

Geospatial Analysis-Based Tidal Flood Vulnerability Mapping in the Coastal Area of Sungai Kakap District, Kubu Raya Regency

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Abstract: Tidal flooding has become an increasingly significant environmental hazard in coastal areas. This study aims to: (1) identify the spatial characteristics of tidal flooding in the coastal area, (2) analyze the spatial factors influencing tidal flood vulnerability; (3) assess the level of tidal flood vulnerability using geospatial analysis; and (4) propose adaptation strategies based on the resulting vulnerability patterns. The analysis includes eight key variables: slope gradient, elevation, distance to the coastline, distance to the river, Topographic Moisture Index (TWI), soil type, rainfall, and land use. The spatial datasets were processed in a Geographic Information System (GIS) environment and integrated using a multi-criteria spatial analysis approach to generate a tidal flood vulnerability map. The results showed that vulnerability to tidal flooding was strongly associated with low elevation, gentle slopes, proximity to the coastline and river network, high TWI values, poorly drained alluvial soils, high rainfall intensity, and land use dominated by settlements, fish farming ponds, and agricultural land. The vulnerability assessment classified the study area into five categories: very high (5,717 ha; 12.62%), high (7,919 ha; 17.47%), moderate (5,515 ha; 12.17%), low (2,404 ha; 5.30%), and very low (23,762 ha; 52.44%). Areas with high and very high vulnerability were concentrated in lowland coastal zones and riverine environments. Adaptation strategies include strengthening coastal protection, improving drainage infrastructure, implementing ecosystem-based coastal management, regulating land use in vulnerable areas, and enhancing community-based disaster preparedness. This study demonstrates the effectiveness of geospatial analysis to support tidal flood risk reduction and sustainable coastal planning.

Keywords: Coastal areas; Geospatial analysis; GIS; Spatial factors; Sungai Kakap regency; Tidal flood vulnerability

Introduction

Landforms have a vital part in examining flooding since landforms could be a cross-sectional shape for the method of streaming water to the ocean. Flooding happens the most in places that are flat or gentle. This can indicate that flood-prone landscapes include floodplains, beaches, swamps, and backwaters. The geomorphological characteristics of flood areas are characterized by morphology in the form of depressions

or flat relief landforms related to streams. Some rivers twist and turn a lot, and these areas could be places where water might overflow and cause floods (Pourali et al., 2018; Riadi, 2018).

Flooding may be an issue for a nation and has indeed become a worldwide issue in different nations. Floods are a natural disaster that causes a lot of damage and is a phenomenon that often occurs in villages and city areas in coastal areas. Floods cause losses in the form of monetary and population losses (Li et al., 2020a;

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Sayama et al., 2015) and social, economic, and educational losses.

Coastal areas, which are transitional zones between land and sea, have abundant natural resources (Hamuna et al., 2018). They also have a strategic role due to their economic value, ecological value, and high zone productivity (K. K. Ahmad et al., 2021). Various other aspects, not only related to the economy, but also the utilization of coastal resources to meet the needs and development in related areas, are also available (T. E. Ahmad et al., 2021). However, it is not uncommon for these potentials to shrink, along with the level of vulnerability of coastal areas to environmental changes that can cause natural disasters (Lestari et al., 2021). In the form of floods, hurricanes, volcanic eruptions, earthquakes, tsunamis, and so on. The level of damage caused by disasters depends on the level of community resilience to the risks posed.

Currently, flood risk analysis is mostly done by focusing on spatial aspects, which include the location and extent of flooding. The components used as the basis for identifying or assessing flood risk are determined by figuring out three, specifically, danger, and flood publicity. Spatial information, risk, and flood inundation predictions are important and can help us get ready and stay safe during floods and planning efforts, or in this case, it can be referred to as adaptation. The risks and impacts of flooding will be easier to understand if there is spatial information on flooding (Singh et al., 2017; Yildirim & Demir, 2021) as well as planning and mitigation as well as adaptation. Prioritizing providing assistance and mitigating damage will be easier if there is accurate information (Purwanto & Paiman, 2023; Rosser et al., 2017). Floods are caused by many factors, such as high precipitation, surface runoff, drainage flows that are no longer able to accommodate runoff, human actions in environmental management, and other issues that significantly influence flooding.

Sungai Kakap District, Kubu Raya Regency, West Kalimantan, is a coastal area that periodically experiences tidal flooding due to a combination of tidal factors, lowland topography, and changes in land use. The development of the Sungai Kakap coastal area, characterized by increased settlements and economic activity, has increased exposure to tidal flooding. However, adaptation efforts are still reactive and not supported by comprehensive spatial information. Information on the distribution of affected areas, vulnerability levels, and spatial factors influencing tidal flooding is essential as a basis for coastal adaptation planning (BPS, 2024).

Spatial information about disasters and the impact of flooding, one of which is the existence of a flood risk map, includes flood risk maps, which are caused by

banjir rob important resource to minimize the impact of flooding that can be included in the mitigation process. A flood risk map and also adaptation processes (Li et al., 2020b, 2020a; Sermet et al., 2020; Xu et al., 2020).

Tidal flood mapping can be done by utilizing the current emerging technology, namely geospatial technology. This technology requires intensive computation, complex data, and the need for calibration from experts (Ramesh & Iqbal, 2022; Teng et al., 2017) and this sometimes becomes an obstacle in the mapping process. One spatial analysis that emphasizes banjir rob catastrophe is with the aid of using geospatial technology (Purwanto & Paiman, 2023).

Tidal flood in the Kakap river frequently occurs with varying volumes. The peak tidal flooding occurred in December 2025. Collecting spatial information on tidal flooding is very useful in determining management priorities, related to necessary mitigation and adaptation, particularly in the Kakap River and also in coastal areas in Indonesia.

The research aims to 1) determine the spatial characteristics of tidal flooding in the coastal area of Sungai Kakap District, 2) determine the spatial factors that influence the level of vulnerability to tidal flooding, 3) determine the level of vulnerability of the coastal area of Sungai Kakap District to tidal flooding based on spatial analysis, and 4) determine what adaptation strategies can be recommended based on the results of the spatial analysis of tidal flooding.

Method

Study Area

The research area is in the Sungai Kakap sub-district, Kubu Raya District. Sungai Kakap sub-district is astronomically located at 100 35' E - 109 58' E and 00 44' N - 10 1' N. Pemangkat District consists of 14 villages. The administrative area of the Pemangkat sub-district is 45.317 ha. The region of the research area can be seen in Figure 1.

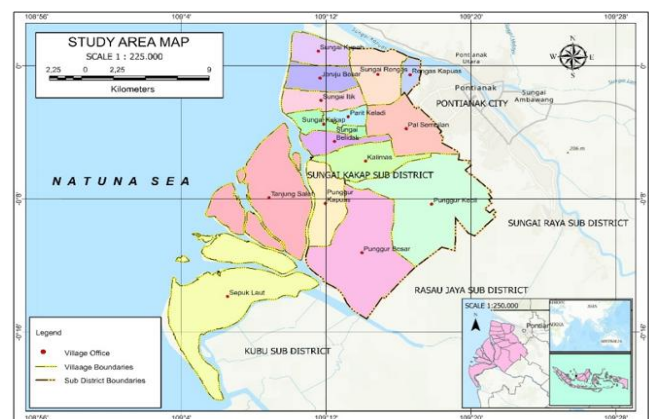


Figure 1. Study area

Geospatial analysis of tidal flooding is the process of predicting and visualizing areas prone to tidal flooding. This analytical approach utilizes spatial data, including thematic maps, topographic data, and rainfall, river flow patterns, and satellite imagery, to identify areas potentially affected by tidal flooding.

The approach used is field surveys and secondary

data. Tidal flood maps are generated from data on slope gradient, elevation, and coast line distance, distance to river, TWI (Topography Wetness Indeks), soil type, rainfall, and land use. In brief, the flowchart of the conducted research is shown in Figure 2. In summary, the weights of factors affecting tidal vulnerability can be seen in Table 2.

Table 1. Factors Used in the Tidal Flood Vulnerability Assessment in the Study Area

Classification	Sub-Classifications	Data Source	Gis Data Type	Derivative Map
Inventory of flood events	Flood inventory	Regional Drinking Water Authority and Field survey	Primary and secondary	-
DEM	Elevation	DEM	GRID	Altitude
	Slope	DEM	GRID	Tilt angle
	Distance from stream	DEM	Channel coverage	Distance to stream
	TWI	DEM	Channel coverage	Wetness index
Land cover type	Land cover	Sentinel 2	GRID	Land cover
Precipitation	Precipitation	CHIRPS 2023	GRID	Precipitation
Coastline distance	Coastline distance			
Distance to river	Distance to river			
Soil type	Soil type	Kalimantan Barat Soil type	Vektor	Soil type

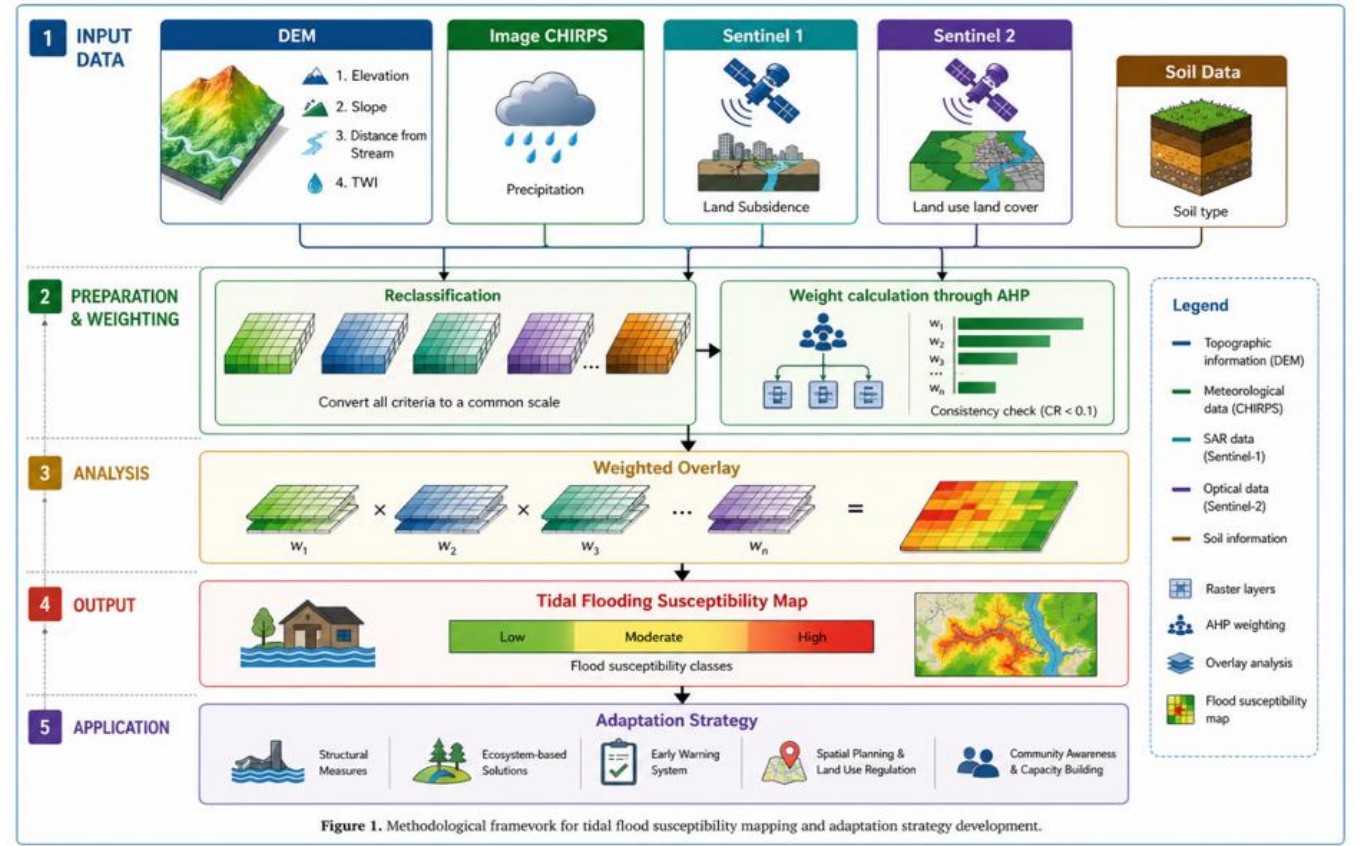


Figure 1. Methodological framework for tidal flood susceptibility mapping and adaptation strategy development.

Figure 2. Methodological framework for tidal vulnerability mapping and adaptation strategy development

Table 2. Tidal Vulnerability Parameter and Their Weights

Tidal Vulnerability Parameters	Descriptive	Reclass	Scoring	Weighted
Elevation (m)	Very low	0 - 0.10	2	4
	Low	0.10 - 1.5	1	
Slope (%)	Very low	0 - 3	3	7
	Low	3- 8	2	

Tidal Vulnerability Parameters	Descriptive	Reclass	Scoring	Weighted
Distance from drainage (m)	Moderate	8 - 13	1	14
	Very low	0 - 100	5	
	Low	100 - 200	4	
	Moderate	200 - 300	3	
	High	300 - 500	2	
Precipitation (mm/h)	Very High	> 500	1	18
	Very low	345.32-407.07	1	
	Low	407.07-444.13	2	
	Moderate	444.13-477.06	3	
	High	477.06-511.65	4	
Land Cover	Very High	511.65-555.29	5	14
	Very low	Trees	1	
	Low	Bare land	2	
	Low	Settlement	2	
	Moderate	Croops	3	
TWI	High	Flooded vegetation	4	11
	Very High	Waterbody	5	
	Very low	2.34-7.30	1	
	Low	7.30-9.94	2	
	Moderate	9.94-12.11	3	
Coastline Distance (m)	High	12.11-14.83	4	18
	Very High	14.83-22.76	5	
	Very low	>3000	1	
	Low	15001-3000	2	
	Moderate	1001-15000	3	
Soil type	High	501-1000	4	14
	Very High	0-500	5	
	Very low	Entisol	1	
	Low	Histosol	2	
	Moderate	Inseptisol	3	

Data Analysis

The Analytic Hierarchy Process serves as a strong method for making decisions. One of the main features that sets the AHP apart is the presence of consistency checks, which validate the pairwise comparison matrix within the decision framework (Purwanto & Andrasmo, 2022; Saravanan et al., 2023; Tikuye et al., 2025). The Principal Component Model evaluates the various parameters in the AHP and assigns a weighting factor to each criterion. It uses a scale ranging from 1 to 9 to determine the relative significance of each influencing factor, where 1 means they are equally important and 9 indicates a high preference. The weights illustrate how much each factor contributes to the final result. This matrix yields eigenvector weights (λ) and consistency ratios for every criterion assessed. The strength of the analysis is validated by calculating the consistency of the evaluations through the consistency ratio (C. R.) formula.

$$C.R = \frac{C.I}{R.I} \quad (2)$$

Where:

C.I. = Consistency index

R.I = Random Consistency Index

$$CI = \frac{\lambda_{\max} - n}{n - 1}$$

Where $\lambda_{\max}$ signifies the Maximum Eigenvalue and n represents the number of rows or columns in the comparison matrix. The evaluation's consistency is deemed sufficient if the consistency ratio (C. R.) is lower than 0. 1. If this standard is not satisfied, it is essential to reassess the evaluation to support strong decision-making. A numerical scale reflects the comparative significance of one element against another. This research utilized the rating scale created by Tikuye et al. (2025) to enable precise pairwise comparisons in the decision-making process. Table 2 presents the pairwise comparison matrix according to the Saaty scale (1 = equally important, 9 = very important).

Result and Discussion

The results of the analysis of tidal flood factors can be presented in the following presentation.

Elevation

Height is a significant factor in the occurrence of banjir rob. Banjir rob will increase as the altitude of a place decreases (Choubin et al., 2019; Mumbai, 2020).

Areas located in lowlands often experience banjir rob every rainy season. The elevation of the study area ranged from 0.10 to 1.5 meters above sea level, as seen in Figure 3.

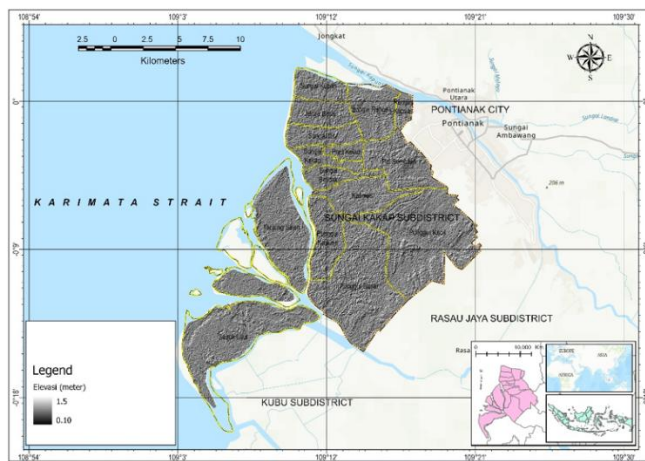


Figure 3. Elevation study area

Elevation is a major determinant of vulnerability to tidal flooding because lower-elevation coastal areas are more susceptible to inundation during high tides, storm surges, and sea-level rise. As elevation decreases, flood frequency, depth, and inundation area generally increase, making low-lying coastal zones particularly vulnerable to tidal flooding (Gesch, 2018; Liu et al., 2026).

Slope

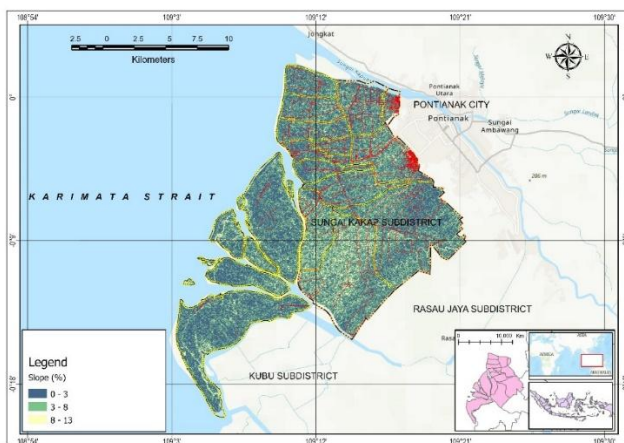


Figure 4. Slope research study

Slope is an important parameter in hydrology. Slope is a function of the ratio of straight-line runoff to surface runoff, which can cause flooding (Mumbai, 2020). In general, lowland areas have flat to gentle slopes, making them more susceptible to flooding and inundation. For flat to gentle slopes, runoff collects in one area and flows back out at different times. Therefore, slopes with low

slopes along the coast are more vulnerable than slopes with high slopes. The resulting elevation and slope show very little spatial variation. The slope of the study area ranges from 0 to 13% divided into three classes, as seen in Figure 4.

Distance from Drainage

Tidal flooding in the study area frequently occurs in coastal areas. River flow contributes to increasing the water supply flowing into the sea and can increase flood levels. Furthermore, distance from the river is important because the river flow accommodates surface runoff and carries some of the material on the water surface along the river's path to the estuary (Ramesh & Iqbal, 2022). Distance from the river plays a significant role in determining flood distribution in an area. Areas with low infiltration and percolation capacity, sparse vegetation, and high slopes generate large amounts of runoff and cause flooding disasters downstream and along the coast. The distance from the drainage in the research area was determined from 100 to more than 500 meters which was divided into five classes, as seen in Figure 5.

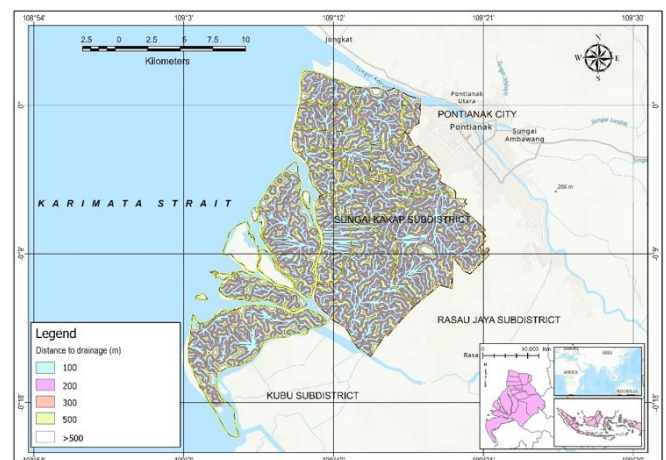


Figure 5. Distance from drainage

Distance from rivers and drainage channels significantly influences the occurrence of tidal flooding because rivers serve as inlet points for tidal water into inland areas. Locations near tidal rivers are more vulnerable to flooding due to their direct exposure to high water levels during high tides and storm surges. As distance from rivers increases, the hydraulic influence of tidal propagation decreases, resulting in decreased flood frequency and inundation depth. Therefore, distance to rivers generally shows a negative relationship with tidal flood vulnerability (Hoitink & Jay, 2016; Narendra et al., 2017; Yonehara & Kawasaki, 2020).

Rainfall

Rainfall data in the study area was used to generate an annual rainfall map. This rainfall map was created using the Inverse Distance Weighting (IDW) interpolation approach. Rainfall in the study area varies. The rainfall classification used can be seen in Figure 6.

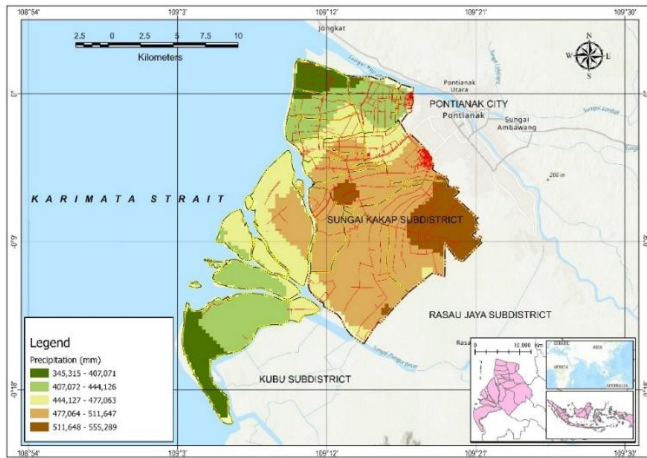


Figure 6. Rainfall

Rainfall significantly contributes to tidal flooding by increasing surface runoff and river discharge within coastal watersheds. When heavy rainfall coincides with high tidal conditions, drainage capacity is reduced as rising sea levels and rivers restrict runoff flow. This interaction results in greater flood depths, longer inundation durations, and larger inundated areas. Therefore, rainfall exhibits a positive relationship with tidal flood vulnerability, particularly in lowland coastal and deltaic environments where combined flooding processes are common (Gasa & Lasminto, 2025; Shen et al., 2019; Zhou et al., 2025).

Land Cover

Land cover influences changes in the flow system in the region (Mehr & Akdegirmen, 2021; Sugianto et al., 2022a) and infiltration capacity (Mehr & Akdegirmen, 2021). Low levels of vegetation cover will affect infiltration rates and alter the acceleration of evapotranspiration (Nahib et al., 2021). This affects the balance of water evaporation (Sugianto et al., 2022a) and water absorption and distribution through rivers (Nahib et al., 2021). Detailed studies of land cover are crucial for flood hazard mitigation. Land cover in the study area can be seen in Figure 7.

Land cover significantly influences the occurrence of tidal flooding by controlling the hydrological response of coastal landscapes. Built-up and impervious surfaces increase vulnerability to tidal flooding by limiting infiltration and increasing water accumulation, while vegetated land cover, wetlands, and mangrove

ecosystems reduce flood risk through water retention, flow damping, and coastal protection functions. Consequently, coastal areas experiencing extensive land cover conversion from natural vegetation to urban development generally exhibit higher vulnerability to tidal flooding (Andika et al., 2021; Muhammad et al., 2025; Sutrisno et al., 2020; Van Coppenolle & Temmerman, 2019).

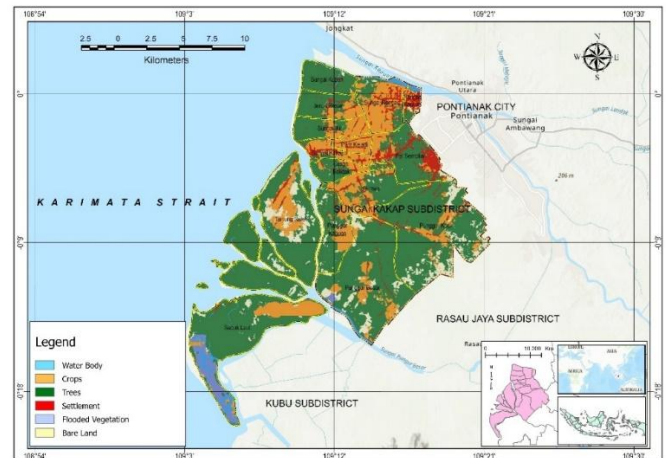


Figure 7. Land cover

TWI

The Topographic Moisture Index (TWI) significantly influences tidal flood vulnerability because it represents the spatial tendency of water accumulation controlled by topography. Areas with high TWI values are generally characterized by gentle slopes and extensive drainage areas, resulting in greater soil saturation and surface water retention (Huang, 2022). TWI analysis result values range from 2.335 to 22.759. The TWI class of the research area can be seen in Figure 8.

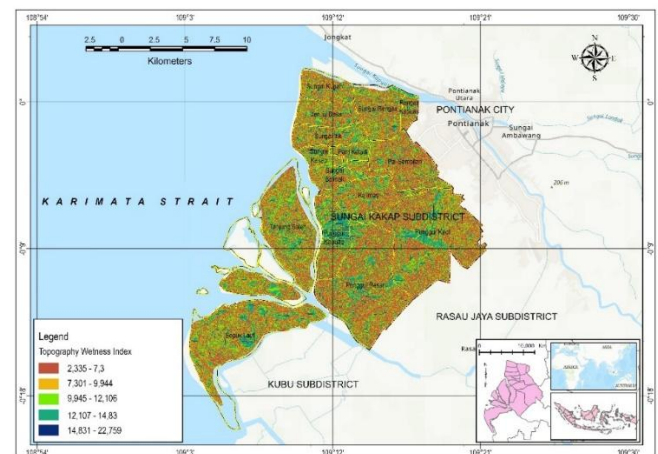


Figure 8. Topographic wetness index

In the context of tidal flooding, areas with high TWI values are generally more susceptible to inundation

because they represent topographic depressions or low-gradient zones where water naturally accumulates and flows slowly. When tidal water enters coastal areas through rivers, estuaries, or drainage channels, these locations with high TWIs tend to retain water for longer periods, resulting in greater flood depth and duration (Khoirunisa et al., 2021; Ma'rufah, 2022; Zuhdi, 2025).

Coastline Distance

Distance from the shoreline is one of the most influential factors controlling tidal flood vulnerability because the shoreline serves as the primary source of tidal intrusion. Areas located near the shoreline are directly exposed to tidal fluctuations, storm surges, and sea-level rise, making them more vulnerable to flooding. As distance from the shoreline increases, tidal energy and depth generally decrease due to topographic barriers, surface roughness, and hydraulic attenuation, resulting in lower flood vulnerability (Pratama et al., 2026). The results of the coastline distance analysis ranged from 500 to 3000 meter. The distance from the coast of the research area can be seen in Figure 9.

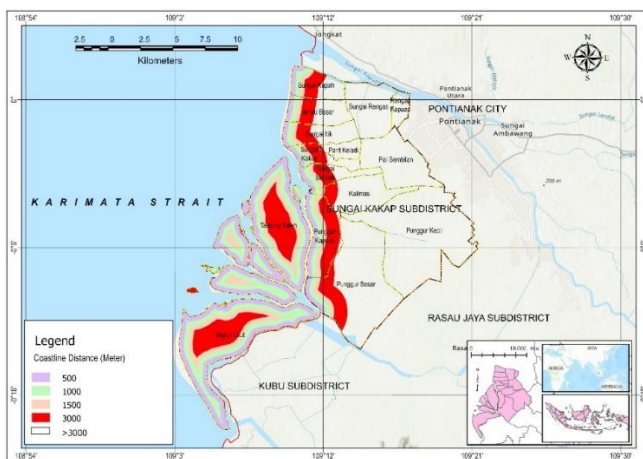


Figure 9. Coastline distance

Distance from the coastline significantly influences the occurrence of tidal flooding because the coastline is the primary entry point for tidal water. Areas located near the coast are directly exposed to tidal fluctuations and storm surges, making it easier for seawater to inundate surrounding low-lying areas. As distance from the coastline increases, tidal energy and flood potential generally decrease due to topographic and hydraulic barriers. Therefore, distance from the coastline exhibits a negative relationship with tidal flood vulnerability, with areas closest to the coastline experiencing the highest flood risk while inland areas tend to be less vulnerable (Hidayah et al., 2022; Sutrisno et al., 2020).

Soil Type

Soil type is an important factor influencing vulnerability to tidal flooding because it controls infiltration capacity, permeability, porosity, drainage efficiency, and water retention. Coastal areas with soils with low permeability, such as clay, sandy loam, and dense alluvial soils, tend to experience more severe and prolonged tidal flooding because seawater and rainwater cannot infiltrate quickly into the soil. As a result, water remains on the surface for longer periods of time, increasing the depth and duration of flooding. In contrast, sandy and coarse-textured soils generally allow for faster infiltration and drainage, thereby reducing surface inundation. Soil type of the study area can be seen in Figure 10.

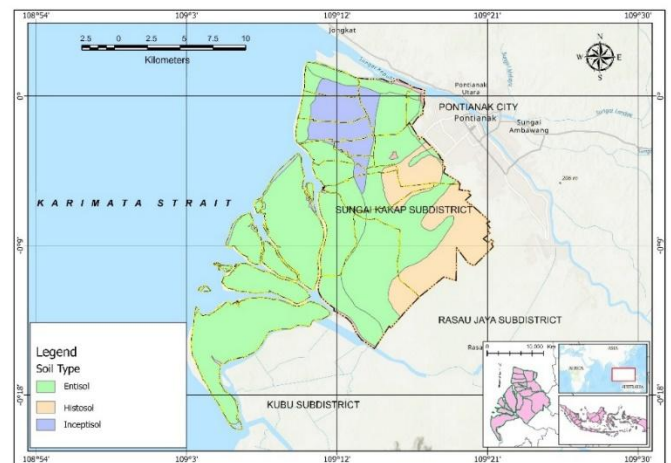


Figure 10. Soil type

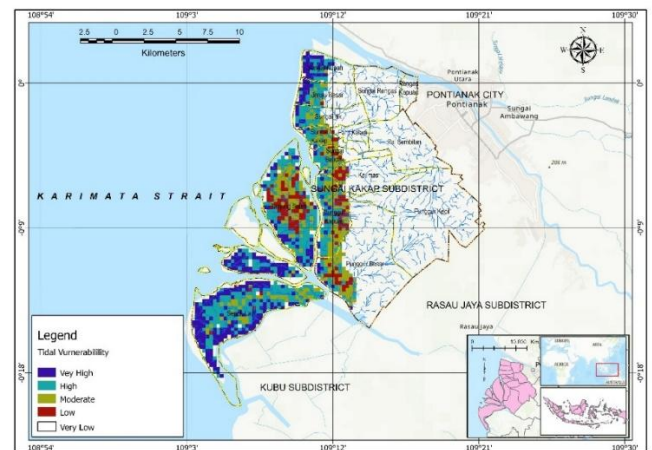


Figure 11. Tidal flood vulnerability

Soil type significantly influences the occurrence of tidal flooding because it controls the infiltration, permeability, and water storage characteristics of coastal landscapes. Fine-textured soils such as clay and sandy loam generally exhibit low permeability and slow drainage, causing tidal water to remain on the land surface for longer periods and increasing flood vulnerability. Conversely, sandy soils typically allow

greater infiltration and more efficient drainage, reducing the extent and duration of inundation. Consequently, soil type exhibits a strong relationship with tidal flood vulnerability, with poorly drained and low-permeable soils generally associated with higher flood risk (Damayanti et al., 2024; Hidayah et al., 2022; Sugianto et al., 2022b).

The analysis using Weighted overlay revealed that the study area has five classes of tidal flooding: very low, low, moderate, high, and very high. The distribution of tidal flood vulnerability levels can be seen in Figure 11.

The extent of each level of tidal flood vulnerability in the study area can be seen in Table 3.

Table 3. Level of Tidal Flood Vulnerability in the Study Area

Class	Area (ha)	%
Very High	5717	12.62
High	7919	17.47
Moderate	5515	12.17
Low	2404	5.30
Very low	23762	52.44
Sum	45317	100

The very low to very high tidal flood hazard classes are spread across coastal villages, such as Sepuk Laut, Tanjung Saleh, Punggur Kapuas, Sungai Belidak, Sungai Kakap, Sungai Itik, Sungai Besar, Sungai Kupah, and parts of Punggur Besar. The results of the study indicate that the Very Low vulnerability class dominates the study area (52.44%), which indicates that more than half of the area has favorable physical characteristics that reduce vulnerability to tidal flooding. However, approximately 30.09% of the area falls into the High and Very High vulnerability classes, which represent zones that require priority attention in coastal management and disaster mitigation.

Slope gradient is one of the most important geomorphological factors influencing flooding. Areas with gentle to nearly flat slopes are prone to water accumulation due to low surface flow velocities and often inefficient drainage. In coastal environments, flat terrain facilitates inland tidal intrusion, increasing vulnerability to tidal flooding. Conversely, steeper slopes encourage rapid surface flow and reduce water inundation. Therefore, High and Very High vulnerability zones are most likely associated with flat coastal plains (Wang et al., 2023).

Elevation significantly influences vulnerability to tidal flooding because high tides naturally inundate low-lying coastal areas first. Areas located only a few meters above mean sea level have limited gravitational resistance to seawater intrusion and are more frequently exposed to tidal flooding. Consequently, areas classified as High and Very High vulnerability are thought to

correspond to low-lying zones near the coastline, while higher inland areas tend to fall into the Low and Very Low vulnerability classes (Hidayah et al., 2022).

Distance from the shoreline directly controls exposure to tidal processes. Areas located close to the shoreline are more vulnerable because tidal waves and storm surges can easily propagate inland. Vulnerability generally decreases with distance from the shoreline due to the dissipation of tidal energy and the presence of natural or artificial barriers. Thus, areas with Very High vulnerability are likely concentrated in the coastal belt adjacent to the sea (Noor et al., 2022).

Rivers serve as tidal channels from the ocean to inland areas. Locations near tidal rivers often experience combined flooding caused by the interaction between river discharge and tidal inundation effects. Therefore, areas located close to river channels generally exhibit higher vulnerability than areas further away. The high vulnerability zones in the study area may reflect the influence of tidal rivers and estuarine systems (Wang et al., 2023).

The Topographic Moisture Index (TWI) represents a location's tendency to accumulate water based on topography. High TWI values indicate areas where water collects and remains there for longer periods. In areas prone to tidal flooding, locations with high TWIs are more vulnerable because incoming tidal water accumulates and drains slowly. Consequently, areas categorized as High and Very High vulnerability likely correspond to zones exhibiting high TWI values (Hidayah et al., 2022).

Soil characteristics influence water infiltration and retention capacity. Fine-textured soils such as clay and sandy loam generally have low permeability, causing water to remain on the surface for extended periods and increasing flood vulnerability. Conversely, sandy soils facilitate infiltration and drainage, reducing the duration of inundation. Therefore, coastal alluvial deposits and clay-rich sediments are generally associated with higher tidal flood vulnerability (Hidayah et al., 2022).

Although tidal flooding is primarily caused by astronomical tides and sea-level fluctuations, rainfall acts as an important aggravating factor. Heavy rainfall coinciding with high tides can produce combined flooding by increasing surface runoff while reducing drainage efficiency due to sea-level rise. Consequently, areas receiving higher rainfall intensity tend to exhibit increased vulnerability, especially in areas with inadequate drainage infrastructure (Sutrisno et al., 2020).

Land use significantly influences hydrological response. Urban and built-up areas characterized by impermeable surfaces reduce infiltration and increase runoff, thereby exacerbating flood impacts. Conversely, wetlands, mangrove forests, and vegetated areas increase water storage and reduce tidal energy.

Therefore, coastal settlements, industrial zones and transport corridors generally have higher levels of vulnerability, while areas covered by mangrove forests and vegetation tend to show lower vulnerability (Tomás et al., 2022).

Conclusion

The dominance of the Very Low vulnerability class (52.44%) indicates that most of the study area is characterized by relatively favorable conditions, such as higher elevation, greater distance from the coastline and rivers, lower TWI values, permeable soils, and vegetation cover. However, the presence of 13,636 ha (30.09%) in the High and Very High vulnerability classes indicates significant exposure of the lowland coastal zone to tidal inundation. The spatial pattern of tidal flood vulnerability is primarily controlled by the interaction between low elevation and flat slopes (facilitating flooding), proximity to the coastline and tidal rivers (increasing exposure), high TWI values (encouraging water accumulation), poorly drained soil types (prolonging inundation), high rainfall intensity (creating severe flooding conditions), and urbanized land use (reducing infiltration and increasing runoff). These findings are consistent with previous coastal flood vulnerability studies in Indonesia and other lowland coastal environments, which identified elevation, slope, distance to sea, distance to river, rainfall, TWI, soil type, and land use as the main conditioning factors of tidal flood vulnerability (Arita et al., 2025).

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Author Contributions

The authors in this study were all involved in implementing the research and in analyzing the data.

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Conflicts of Interest

The authors declare no conflict of interest in this research.

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