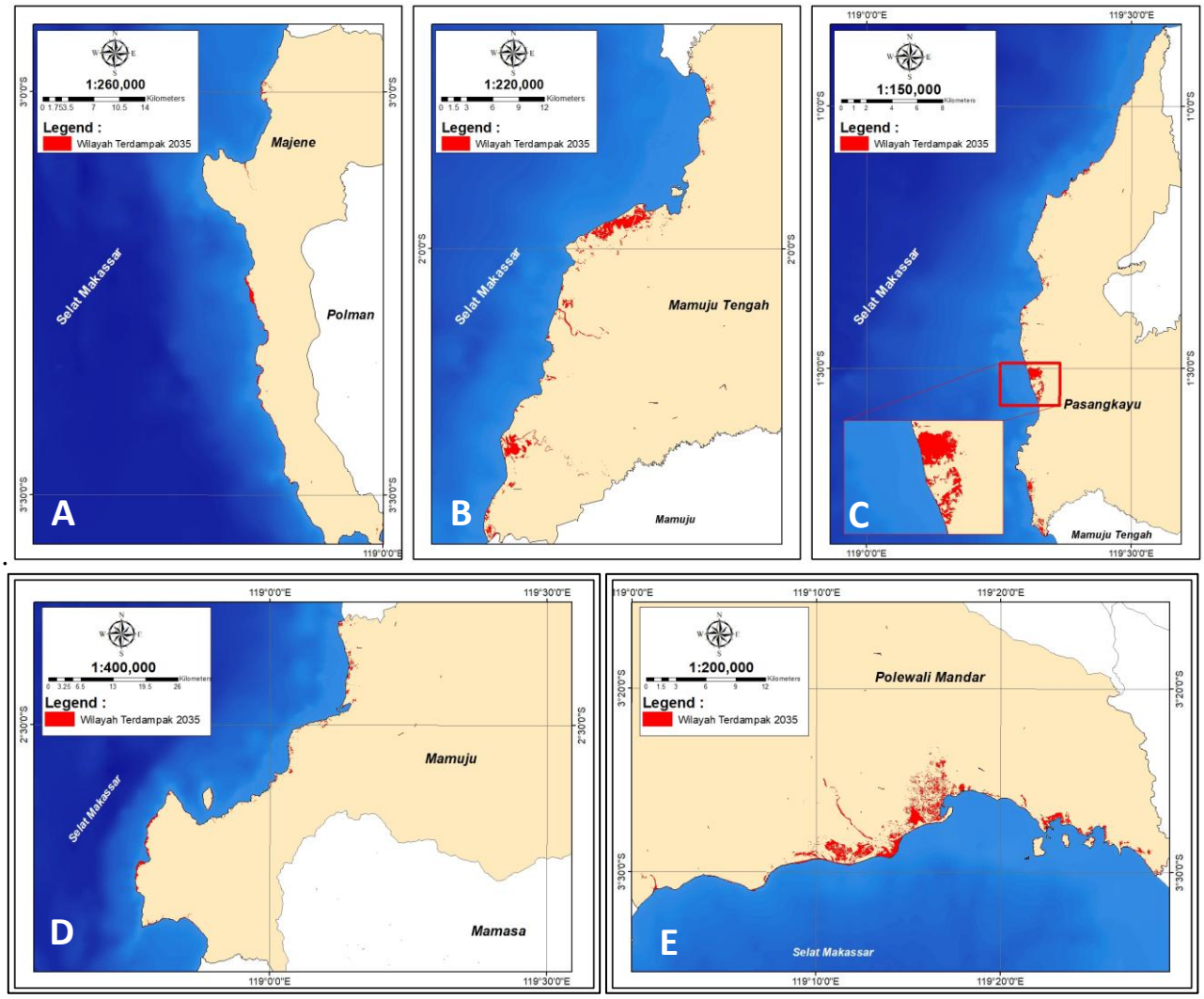


Figure 13. Prediksi Kerawanan Banjir Rob Tahun 2035 (A=Majene, B=Mateng, C=Pasangkayu, D=Mamuju, E=Polman).

3.3.2 Tidal Flood Vulnerability in 2075

Spatial modeling for the year 2075 indicates a significant increase in the extent of tidal flood inundation across the coastal areas of West Sulawesi Province compared to 2035. Sea-level rise and the predominance of low-lying coastal morphology are the main factors driving the expansion of high-vulnerability zones into settlement and aquaculture areas.

In Polewali Mandar, high to very high vulnerability zones in Binuang, Polewali, and Campalagian are projected to extend up to approximately 2 km inland from the coastline, indicating a growing socio-economic risk in the absence of ecosystem-based mitigation efforts. In Majene, high-vulnerability areas are expected to expand by more than 30%, particularly in Banggae, Banggae Timur, and Pamboang, due to rising sea levels and reduced coastal vegetation cover.

Mamuju shows a drastic change in Simboro, Mamuju, and Kalukku, where previously high-vulnerability zones evolve into very high, encompassing settlements and public facilities. In Mamuju Tengah, high to very high vulnerability zones begin to dominate the coastal areas of Karossa and Budong-Budong due to seawater intrusion into productive aquaculture and agricultural lands.

Pasangkayu exhibits the most significant increase, with the coastal regions of Bambaira, Bambalamotu, and Sarjo transforming into high to very high vulnerability zones as a result of combined factors including sea-level rise, flat coastal topography, and river mouth sedimentation

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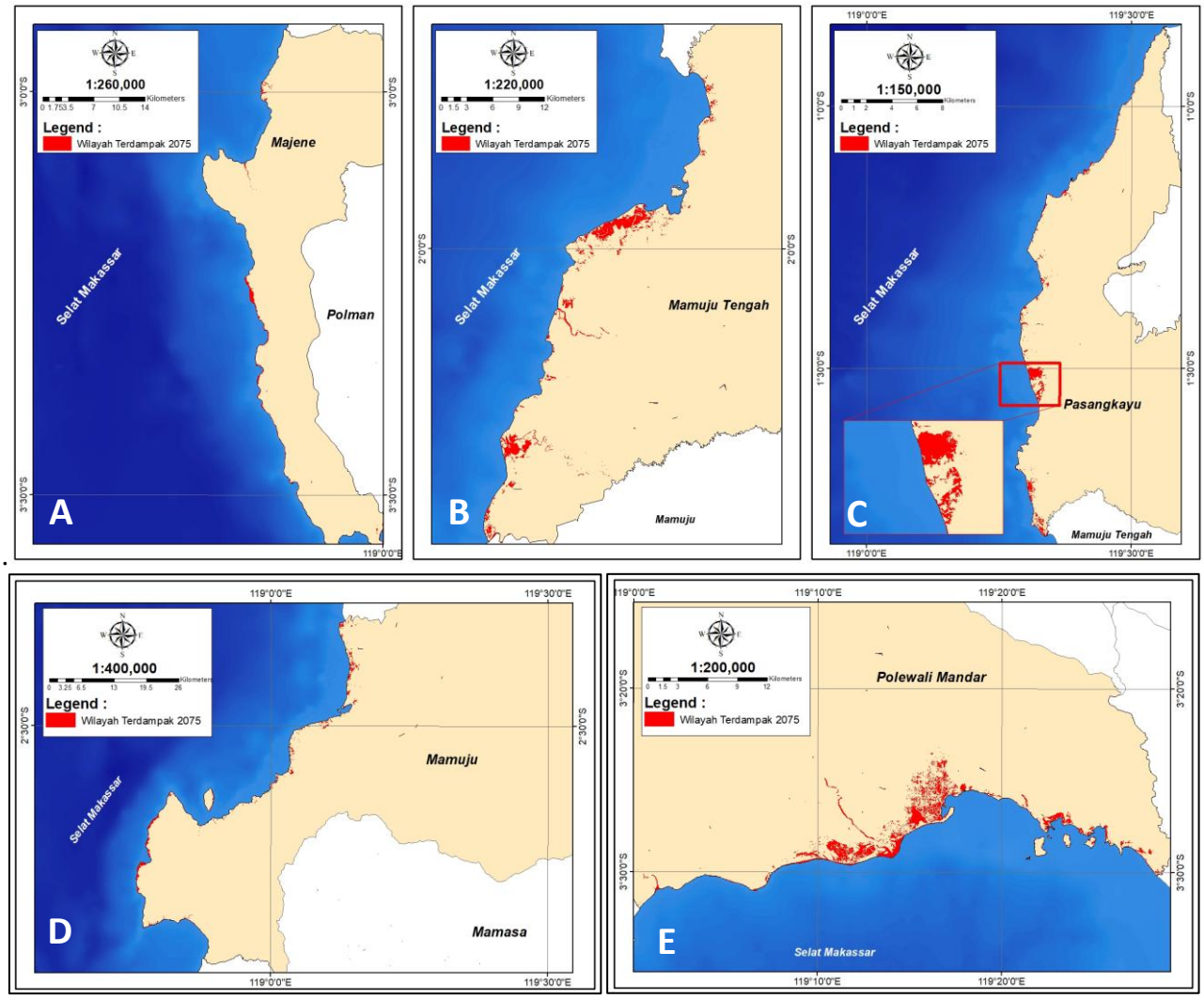


Figure 14. Tidal Flood Vulnerability Prediction for 2075 (A=Majene, B=Mateng, C=Pasangkayu, D=Mamuju, E=Polman).

3.4. Data Validation

Data validation was carried out by comparing the results of tidal flood inundation modeling from spatial analysis with actual field events based on official agency reports and observations from coastal communities. The objective was to ensure that the mapped results correspond accurately to real conditions in the coastal areas of West Sulawesi Province.

The overlay between inundation maps and recorded events indicates that most spatially identified inundation points overlap with actual tidal flood occurrences in recent years. In Polewali Mandar Regency, inundation was detected in Ujung and Takatidung Villages locations that are empirically known to experience tidal flooding during transitional seasons. In Majene, the modeling results correspond to reported tidal flood incidents in Banggae Timur, which have disrupted port operations and coastal public facilities. In Mamuju, the Simboro area shows a strong correlation between modeled and observed inundation, where seawater frequently floods residential areas, particularly around Bhayangkara Police Hospital, a location repeatedly affected by tidal floods each year.

Similarly, the Budong-Budong area (Central Mamuju) and Bambalamotu (Pasangkayu) exhibit a high degree of consistency, supported by local reports of flooding due to simultaneous extreme tides and high rainfall. Overall, the validation results demonstrate good spatial accuracy, as the modeled inundation patterns reflect real-world events. Minor discrepancies are likely due to shoreline changes, temporal variations in tides, and the limited resolution of satellite imagery

A total of 32 validation points representing documented tidal-flood locations across the five coastal regencies were overlaid onto the vulnerability map. The overlay showed that all 32 recorded points (100%)

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fell within the high to very-high vulnerability zones, indicating strong spatial agreement between the model output and observed conditions (Table 8). The model detection accuracy defined as the proportion of recorded tidal-flood events correctly located within the high to very-high vulnerability zones therefore reached 32/32 (100%), confirming that the mapping method reliably represents the spatial pattern and distribution of tidal-flood-prone areas in West Sulawesi. It should be noted that this validation relies on positive (flooded) reference points only; incorporating non-flooded control points in future work would enable computation of a complete confusion matrix and complementary metrics such as the Kappa coefficient. Minor discrepancies may still arise from the limited resolution of the imagery, shoreline change, and the temporal dynamics of tides.

Table 8. Validation summary of modeled vulnerability against field-recorded tidal-flood events

Field recorded points	Located in High Very High zone	Spatial agreement
32	32	100%

3.5. Climate Change Adaptation Strategies to Reduce the Impact of Tidal Flooding in Coastal Areas

The following are the IFAS (Internal Factors Analysis) and EFAS (External Factors Analysis) presented in Table 9 below:

Table 9 presents the analysis of internal (IFAS) and external (EFAS) factors.

	Internal Strategic Factors	Weight	Rating	Score
A	**Streght**			
1	The Provincial Government of West Sulawesi has designated the Balabalakang Islands as a marine conservation area	0,05	4	0,2
2	Coral reefs covering an area of 8,049.26 hectares in the waters of West Sulawesi function as blue carbon ecosystems	0,4	5	2
3	Initiatives from local communities in developing agroecology-based farming systems	0,04	3	0,12
4	West Sulawesi has abundant natural resources, such as mangrove forests and coral reefs	0,05	5	0,25
5	Collaboration between the government and Muhammadiyah University of Mamuju in the coral reef rehabilitation program in the Karampuang Islands	0,1	3	0,3
	Sub Total	**0,64**		**2,87**
B	**Weakness**			
1	Many coastal areas still lack infrastructure for tidal flood mitigation	0,1	2	0,2
2	Several coastal areas still lack an effective early warning system for tidal flooding	0,06	3	0,18
3	Coastal communities, especially fishermen, still face challenges in accessing technological information	0,05	2	0,1
4	Human activities, such as land conversion into fishponds, have caused damage to coastal ecosystems	0,1	2	0,2
5	Limited budget and resources for climate change adaptation programs	0,05	2	0,1
	Sub Total	**0,36**		**0,78**
	TOTAL	**1**		
	Score IFAS 2,87 – 0,78 = 2,09			
	External Strategic Factors	**Weight**	**Rating**	**Score**
A	**Opportunity**			
1	Collaboration between the government, non-governmental organizations, and universities to strengthen adaptive capacity	0,1	4	0,4
2	Potential development of conservation-based ecotourism (coral reefs, mangroves)	0,05	3	0,15
3	Interest from the private sector to invest in climate change adaptation projects	0,05	3	0,15

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	External Strategic Factors	Weight	Rating	Score
A	**Opportunity**			
4	The presence of national and international programs supporting climate change adaptation	0,15	4	0,6
5	Increasing public awareness of coastal conservation and climate change	0,15	4	0,6
	Sub Total	**0,5**		**1,9**
B	**Threats**			
1	Sea-level rise and global climate change increase the frequency of tidal flooding	0,2	2	0,4
2	Uncontrolled development activities reduce the function of coastal ecosystems as natural protective barriers	0,1	2	0,2
3	Low public awareness of the importance of coastal conservation	0,05	2	0,1
4	Changes in extreme weather patterns, such as tropical storms, increase the risk of tidal flooding	0,05	1	0,05
5	Competition in the use of natural resources among the fisheries, agriculture, and tourism sectors	0,1	2	0,2
	Sub Total	**0,5**		**0,95**
	TOTAL	**1**		
	Score EFAS 1,9 – 0,95 = 0,95			

The analysis shows that the IFAS (internal factors) score for strengths and weaknesses is 2.87 – 0.78 = 2.09, while the EFAS (external factors) score for opportunities and threats is 1.9 – 0.95 = 0.95. When plotted on a quadrant diagram, this position falls in Quadrant I (development and growth quadrant). In this quadrant, the existing strengths outweigh the weaknesses, and the growth opportunities are very favorable. Therefore, performance enhancement is required to support development and pursue growth. This indicates that Mamuju District is in a stage of development and growth, making the most appropriate strategy an offensive strategy (S-O strategy).

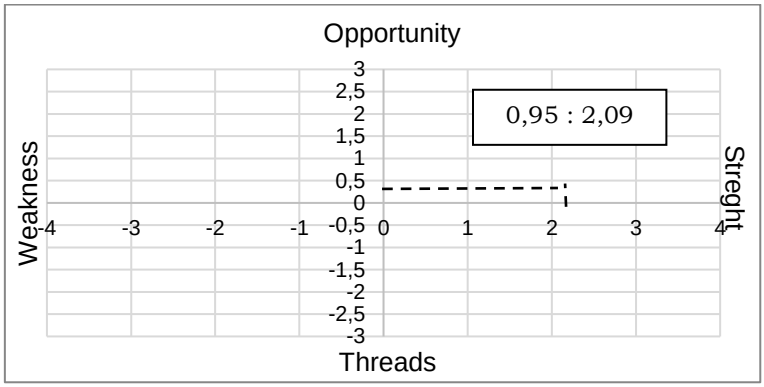


Figure 16. IFAS and EFAS Strategies.

Strategic factors are key elements encompassing strengths, weaknesses, opportunities, and threats that influence a particular condition or situation, and can become advantages if appropriately addressed. Strategy formulation, also known as strategic planning, is the process of designing long-term plans that require in-depth analysis [20]. After strategies are established through the SWOT matrix, the next step is to determine priority strategy programs by referring to the IFAS–EFAS matrix quadrant. Based on the quadrant analysis, the most appropriate strategy for both internal and external conditions in tsunami disaster mitigation is an offensive strategy (S-O strategy), which is :

1. Utilize government support and conservation policies to develop mangrove- and coral reef-based ecotourism that can enhance the local economy.
2. Optimize the involvement of local communities and academics in implementing climate change adaptation training programs based on agroecology and sustainable fisheries.
3. Leverage blue carbon ecosystems and coastal natural resources as living laboratories for climate change adaptation research and innovation.

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4. Strengthen government–local–academic collaboration to secure support from national and international programs related to climate adaptation.
5. Promote community participation by capitalizing on the increasing public awareness of conservation and climate change.

The results underline the strategic role of mangrove ecosystems in mitigating tidal-flood impacts along the West Sulawesi coast. Areas with dense mangrove cover, such as the Mamuju River mouth, consistently corresponded to lower vulnerability scores, whereas coastal segments with sparse or degraded mangroves exhibited higher vulnerability. This pattern reflects the capacity of mangroves to attenuate wave and tidal energy, trap sediment, and stabilize shorelines through their dense root systems, thereby reducing the landward penetration of seawater. Under climate-change conditions this protective function becomes increasingly critical: rising sea levels and intensified tidal surges elevate the exposure of low-lying coasts, while continued mangrove degradation would further amplify vulnerability. Consequently, mangrove conservation and rehabilitation should be regarded not merely as a biodiversity measure but as a core ecosystem-based adaptation strategy that provides a cost-effective, self-sustaining coastal defense complementary to structural approaches.

The projected expansion of high-vulnerability zones carries significant socio-economic implications for coastal communities in West Sulawesi. The fisheries and aquaculture sector is particularly exposed, as brackish water ponds which received the highest land-use vulnerability score are directly threatened by inundation, salinity intrusion, and infrastructure damage, potentially reducing household incomes that depend on these activities. Coastal settlements in rapidly developing areas such as Mamuju, Simboro, and Polewali are at risk of recurrent flooding of housing and public facilities, while critical infrastructure including roads, ports, and drainage networks faces accelerated deterioration. The cumulative effect of these impacts may disrupt local livelihoods, increase adaptation costs, and heighten the socio economic marginalization of coastal populations, underscoring the urgency of integrating flood-risk considerations into local development planning.

From a policy perspective, the findings can be aligned with the framework of Integrated Coastal Zone Management (ICZM), which emphasizes the coordinated management of coastal resources across sectors and administrative boundaries. The vulnerability maps provide a spatial basis for prioritizing intervention zones and can be integrated into regional spatial plans (RTRW) and coastal zoning plans (RZWP3K). The offensive (SO) strategy derived from the SWOT analysis is consistent with the principle of ecosystem-based adaptation (EbA), which leverages the protective services of mangroves and other blue-carbon ecosystems to reduce coastal risk. Furthermore, these results support the implementation of Indonesia's national climate-adaptation agenda, particularly the National Action Plan for Climate Change Adaptation (RAN API), by providing locally specific evidence for adaptation targeting. Embedding the vulnerability outputs within ICZM, EbA, and national adaptation frameworks would strengthen the translation of scientific findings into actionable coastal-management policy.

4. CONCLUSION

The conclusions of this study are as follows:

1. This study demonstrates that the coastal areas of West Sulawesi Province are highly vulnerable to tidal flooding, particularly in the regencies of Polewali Mandar, Majene, and Mamuju, with vulnerability primarily influenced by low land elevation (<5 m above sea level), flat to gentle slopes, proximity to the coast and rivers, and low mangrove density.
2. The modeling results indicate a significant increase in the extent of affected areas by 2075 due to sea-level rise, highlighting the urgency of implementing effective mitigation and adaptation measures.
3. Based on the SWOT analysis, the recommended adaptation strategy is an offensive strategy (S–O) that leverages the potential of coastal ecosystems, strengthens community capacity, and fosters synergy among government, academics, and local communities, thereby supporting climate change adaptation planning and sustainable coastal development in West Sulawesi.

Limitations and Future Research.

This study is subject to several limitations. First, the sea-level-rise projection relies on a linear extrapolation of the assumed constant rate and does not incorporate the full range of IPCC emission scenarios or non-linear ice-sheet dynamics. Second, the semi-quantitative scoring and weighting, although grounded in the CVI

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framework, retain a degree of subjectivity that could be refined through structured methods such as the Analytical Hierarchy Process (AHP). Third, model accuracy is constrained by the spatial resolution of the DEMNAS elevation data and the use of static land-use inputs, which do not capture dynamic coastal change. Finally, validation was limited to documented historical events based on positive reference points. Future research is therefore recommended to (1) apply higher-resolution elevation data such as LiDAR; (2) integrate dynamic hydrodynamic modeling to represent tidal and storm-surge processes; (3) employ AHP or other robust multi-criteria weighting techniques; and (4) incorporate a socio-economic vulnerability index and non-flooded control points to produce a more holistic and statistically complete coastal-risk assessment.

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