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Analysis of the vulnerability level of coastal settlements to tidal flooding in Kelapa Lima District, Kupang City

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ABSTRACT

Tidal inundation has progressively impacted coastal residential areas in Kelapa Lima District, Kupang City, as a consequence of sea-level rise, accelerated urban expansion, and insufficient drainage infrastructure. Notwithstanding the recurrence of flooding incidents, a spatially integrated vulnerability evaluation for this locality has not yet been systematically established. This research seeks to examine the degree of vulnerability within coastal settlements by applying a Geographic Information System (GIS)-driven multi-criteria spatial methodology. Physical variables (elevation, proximity to the coastline, slope gradient, and land utilization) were synthesized with a social indicator (population density) through procedures of scoring, normalization, and weighted assessment techniques. Spatial synthesis was conducted using weighted overlay analysis within a GIS environment to generate vulnerability zoning maps. The findings categorize the coastal territory into three levels of vulnerability: non-vulnerable (24%), vulnerable (46%), and highly vulnerable (30%). Roughly 76% of the investigated area is situated within zones classified as vulnerable. Field verification demonstrates the correspondence between the spatial simulation results and the actual occurrence of tidal flooding events. The principal contribution of this study resides in the incorporation of spatial and socio-environmental indicators within a GIS-oriented analytical framework to inform adaptive coastal planning and mitigation measures.

Introduction

Urban coastal environments are progressively subjected to tidal inundation as a consequence of sea-level rise, land-use transformation, and accelerated urban growth. Within Indonesia, tidal flooding events (rob) have exhibited a marked increase in both frequency and spatial coverage over the past decade, particularly within densely inhabited coastal settlements (Fadhil et al. 2020; Salsabillah et al. 2024). The combined influence of rising sea levels, land subsidence, and poorly regulated coastal development significantly amplifies levels of exposure and vulnerability. At the national scale, hydrometeorological hazards dominate disaster statistics, underscoring the pressing need to reinforce coastal resilience strategies (Marfai and King 2008). Physical exposure determinants, including low elevation, close proximity to the shoreline, and alterations in land cover, substantially shape the vulnerability of urban areas to flooding.

The vulnerability of coastal territories is becoming increasingly intricate in parallel with rapid demographic expansion, particularly due to phenomena such as sea-level rise, saltwater intrusion, and the growing prevalence of unplanned development, in addition to biophysical characteristics including low-lying topography and insufficient drainage infrastructure (Handayani et al. 2017). Geographic Information Systems (GIS) have emerged as an essential instrument in urban flood risk evaluation because of their capacity to synthesize diverse spatial variables within a single analytical framework. Multi-criteria spatial evaluation and weighted overlay methods allow the integration of parameters such as elevation, slope gradient, land use, and demographic attributes to produce vulnerability zoning maps (Fadhil et al. 2020; Nur, Alimuddin, and Albab 2025). Consequently, these approaches are increasingly employed to facilitate risk-informed urban planning and the formulation of coastal mitigation policies.

Kelapa Lima District, located in Kupang City within East Nusa Tenggara Province, represents a clear example of a coastal region experiencing substantial residential expansion along its shoreline. The district comprises several densely inhabited sub-districts, including Oesapa, Pasir Panjang, and Namosain, all of which directly border the Sawu Sea and are characterized by relatively low elevations that heighten susceptibility to extreme seawater inundation (Lusi, Rukmi, and Purnamasari 2021; Salsabillah et al. 2024). In recent years, tidal flooding has become a recurrent phenomenon in this locality, with a major incident recorded in early 2024 that inundated dozens of homes for several consecutive days. Additional tidal flood events during 2023–2024 affected residential areas in Oesapa and West Oesapa, demonstrating the urgent need for spatially explicit vulnerability assessments (Seprianto et al. 2024). These events not only damaged physical infrastructure but also disrupted the socio-economic activities of the surrounding community.

Beyond direct physical exposure, spatial configuration and land-use transformation also play significant roles in shaping environmental vulnerability. Research conducted in East Nusa Tenggara highlights the importance of landscape environment interactions and spatial adaptation strategies within settlement systems (Bria and Suartika 2022; Robert U. Roka Laki Mara, Debora Budiyono, and Hendra Kurniawan 2024). Although these investigations primarily address traditional settlements, their spatial–environmental perspectives illustrate how land arrangement and the density of the built environment influence environmental risk.

Vulnerability emerges from the interaction between regional biophysical conditions and social pressures, including population growth, conversion of coastal land, and weak regulation of spatial utilization (McGranahan, Balk, and Anderson 2007). In this context, a Geographic Information System (GIS)-based spatial approach has proven effective in identifying and mapping vulnerability zones through the integration of variables such as elevation, distance to the shoreline, slope gradient, land use, and population density (Abidin et al. 2013; Fadhil et al. 2020). GIS-based spatial mapping enables a quantitative and comprehensive analysis of vulnerability that can serve as a foundation for developing regionally based climate change mitigation and adaptation strategies. Recent studies further emphasize the significance of community-oriented mitigation initiatives and sustainability-based spatial planning in reducing disaster vulnerability (Tanggela and Bawole 2024; Bawole et al. 2025). Accordingly, integrating spatial parameters with socio-demographic indicators within a GIS framework facilitates a more holistic understanding of urban vulnerability.

Kelapa Lima District also constitutes a strategic zone within Kupang City because of its arterial road network and its concentration of economic activities within the service and trade sectors. Nevertheless, rapid residential expansion that is not accompanied by adequate drainage infrastructure, coupled with weak supervision of coastal land utilization, has increased the risk of tidal flooding (Tallo, Amnifu, and Tallo 2023). Additional challenges, including development within coastal boundary zones, the proliferation of unauthorized buildings lacking official permits, and inadequate sanitation conditions, have further intensified the area's vulnerability (Lusi, Rukmi, and Purnamasari 2021).

A number of previous investigations have demonstrated that coastal regions characterized by low elevations and high population densities are considerably more susceptible to tidal flooding (Hidayah, Sari, and Lestari 2018; Mintiea and Pigawati 2018). Consequently, GIS-based analyses capable of integrating both physical and social dimensions are required to evaluate the spatial vulnerability of coastal settlements.

Despite the recurring occurrence of tidal flooding, vulnerability assessment within Kelapa Lima District remains largely descriptive and has not yet been systematically modeled through GIS-based multi-criteria analysis. Moreover, relatively few studies address medium-sized coastal cities in eastern Indonesia, thereby creating a research gap in the spatial modeling of vulnerability.

Accordingly, this research addresses the following question: How vulnerable are coastal settlements in Kelapa Lima District to tidal flooding when analyzed through an integrated GIS-based multi-criteria spatial approach? This study therefore aims to develop a GIS-based urban vulnerability model that integrates physical parameters with population density in order to classify tidal flood vulnerability levels and support evidence-based coastal urban planning.

Methods

This research adopts a spatially oriented quantitative–descriptive approach supported by Geographic Information Systems (GIS), utilizing ArcGIS and Quantum GIS (QGIS) software. The principal objective of the study is to analyze the vulnerability level of coastal settlements. The assessment of coastal flood risk in Kelapa Lima District, Kupang City, concentrates on residential areas located within a 1-kilometer buffer from the coastline. This study area was selected because of its low-lying characteristics, the high density of settlements along the shoreline, and the documented history of recurring tidal flooding.

This study uses spatial and non-spatial data, as summarized in table 1.

Tabel 1. Types of data used

Data Types	Parameters	Data source
Elevation Data (DEM)	Altitude (meters)	DEMNAS
Distance to the beach	Buffer against the coastline	Coastline digitization (RBI map)
Slope gradient	Slope gradient class (e.g.: 0–8%, 8–15%, etc.)	Spasial analysis (QGIS/ArcGIS)
Land use 2023	Land classification (residential, bush, etc.)	Landsat/Sentinel Satellite Imagery
Population density	Number of residents per sub-district area	BPS Kota Kupang

The first stage of the research concentrated on the collection and processing of spatial datasets that served as the foundation for vulnerability analysis. All spatial data were projected into the Universal Transverse Mercator (UTM) coordinate system for zone 51S in order to ensure consistent spatial referencing and mapping accuracy. This preliminary spatial data processing stage was essential to guarantee that all vulnerability parameters shared a uniform reference framework and maintained scientific reliability.

The spatial datasets employed include: [1] a Digital Elevation Model (DEM) with a minimum resolution of 30 meters, which was utilized to generate elevation and slope maps. Derivative spatial analysis was subsequently performed to obtain slope values derived from the elevation dataset. The application of DEM data is widely recognized as crucial for topographic and geomorphological slope analysis in identifying flood-prone areas (Li, Zhang, and Goodchild 2008).

[2] Medium-resolution satellite imagery (e.g., Sentinel-2) was applied for land cover classification. [3] Coastline data were manually digitized from high-resolution imagery and subsequently used as the basis for calculating distance to the shoreline. The Euclidean Distance function within GIS software was applied to generate a distance layer from each settlement location to the coastline. [4] Social data in the form of population density were obtained from the Central Statistics Agency (BPS) or other relevant institutions and incorporated as a complementary parameter within the spatial vulnerability analysis. Population density constitutes an important component within vulnerability indices (Cutter, Boruff, and Shirley 2003). However, this parameter was excluded from the raster-based weighted overlay process because of differences in spatial scale between administrative boundaries and pixel-based spatial variables, thereby avoiding spatial distortion. Instead, population density was integrated during the interpretation phase to strengthen the analysis of social vulnerability.

During the second stage, each parameter namely elevation, slope gradient, distance to the coastline, land cover, and population density was assigned a score according to its level of vulnerability to tidal flooding. The scoring process employed a Likert scale (for example, 1 = not vulnerable to 3 = very vulnerable). Within the spatialization of disaster risk, scoring procedures and Likert scales are commonly utilized to categorize levels of threat and vulnerability (Armaş 2008). The classification criteria were established based on a review of previous literature and were subsequently adjusted to the specific biophysical and socio-spatial characteristics of the study area. To maintain consistency among the indicators, a normalization process was applied to all score values so that each parameter possessed an equivalent analytical scale. Subsequently, each indicator was assigned a weight corresponding to its relative contribution to tidal flood vulnerability (Tingsanchali 2012). The determination of these weights was informed by relevant previous studies.

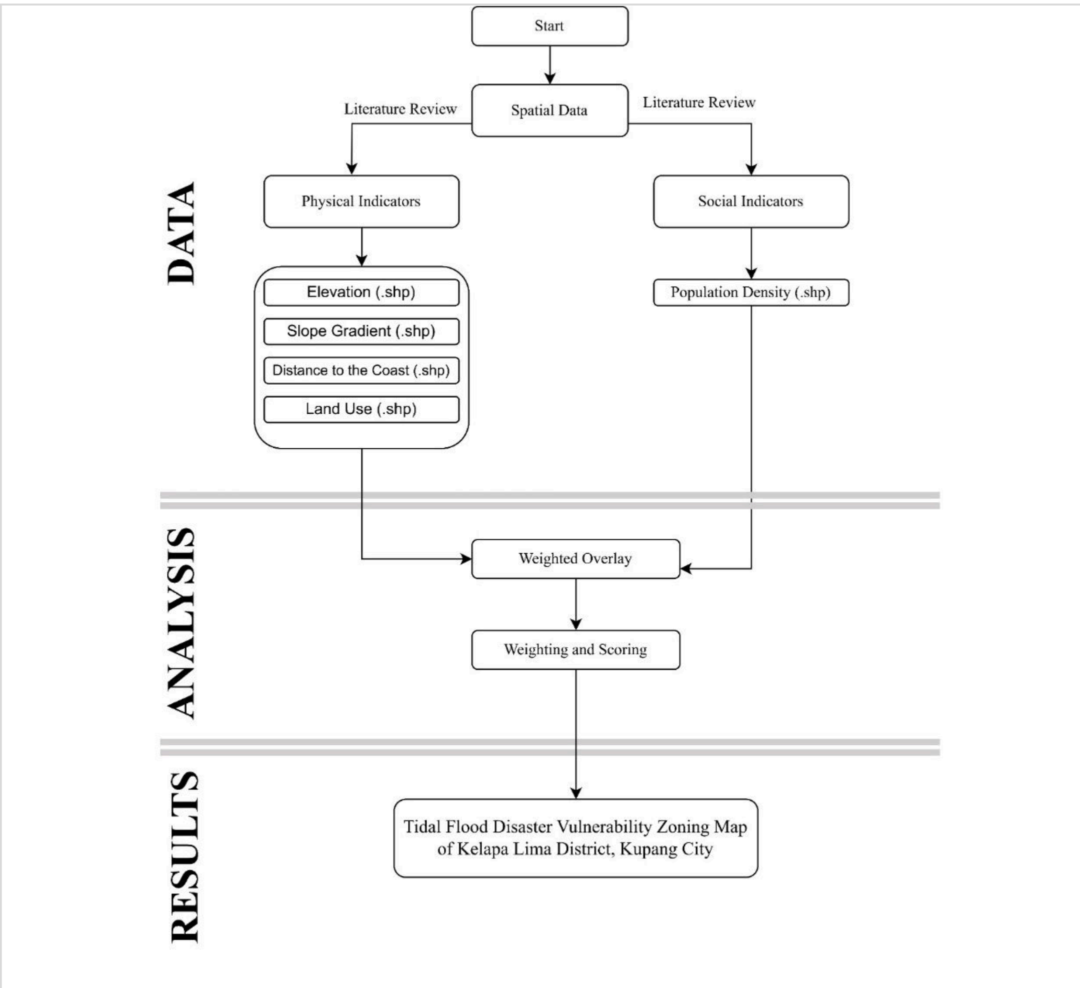

Figure 1. Research flowchart

The third stage involved integrating the spatial indicators after the scoring and weighting processes had been completed. Data integration was conducted using the Weighted Overlay Analysis technique (Murray 2002). The outcome of this process was a zoning map illustrating the vulnerability of coastal settlements to tidal flooding, classified into five categories: very low, low, medium, high, and very high. To ensure the reliability of the modeling results, qualitative validation procedures were performed. The resulting vulnerability zoning map was compared with historical tidal flood records obtained from the Kupang City Regional Disaster Management Agency (BPBD) as well as local media archives (Seprianto et al. 2024). Validation was conducted by overlaying the spatial locations of tidal flood events onto the vulnerability analysis map to evaluate the spatial accuracy of the model outputs (Nur, Alimuddin, and Albab 2025). The expected output of this study is a final zoning map that delineates the levels of coastal settlement vulnerability to tidal flooding within Kelapa Lima District, Kupang City. The complete research workflow is illustrated in figure 1, which provides the conceptual basis for the spatial modeling process used to represent the overall vulnerability conditions of the study area.

Results and discussion

Flood risk parameters

1. Elevation

Elevation represents a critical parameter in assessing vulnerability to tidal flooding because lower terrain relative to sea level substantially increases the likelihood, depth, and persistence of inundation within coastal residential environments. The elevation parameter map (figure 2) illustrates the spatial distribution of tidal flood susceptibility in the coastal zone of Kelapa Lima District according to variations in elevation above mean sea level. Overall, the study area is categorized into three vulnerability classes: low, moderate, and high. The not vulnerable category (green, 30–69 m) corresponds to inland areas that are comparatively protected from tidal flooding during high-tide conditions and are primarily located in the southern section of the district. The vulnerable category (yellow, 17–30 m) forms a transitional corridor situated behind the coastal belt, where inundation remains possible when extreme tidal conditions coincide with intense rainfall and blocked drainage systems. Mid-elevation zones frequently function as flood accumulation areas because drainage capacity is often insufficient to accommodate incoming water volumes (Azhari, Lestari, and Arifin 2022).

Tabel 2. Elevation parameter weights

Class (meters)	Fragility	Weight
30 -69	Not Vulnerable	1
17-30	Prone to	2
3 – 17	Very Vulnerable	1

The highly vulnerable category (red, 3–17 m) dominates the coastal belt characterized by extremely low elevations. These zones directly face the shoreline and are therefore highly exposed to tidal runoff during peak tidal events. In addition, inundation in these areas tends to persist for extended periods due to limited water outflow capacity. This category includes the sub-districts of Oesapa, West Oesapa, and portions of Lasiana, which function as major centers of coastal residential activity.

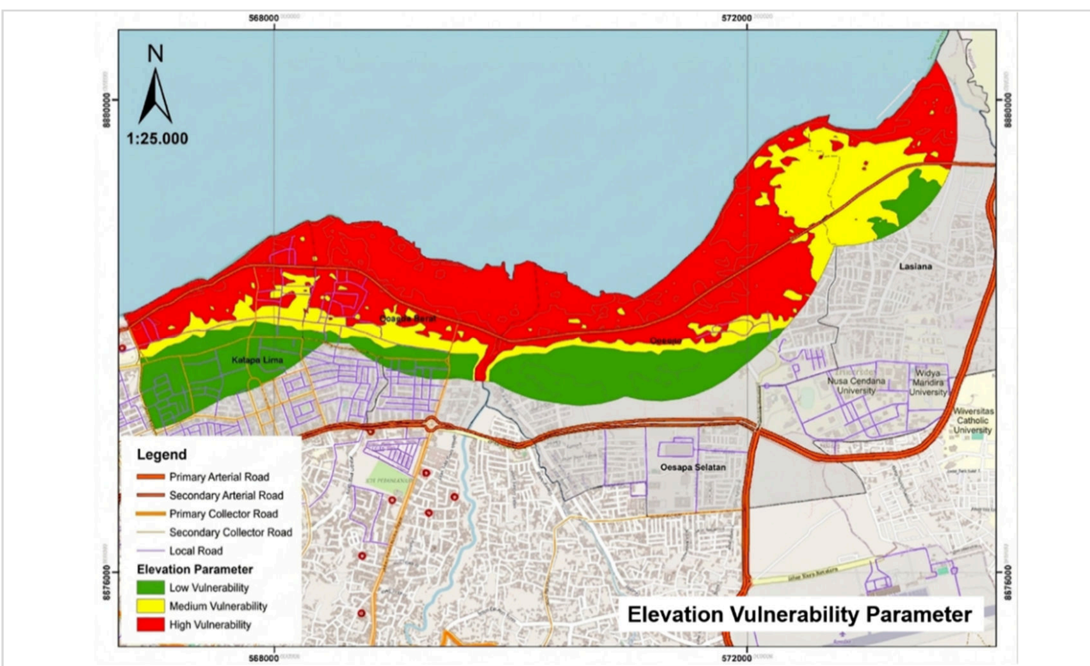

Figure 2. Elevation parameter map

2. Distance to Beach

The highly vulnerable category (red, 3–17 m) dominates the coastal belt characterized by extremely low elevations. These zones directly face the shoreline and are therefore highly exposed to tidal runoff during peak tidal events. In addition, inundation in these areas tends to persist for extended periods due to limited water outflow capacity. This category includes the sub-districts of Oesapa, West Oesapa, and portions of Lasiana, which function as major centers of coastal residential activity.

Tabel 3. Weighting of distance to coast parameters

Class (meters)	Fragility	Weight
600–1000	Not Vulnerable	1
300–600	Prone to	2
0–300	Very Vulnerable	3

Areas situated 300–600 meters from the coastline are classified as moderately vulnerable (yellow). These areas still face the potential impact of tidal flooding, particularly when extreme tidal levels coincide with heavy rainfall events or when drainage infrastructure becomes obstructed.

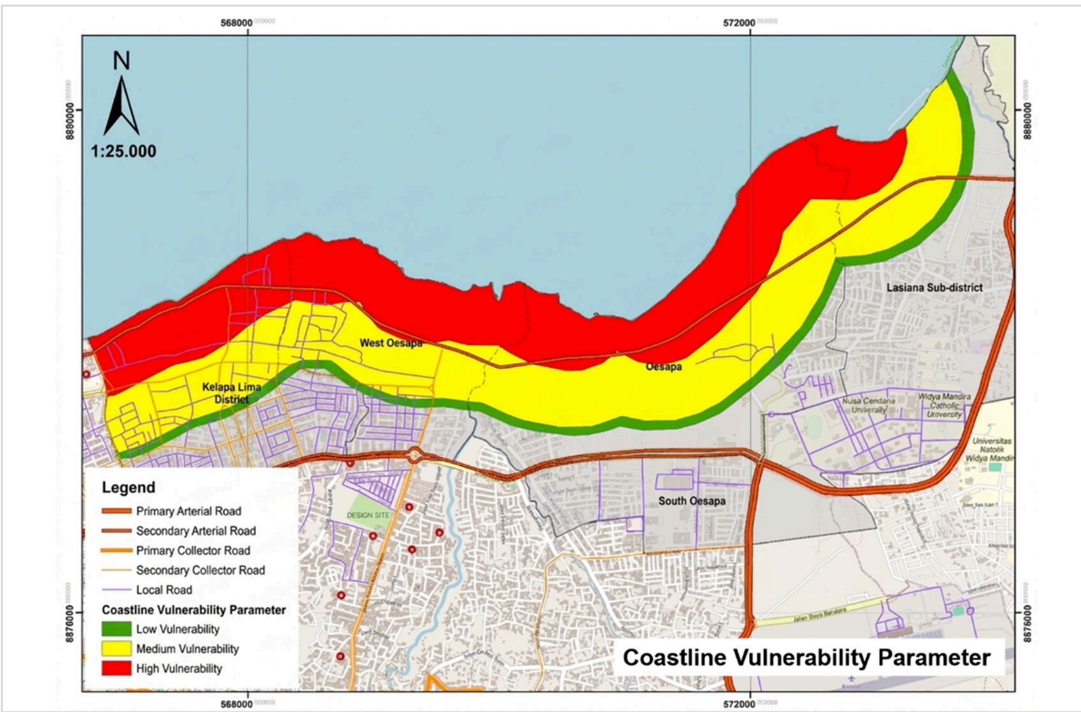

Figure 3. Coastline distance parameter map

Zones located 600–1,000 meters from the shoreline fall into the not vulnerable category (green). These areas are comparatively secure from tidal inundation, although localized runoff may still occur under extreme climatic conditions or when drainage systems operate inefficiently.

3. Slope gradient

The slope gradient map reveals a strong relationship between land morphology and tidal flood vulnerability in Kelapa Lima District. In general, three principal slope classes are identified. First, gentle slopes (0–8%) are classified as high vulnerability zones. This class occupies approximately 65–70% of the coastal area, particularly in northern sections such as West Oesapa, Oesapa, and parts of Lasiana. The flat terrain allows tidal water to disperse easily and remain stagnant for extended periods, making it a dominant vulnerability factor. Second, moderately steep slopes (8–15%), covering approximately 20–25% of the study area, are categorized as moderate vulnerability zones.

Tabel 4. Weighting of distance to coast parameters

Class	Fragility	Weight
Steep slope (>15%)	Not Vulnerable	1
Rather steep slope (8–15%)	Prone to	2
Gentle slope (0–8%)	Very Vulnerable	3

This intermediate zone functions as a transitional belt behind the coastline where water flow occurs more rapidly, although inundation risk remains when extreme tides combine with heavy rainfall. Third, steep slopes (>15%), representing approximately 10% of the area, are categorized as low vulnerability and are distributed mainly in the southern region of the district, further from the shoreline. In these zones, steeper terrain accelerates surface runoff, thereby reducing the probability of prolonged inundation. These findings reinforce the argument that flat coastal topography significantly intensifies tidal flood vulnerability.

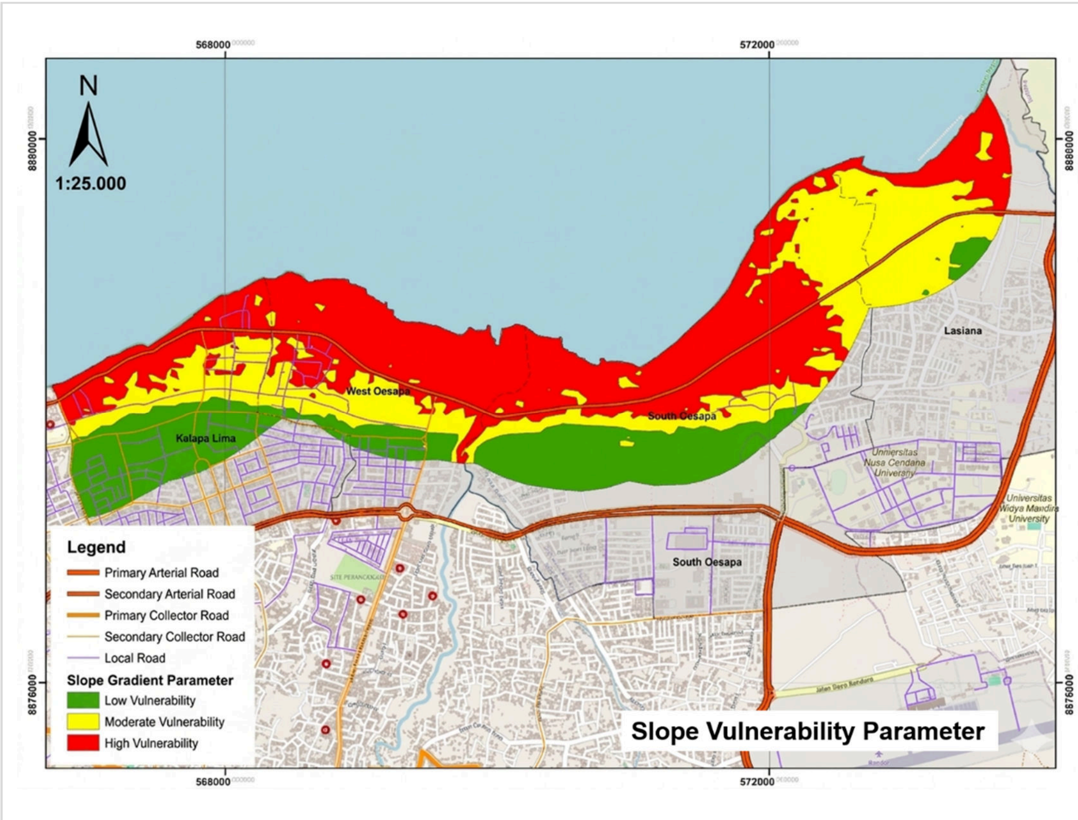

Figure 4. Slope gradient parameter map

4. Land use

Land use constitutes a significant indicator in tidal flood vulnerability assessment because land-cover types influence infiltration capacity, surface runoff behavior, and the level of exposure of coastal settlements to flooding.

a. Not Vulnerable (Green: water bodies and natural vegetation)

This category demonstrates relatively high-water absorption capacity and functions as a natural buffer against tidal runoff. Vegetation types such as mangrove forests and coastal shrubs contribute to absorbing wave energy and decreasing water flow velocity.

Tabel 5. Weighting of land use parameters

Class	Fragility	Weight
Water Bodies and Natural Vegetation	Not Vulnerable	1
Agriculture	Prone to	2
Flooded Vegetation and Built-up Land	Very Vulnerable	3

b. Vulnerable (Yellow: agriculture)

Agricultural zones demonstrate moderate vulnerability because, although infiltration remains possible, their proximity to the shoreline still exposes them to flooding hazards. Seasonal cropping patterns and limited permanent vegetation reduce their protective capacity against tidal inundation.

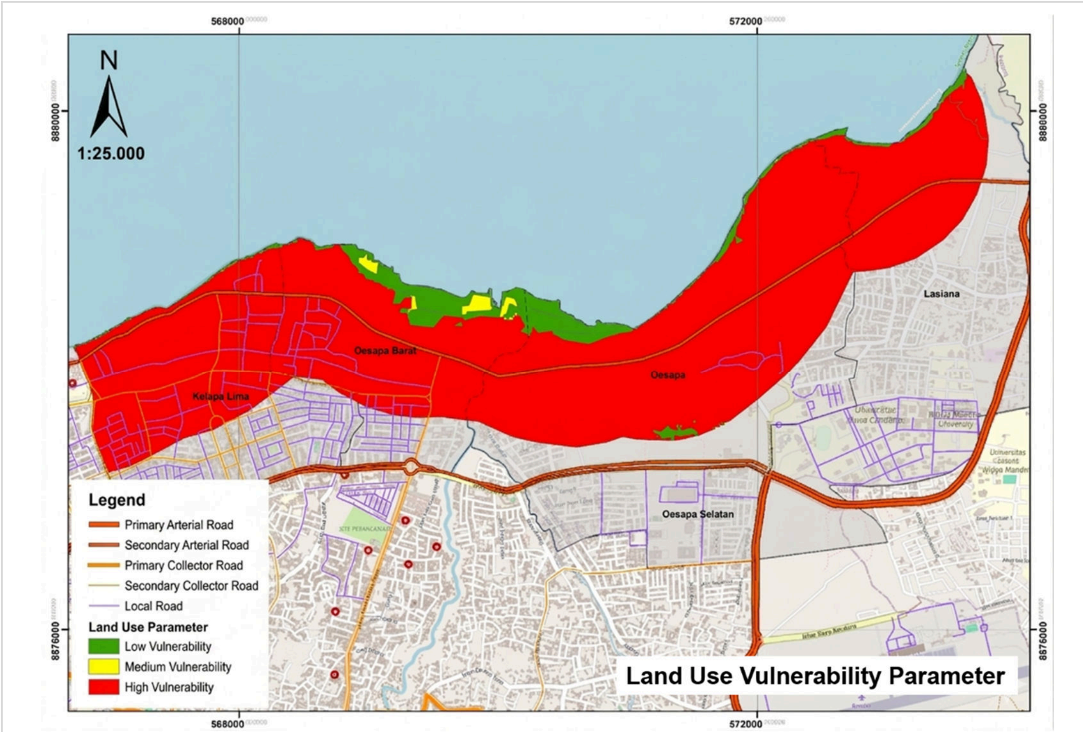

Figure 5. Land use parameter map

c. Very Vulnerable (Red: flooded vegetation and built-up land)
This category dominates coastal sections of Kelapa Lima District, particularly within Oesapa, West Oesapa, and parts of Kelapa Lima. Built-up environments, including dense settlements, transportation networks, and public facilities, are highly vulnerable due to low infiltration capacity and high exposure to tidal flooding. Flooded vegetation also indicates ecological degradation caused by repeated inundation, rendering these areas ineffective as natural protective barriers.

5. Population Density

In addition to spatial–physical parameters, this research incorporates social dimensions in the form of population density as an indicator of tidal flood vulnerability. Population data for the coastal areas of Kelapa Lima District reveal substantial variation. Kelapa Lima records 10,492 inhabitants with a density of 6,320 people/km², Oesapa 16,796 inhabitants with 5,105 people/km², West Oesapa 12,035 inhabitants with 6,649 people/km², while Lasiana contains 3,429 inhabitants with a density of 3,089 people/km², producing an overall density range of 3,089–6,649 people/km².

Tabel 6. Weighting of population density parameters

Class (deaths/km²)	Fragility	Weight
⩽ 4,276	Not Vulnerable	1
4,277 – 5,462	Prone to	2
⩾ 5,463	Very Vulnerable	3

The social vulnerability classification indicates that areas with densities ⩽ 4,276 people/km² fall into the low vulnerability category, densities of 4,277 – 5,462 people/km² represent moderate vulnerability, and densities ⩾ 5,463 people/km² correspond to high vulnerability. Consequently, Lasiana belongs to the low category, Oesapa to the moderate category, while Kelapa Lima and West Oesapa fall into the high vulnerability class.

Population density is therefore interpreted as a social factor that intensifies vulnerability risk, since higher population concentrations increase the potential for casualties, economic losses, and pressure on regional adaptive capacity. Social dimensions, particularly population distribution and density, constitute important determinants of disaster vulnerability (Cutter, Boruff, and Shirley 2003).

Flood risk

The first step undertaken to produce the tidal flood vulnerability map involved processing each parameter through classification and scoring procedures for every category (Nur, Alimuddin, and Albab 2025). In coastal vulnerability analysis, parameters are typically grouped into spatial (biophysical) and social components. Spatial parameters represent the environmental conditions of the area and can be modeled using raster datasets, whereas social parameters represent demographic characteristics that influence the magnitude of disaster impacts on communities. This distinction is essential for maintaining analytical accuracy because spatial parameters can be processed directly using the weighted overlay method, while social parameters require interpretative integration during the results analysis stage (Cutter, Boruff, and Shirley 2003; Djalante and Garschagen 2017).

Tabel 7. Weighting in the weighted overlay method

Parameter	Parameter	Parameter
Elevation	35%	main factor, the lower the more vulnerable
Distance to Beach	30%	the closer to the coast the higher the risk.
Land use	20%	The type of land cover/use influences the level of exposure and loss.
Slope gradient	15%	The gentle slope makes it easier for the floodwater to spread.

In this study, spatial parameters consisted of distance to the coastline (35%), elevation (30%), land use (20%), and slope gradient (15%). These parameters were processed using the weighted overlay method to generate spatial vulnerability maps. Distance to the shoreline and elevation received the highest weighting because they directly determine exposure to tidal flooding, while land use and slope gradient function as secondary factors influencing flood intensity and spatial distribution.

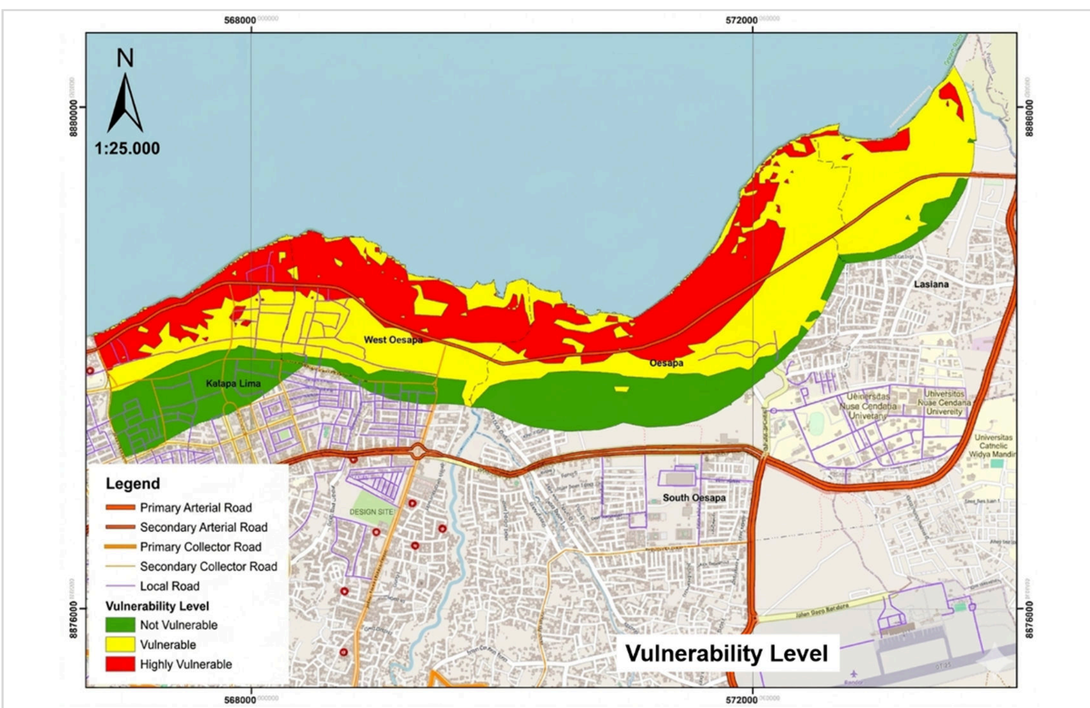

Figure 6. Flood vulnerability map of coastal residential areas in Kelapa Lima District

Population density, meanwhile, was treated as a social parameter and excluded from the raster-based weighted overlay process due to limitations associated with raster data formats. Nevertheless, it was incorporated during the interpretation phase as a reinforcing factor with a relative weight of

20% within the overall assessment. Through this approach, the spatial vulnerability map can be reinterpreted from a socio-economic perspective, enabling areas with both high physical vulnerability and dense populations to be categorized as high-priority zones for mitigation. Conversely, areas with high physical vulnerability but lower population density remain vulnerable but present lower social risk levels.

Tabel 8. Area and percentage of susceptibility to tidal flooding

Sub-district	Area of Vulnerability			Area (Km^2)
	Not vulnerable	Prone to	Very vulnerable	
Kelapa Lima	0,71	0,44	0,50	1,65
Lasiana	0,12	0,90	0,07	1,09
Oesapa	0,86	1,38	1,02	3,26
Oesapa Barat	0,21	0,84	0,74	1,79
Total Area	**1,90**	**3,56**	**2,34**	**7,80**
Percentage (%)	**24%**	**46%**	**30%**	**100%**

The results indicate that tidal flood vulnerability within the coastal zone of Kelapa Lima District covers an area of 7.80 km² and is distributed into three categories: not vulnerable (24%), vulnerable (46%), and very vulnerable (30%). The non-vulnerable category is concentrated primarily in Kelapa Lima (0.71 km²) and Oesapa (0.86 km²) within inland areas characterized by relatively higher elevation. The vulnerable category covers the largest area (3.56 km²) and is mainly concentrated in Oesapa (1.38 km²) and West Oesapa (0.84 km²), representing transitional zones susceptible to flooding during extreme tides combined with heavy rainfall events.

The very vulnerable category, covering 2.34 km², is predominantly distributed in Oesapa (1.02 km²) and West Oesapa (0.74 km²), located along low-elevation coastal zones with dense settlement patterns that are highly susceptible to repeated tidal inundation. The data reveal that nearly three-quarters of coastal areas (76%) fall within vulnerable to highly vulnerable categories, emphasizing the necessity for spatially based mitigation strategies, particularly in Oesapa and West Oesapa as primary coastal settlement centers with the highest vulnerability levels.

Data validation

Validation through field verification is essential to confirm the accuracy of vulnerability mapping results against actual flood events. The tidal flood vulnerability map for Kelapa Lima District indicates high-risk zones along the coastline, particularly in Oesapa and West Oesapa villages. This finding is supported by secondary information obtained from the NTT Provincial Disaster Management Agency (BPBD) and local media sources, which documented at least four tidal flood incidents during 2023–2024, including one event that affected Oesapa Market on 12 March 2024, inundating dozens of houses in Oesapa and Pasir Panjang.

Furthermore, field surveys conducted between February and March 2025 confirmed the consistency between the vulnerability map and real conditions in the study area. In Oesapa Village, tidal flooding occurs approximately two to three times per year, with an average inundation height of 50 cm and durations ranging between 42–72 hours. The prolonged duration of inundation is largely attributed to damaged drainage infrastructure that obstructs the return flow of tidal water to the sea.

In contrast, West Oesapa recorded its last major tidal flooding event in 2021, with an inundation depth of 50 cm lasting approximately 24 hours, prior to the construction of a coastal retaining wall. Following the construction of this embankment, the frequency of tidal flooding decreased significantly. However, during January–February 2025, tidal flooding reoccurred with a frequency of two to three events, although the impacts were relatively minor, with water depths of 30 cm and durations of only three hours. Interestingly, these incidents did not disrupt clean water supply because most residents rely on water storage tanks as their primary source.

Overall, the spatial vulnerability mapping results demonstrate a high level of agreement with field observations. Differences between modeled and observed conditions are primarily associated with structural mitigation measures (such as coastal embankments) and local infrastructure conditions (particularly drainage systems), both of which significantly influence the severity of tidal flood impacts. These findings highlight that vulnerability assessment must consider not only biophysical and spatial parameters but also socio-technical conditions present in the field.

The results confirm that elevation and proximity to the coastline represent dominant determinants of tidal flood exposure. Low-lying areas located 0–300 meters from the shoreline exhibit the highest vulnerability levels due to their direct exposure to tidal inundation. These findings correspond with recent GIS-based vulnerability studies in Indonesian coastal regions that identify elevation and coastal distance as primary spatial determinants of tidal flood susceptibility (Fadhil et al. 2020; Salsabillah et al. 2024). Spatial overlay analysis further demonstrates that areas characterized by low topographic relief and minimal drainage gradients are more susceptible to prolonged flooding.

Nevertheless, vulnerability intensifies in locations with high population density and inadequate drainage infrastructure. Dense settlement patterns increase the magnitude of potential socio-economic losses and reduce adaptive capacity, reinforcing the argument that disaster vulnerability is not determined solely by physical exposure but also by social sensitivity (Cutter, Boruff, and Shirley 2003; Nur, Alimuddin, and Albab 2025) In Kelapa Lima District, particularly in Oesapa and West Oesapa, the concentration of built-up land combined with insufficient drainage systems increases both flood duration and impact severity, a pattern similarly observed in flood studies conducted in other Indonesian cities (Tallo, Amnifu, and Tallo 2023).

These findings indicate that vulnerability cannot be understood solely through physical exposure but must be interpreted within a socio-spatial framework. Urban vulnerability arises from interactions among environmental characteristics, land-use configuration, and demographic concentration. Research on spatial–environmental relationships in East Nusa Tenggara further emphasizes that settlement structures and landscape transformation significantly influence environmental resilience (Bria and Suartika 2022; Robert U. Roka Laki Mara, Debora Budiyono, and Hendra Kurniawan 2024)`. The conversion of permeable surfaces into dense built-up environments reduces infiltration capacity and increases surface runoff accumulation, thereby intensifying tidal flood impacts. In this study, the overlay results highlight the importance of improving drainage infrastructure, regulating land use within coastal buffer zones, and prioritizing population-based mitigation in highly vulnerable areas. Overall, integrating physical and socio-demographic indicators within a GIS framework strengthens the analytical foundation for adaptive coastal planning. The findings underscore the need to transition from descriptive flood reporting toward spatially quantified vulnerability modeling to support sustainable management of urban coastal environments.

Conclusions

This study demonstrates that the coastal zone of Kelapa Lima District exhibits a high level of vulnerability to tidal flooding. GIS-based analysis incorporating spatial parameters (distance to shoreline, elevation, slope gradient, and land use) together with social indicators (population density) classified the study area into three categories: not vulnerable (24%), vulnerable (46%), and very vulnerable (30%). Consequently, approximately 76% of the coastal area falls within vulnerable categories. Field validation conducted in Oesapa and West Oesapa confirmed the consistency of the vulnerability map with observed conditions, with repeated tidal events ranging from 30–50 cm in height and lasting 3–72 hours. Vulnerability is further intensified by damaged drainage infrastructure, although the construction of coastal embankments has reduced impacts in certain locations. These findings emphasize the necessity of strengthening spatial planning control, enhancing coastal infrastructure, and protecting communities located within highly vulnerable zones. The vulnerability zoning map provides an important spatial basis for regulating land use within 0–300 meters from the coastline, improving drainage infrastructure, and prioritizing mitigation measures in Oesapa and West Oesapa villages. Moreover, the GIS-based overlay model developed in this research can be replicated in other small and medium-sized coastal cities experiencing similar tidal flood risks.

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Author(s) contribution

Susana Maria Suratama contributed to the research concepts preparation, methodologies, investigations, data analysis, visualization, articles drafting and revisions.

Amandus Jong Tallo contribute to the research concepts preparation and literature reviews, data analysis, of article drafts preparation and validation.

Maria Imanuela Doko contribute to methodology, supervision, and validation.

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