Geoid
Journal of Geodesy and Geomatics

Geoid Vol. 20, No. 2, 2025, 60-70

P-ISSN: 1858-2281; E-ISSN: 2442-3998

Simulation of Tidal Inundation along the Northern Coast of Central Java (Pantura) Using GIS-Based Analysis

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Received: 01 August 2025; Revised: 08 September 2025; Accepted: 09 September 2025; Published: 06 October 2025

Abstract: The northern coast of Java Island (locally known as Pantura) is a strategically important area, particularly in the distribution sector. However, its topographical characteristics and proximity to the Java Sea make it vulnerable to the threat of tidal inundation. Moreover, environmental factors such as sea level rise, land subsidence, and coastal abrasion further exacerbate its susceptibility to flooding. The phenomenon of tidal inundation, locally referred to as rob, occurs when seawater overflows onto low-lying coastal areas during high tides. The rob phenomenon significantly impacts the socio-economic conditions of coastal communities, disrupting daily activities and damaging critical infrastructure. This study simulates potential inundation using a uniform Highest High Water Level (HHWL) scenario of 1.2 meters to estimate flood depth and spatial extent. The modeling approach applies a consistent water surface elevation across the study area, without considering storm surge and hydrodynamics, resulting in generalized inundation patterns. The methodology follows the Technical Guidelines for Disaster Risk Assessment issued by Indonesia's National Disaster Management Agency (BNPB) and integrates various spatial datasets, including land cover data from Sentinel Land Cover by ESRI, topographic data from the Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (DEM), and maximum tidal height data processed using the Admiralty method. The analysis shows that, assuming a Highest High Water Level of 1.2 meters, Kendal Regency, Brebes Regency, and Semarang City are the most affected areas in terms of both flood depth and extent. The inundated areas are estimated at 3,744.91 hectares in Kendal Regency, 2,880.58 hectares in Brebes Regency, and 513.17 hectares in Semarang City. This situation could become more severe in the event of storm surge, extreme weather, or climate anomalies if timely and effective mitigation measures are not implemented. These findings are expected to provide a strong foundation for policymakers to formulate targeted, data-driven, and sustainable mitigation strategies to protect communities and infrastructure along Java's northern coastal region.

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Keywords : Tidal inundation ; Sea Level Rise ; Pantura

How to cite: Robbani, H. W., Kartikasari, A. N. I., Pranantya, V., & Kaffa, N. S. (2025). Simulation of Tidal Inundation along the Northern Coast of Central Java (Pantura) Using GIS-Based Analysis. *Geoid, 20*(2), 60-70.

Introduction

The northern coast of Java (commonly referred to as Pantura) is one of the most critical regions in Indonesia due to its dense population, intensive economic activities, and strategic role as a transportation corridor. Major cities along this coast such as Semarang (Irawan et al., 2021; Setiyono et al., 2023), Pekalongan (Maharlika et al., 2020), and Brebes (Purnomo et al., 2023) are situated on low-lying topographical areas that are directly adjacent to the Java Sea. This geographical setting makes Pantura highly vulnerable to tidal inundation, locally known as *rob*. Tidal inundation in this region primarily occurs during periods of high tide, storm surge, or a combination of both, when seawater overtops or seeps through the coastal.

In recent decades, the frequency, intensity, and spatial extent of inundation have shown a progressive increase(Andreas, Usriyah, et al., 2017), indicating that the problem is not only persistent but also escalating. Several interrelated factors contribute to this worsening condition. Firstly, land subsidence caused by excessive groundwater extraction (Erban et al., 2014), particularly in urban and industrial zones, has significantly lowered ground elevation, thereby amplifying the exposure of coastal settlements to tidal flooding (Andreas, Abidin, et al., 2017; Hamlington et al., 2024; Sidiq et al., 2023). Secondly, sea-level rise, driven by global climate change, exacerbates the pressure on coastal ecosystems and infrastructure (Griggs & Reguero, 2021; Intergovernmental Panel on Climate Change (IPCC), 2023; Nicholls et al., 2021; Vitousek et al., 2017). Thirdly, the degradation of natural coastal buffers (Widada et al., 2022) such as mangrove forests has further diminished the region's natural resilience to tidal and storm-induced flooding.

The occurrence of tidal inundation in Pantura has evolved from a seasonal hazard into a chronic socio-economic and environmental crisis. These impacts including infrastructure damage (Hakim et al., 2022), decreasing of economic productivity particularly in agriculture and fisheries (Mehvar et al., 2018; Muktiali et al., 2023; Nirwansyah & Suwarsito, 2020), and increased risk of waterborne disease due to prolonged inundation(de Man et al., 2014). Understanding the spatial-temporal dynamics of rob flooding in Pantura is essential for effective risk assessment and climate adaptation planning. Hence, comprehensive and integrated hazard modelingis crucial for simulating future scenarios and guiding evidence-based mitigation strategies.

In Indonesian disaster management framework, the National Disaster Management Agency (BNPB) developed Disaster Risk Assesment (Kajian Resiko Bencana, KRB), which is typically applied to simulate potential hazard of tsunami. However, this approach can be further developed to simulate tidal inundation due to tidal activity, especially by adjusting oceanographic and topographic parameters (BNPB, 2018). This study use the Highest High Water Level (HHWL) scenario as an extreme case projection to estimate depth and extent of coastal inunation based on maximum tidal data. This study used Digital Elevation Model from SRTM to obtain contour and elevation of the study area. Land cover from Sentinel Land Cover also used to obtain roughness index to determining direction of tidal water flow on land. These two parameters influence inundation spread, thereby enchancing the accuracy of tidal inundation.

Methodology

Study Area

Study area is located along the northern coastal region of Central Java Province, Indonesia, commonly referred to as Pantura (Pantai Utara). This region encompasses several key coastal districts and cities that are geographically situated adjacent to the Java Sea, including Semarang City, Pekalongan City, Tegal City, and the regencies of Brebes, Kendal, Batang, and Demak. That characterized by its low-lying topoghraphy and has close proximity to the Java Sea, with elevations often less than 2 meters above sea level, making them highly vulnerable to coastal hazards mainly tidal inundation (rob) (Widada et al., 2020)

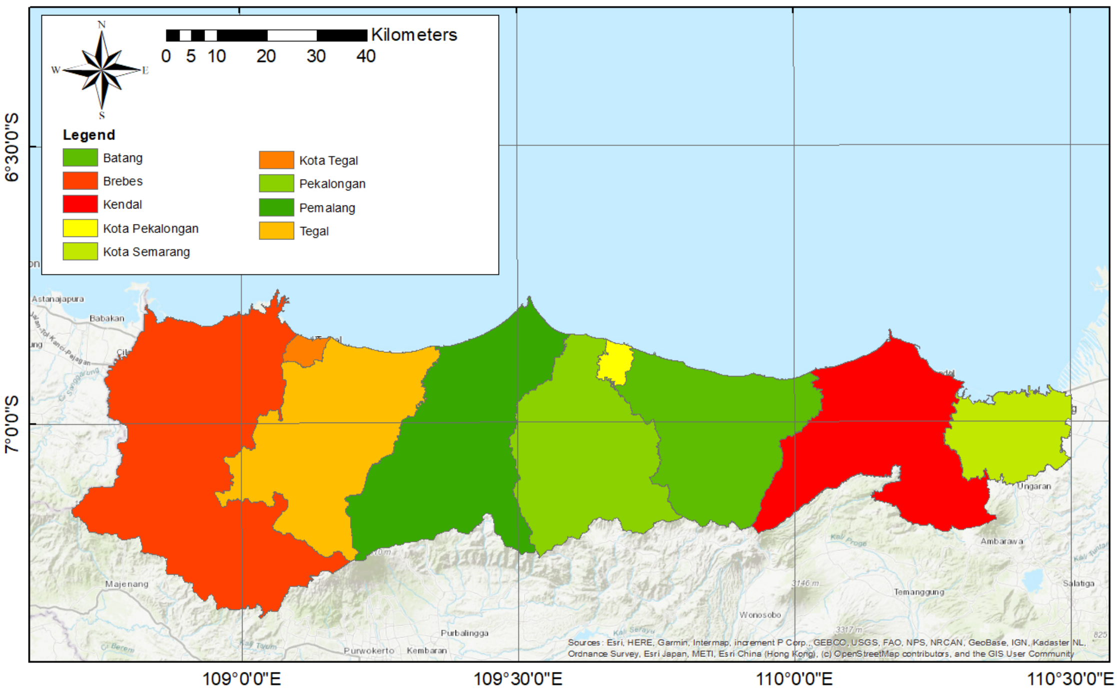

Figure 1. Study Location

Data

This study integrates Sentinel Land Cover data developed by ESRI with Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (DEM) with a 30-meter spatial resolution. Land cover data is used to classify surface type and calculate surface roughness coefficient, while teh DEM provides elevation and slope information that influences flow direction and spatial distribution of inundation. The inundation simulation is conducted using extreme tidal scenario represented by Highest High Water Level (HHWL). HHWL values derived from multiple point along Pantura, sourced from Indonesian Geospatial Reference System (SRGI) by Geospatial Information Agency (BIG). Data processing flowchart shown on Figure 2 derived from hazard index formulation in disaster risk assessment by BNPB which refers to the formula proposed by Berryman (Berryman, 2006)

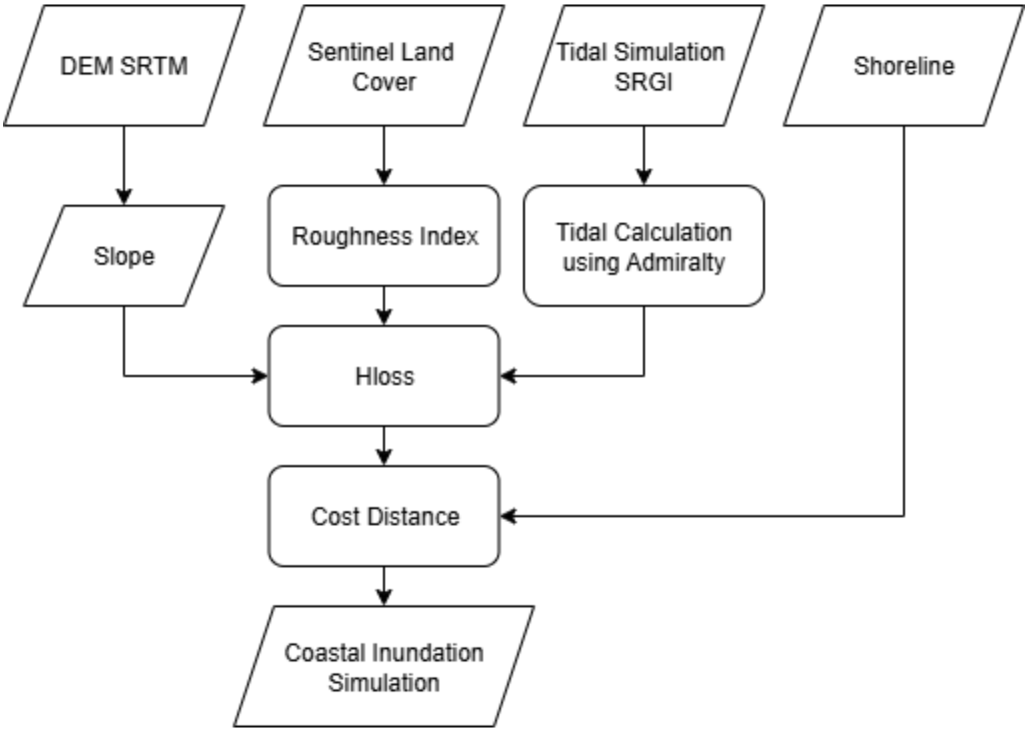

Figure 2. Data Processing Chart

Roughness Index

Roughness index or roughness coefficient (n) is a parameter to represent level of resistance or friction that a surface exerts against wave propagation, as observed during rob flooding or tidal inundation. This value reflects how rough land surface which significantly influences the dissipation of energy and wave propagation speed. In this study, this parameter is derived from the land cover classification of the Sentinel Land Cover 2024 by ESRI, and its roughness index was determined based on Table 1. (Berryman, 2005)

Table 1. Roughness Indeks (Berryman, 2005)

Land Cover	Roughness Index
Water Body	0.007
Rangeland	0.015
Built Area	0.080
Trees	0.070
Crops	0.020

Tide Prediction

The calculation of tidal height predictions and the classification of tidal types—whether diurnal or semi-diurnal—is conducted by processing tidal forecast data provided by the Geospatial Information Agency (BIG) through the Indonesian Geospatial Reference System (SRGI-BIG) platform. This data offers daily and hourly information on tidal parameters. In this study, observation points for tides are strategically selected along the study area to represent the spatial variation of hydrodynamic conditions. The tidal prediction is carried out using the Admiralty Method, a semi-graphical and harmonically based approach designed to estimate sea level heights at hourly intervals with sufficient accuracy (Glen, 2015).

Figure 3. Tidal Observation Point

In this study, the determination of the Highest High Water Level (HHWL) was based on tidal prediction data rather than direct tidal observations. The tidal predictions were obtained BIG (Geospatial Information Agency) at 2 observation point served in Figure 3. The prediction dataset covers the period of 27 days with a hourly temporal resolution. Tidal predictions are generated by applying harmonic analysis, which decomposes tidal motion into a series of astronomical constituents (such as M2, S2, K1, and O1) derived from long-term tide gauge records and global tidal models. This approach provides consistent and continuous estimates of tidal elevation, even in the absence of direct measurements.

To determine the HHWL, all predicted high-water levels within the dataset were extracted and analyzed. The maximum predicted tidal elevation within the chosen period was then identified as the HHWL. Unlike simple tidal range values, the HHWL represents the theoretical extreme condition of tidal elevation, incorporating both diurnal and semidiurnal tidal constituents as well as long-period astronomical cycles. This ensures that the HHWL value reflects the highest possible tidal height expected at the site under purely astronomical forcing.

Although tidal predictions do not account for meteorological effects such as wind setup or storm surge, they provide a robust baseline for assessing extreme tidal conditions. The HHWL obtained from tidal prediction therefore serves as a critical parameter in tidal inundation modeling, particularly when observed tidal records are unavailable or incomplete.

Tidal inundation Simulation

This study employs spatial approach to simulate tidal inundation by extreme tidal event by integrating topographic, land cover, and tidal data to calculate wave height loss per meter of inland inundation (Hloss). The calculation using mathematical model of inundation developed by Berryman (Berryman, 2005) :

$$H_{loss} = \left(\frac{167 \, . n^2}{H_0^{\frac{1}{3}}}\right) + 5 \, . \sin\,(S) \tag{1}$$

Where :

H_{loss} = height loss per meter of inland inundation
n = roughness index
H_0 = extreme tidal height
S = slope

In tidal inundation simulation, the variable Hloss represents the reduction in energy or sea surface height as tidal water moves from the shoreline toward inland areas. This concept is critical for realistically modeling the propagation of tidal flooding, particularly in the context of disaster risk mitigation and flood-prone area mapping. Hloss is calculated by integrating several physical factors: land slope derived from Digital Elevation Model (DEM SRTM) data, surface roughness index obtained from land cover classification using Sentinel imagery, and tidal height predicted through harmonic analysis using the Admiralty Method based on tidal forecast data from SRGI-BIG. Each of these components influences the extent to which tidal energy is dissipated as it travels inland. Surfaces with higher roughness or steeper slopes generate greater resistance to water movement, resulting in higher Hloss values. These values are then used in cost distance analysis to determine the inland reach of tidal inundation. Thus, incorporating Hloss into tidal inundation modeling enables more accurate spatial representation of flood spread and serves as a critical element in GIS-based modeling and coastal vulnerability assessment in response to climate change and sea level rise threats.

The inundation model in this study adopts a simplified representation of water level based on the Highest High Water Level (HHWL) obtained from tidal data processing. In this paradigm, the water surface elevation is applied uniformly across the study area, providing a benchmark for assessing the maximum potential extent of tidal inundation under astronomical forcing. This approach is frequently used in preliminary risk assessments because it offers a straightforward method to estimate coastal flood exposure with relatively limited data and computational requirements.

Nevertheless, this modeling strategy is subject to important limitations. First, it does not incorporate storm surge contributions, which can substantially elevate sea levels beyond the tidal component during extreme meteorological events. Second, it assumes no spatial variation in water level, even though actual inundation depths are influenced by local conditions such as topography, land subsidence, and coastal morphology. Third, the model excludes hydrodynamic processes, meaning that critical factors such as flow direction, current velocity, and interactions with drainage systems are not represented.

For these reasons, the inundation maps generated from this approach should be interpreted as a baseline or worst-case tidal flooding scenario, rather than an exact replication of real-world conditions. While the actual depth and distribution of inundation may vary considerably in practice, the simplified model remains valuable as a first-order tool for visualizing potential risks, informing spatial planning, and identifying priority areas for more detailed hydrodynamic modeling.

Results and Discussion

Tidal Calculation

Tidal data were collected from two observation point as shown on Figure 3 along the northen coast over a 29-day period, from May 1 to May 29, 2025. The observation were further analyzed using Admiralty method.

Table 2. The comparison of tidal datum on Obsevation A and Observation B

Tidal Datum	Observation A (m)	Observation B (m)
HHWL (Highest High Water Level)	1.0	1.2
MHWL (Mean High Water Level)	0.8	0.9
MSL (Mean Sea Level)	0.0	0.0
MLWL (Mean Low Water Level)	-0.1	-0.1
LLWL (Lowest Low Water Level)	-0.3	-0.5

The tidal datum derived from calculations at both observation points, as shown in Table 2, indicates that the Highest High Water Level (HHWL) was recorded at 1.0 meters at Point A and 1.2 meters at Point B. These values represent the historical maximum sea level elevations and are used as input for inundation simulations. The variation in water levels is influenced by differences in local oceanographic and morphological conditions.

In this study, a value of 1.2 meters—obtained from observations at Point B—is used for the simulation. This value is selected as a modeling parameter to simulate an extreme scenario of potential tidal inundation in the northern coastal waters of Java. The aim is to ensure that the simulation results are relevant for vulnerability assessment and can be further utilized as a basis for decision-making and coastal mitigation planning

Tidal inundation along Java's North Coast (Pantura)

The simulation was conducted by integrating slope data derived from the SRTM DEM, roughness index derived from land cover, and the assumed highest high water level (HHWL) obtained from tidal prediction processing by SRGI BIG using the 29-cycle Admiralty Method

As shown in Figure 3, the slope derived from the DEM indicates that the northern coastal region of Pantura, which directly borders the Java Sea, exhibits a relatively flat topography. This flat slope is observed across almost the entire study area, except for the southernmost region. The flatness of the terrain facilitates the inland intrusion of inundation, as there is minimal topographic resistance to hinder the flow of water.

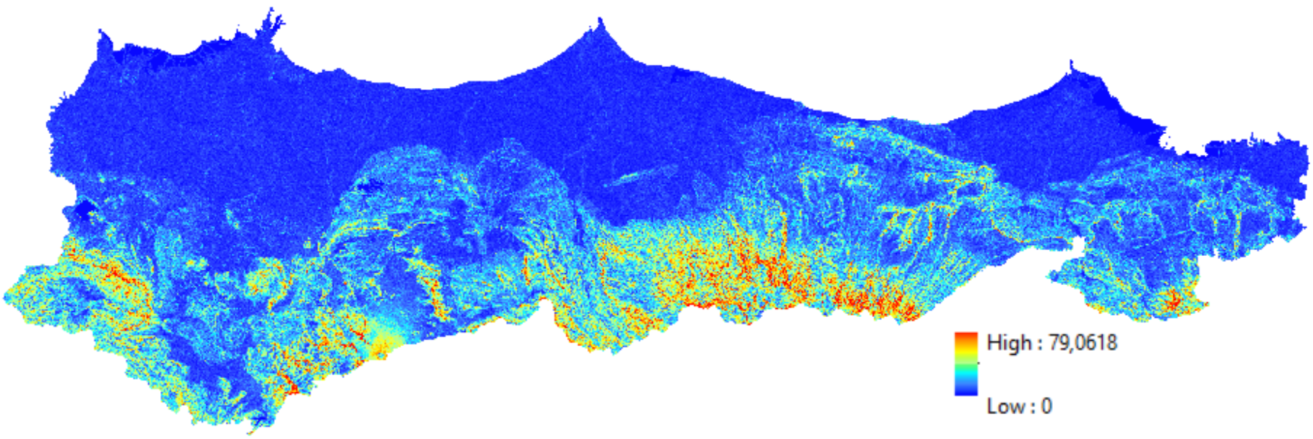

Figure 3. Slope Map of Pantura Districts

Another factor considered is land cover (Figure 4), which is translated into a roughness index. The rougher the surface of the land cover, the more it can impede and influence the dissipation of energy and the speed of wave propagation. The highest roughness coefficient is observed in built-up areas ($n = 0.08$), which dominate the coastal zones in nearly all regencies and municipalities within the Pantura region. Although these built-up areas can somewhat hinder the progression of inundation, the high population density in these affected zones results in substantial losses, both materially and non-materially.

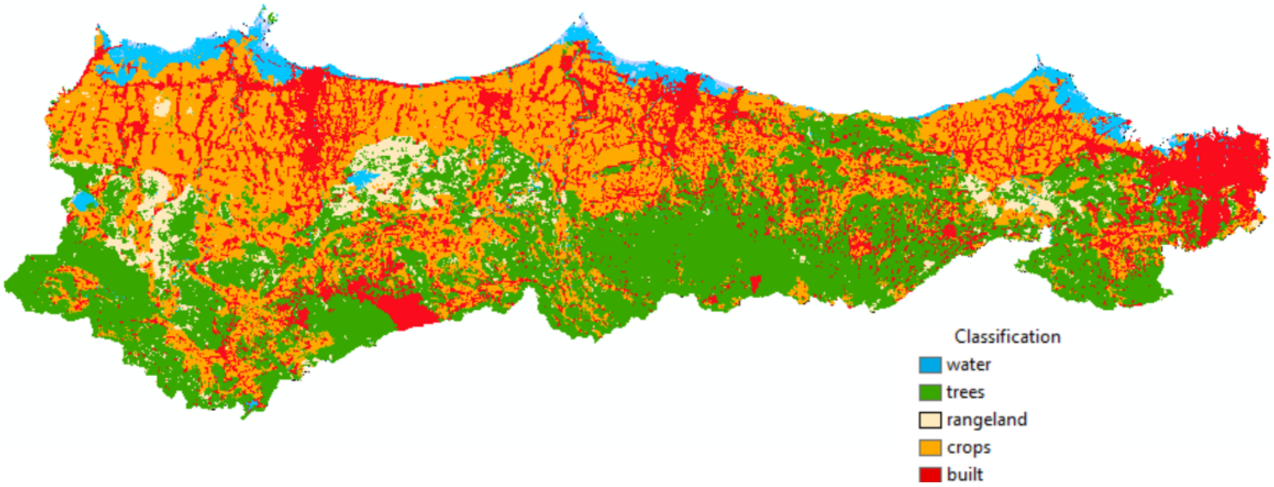

Figure 4. Land Use Land Cover (LULC) of Pantura Districts

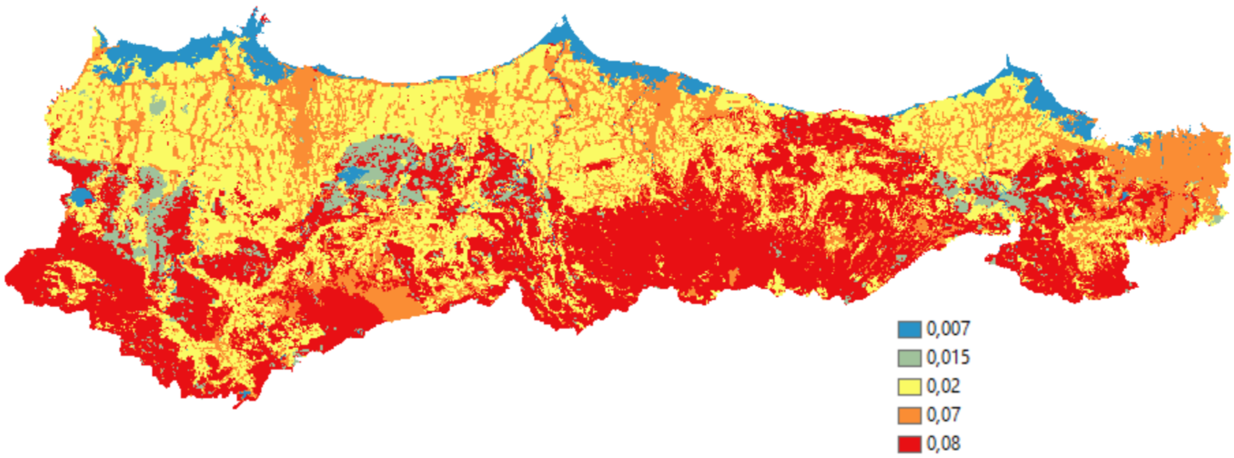

Figure 5. Roughness Index

The inundation simulation was conducted using the wave energy loss (Hloss) approach proposed by Berryman, as illustrated in Formula 1. This approach accounts for energy dissipation resulting from elevation differences (slope) as well as resistance from land cover characteristics. To carry out the simulation, an initial wave height parameter is required, which in this case is assumed based on the *Highest High Water Level* (HHWL), representing the maximum tidal elevation. Using this assumption, the potential spatial extent of inundation within the study area can be determined. Based on the results of the inundation simulation, using the assumption of a highest tidal level of 1.2 meters, several cities along the northern coast of Java (Pantura) experienced extensive tidal inundation. This spatial simulationhighlight three critical zone, particularly in Brebes Regency (Figure 1), Kendal Regency (Figure 2), and Semarang City(Figure 3) which show significant inundation both in extent and depth.

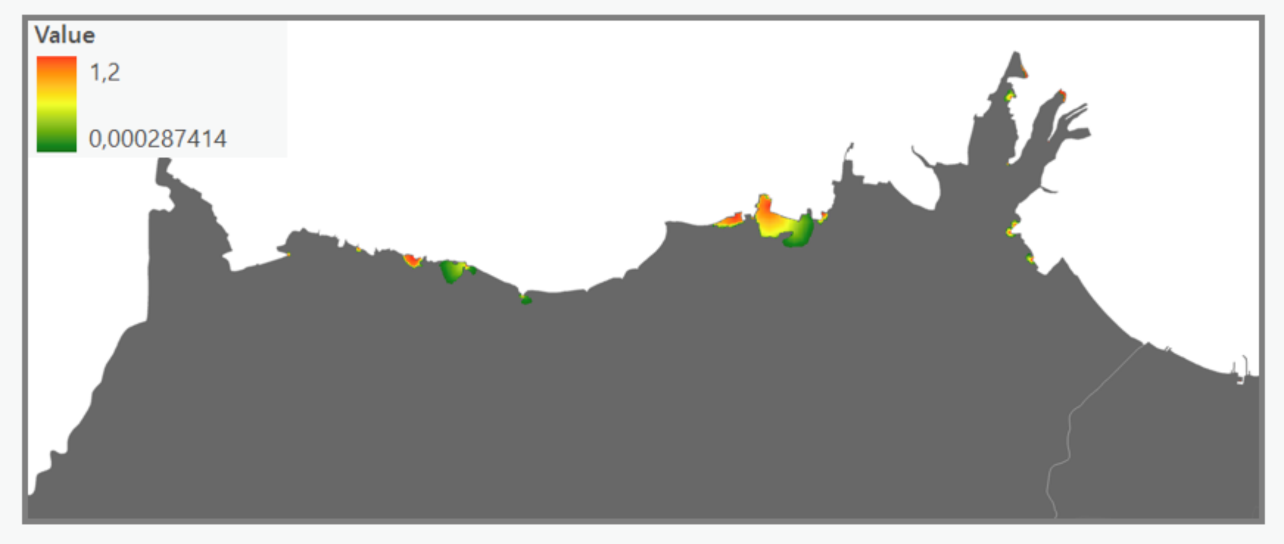

Figure 6. Brebes Inundated Area

The simulation in Brebes shows concentrated inundation in low-lying coastal zones, particularly near the estuarine and fishpond (tambak) areas. The flood extent appears limited in inland reach but covers critical agricultural and aquaculture zones. Elevation and gentle slope contribute to moderate water penetration. The deepest areas are shown in blue to magenta, indicating inundation depths close to 1.2 meters.

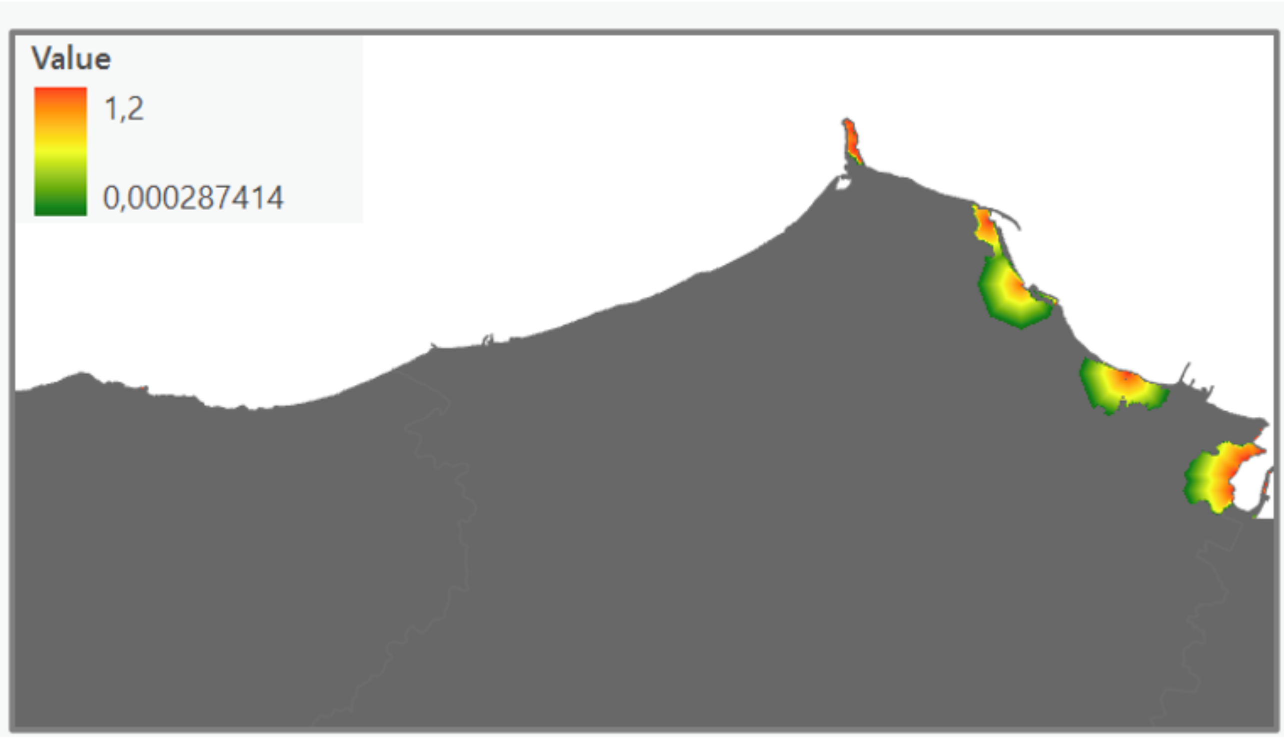

Figure 7. Kendal Inundated Area

In Kendal, inundation is distributed along river mouths and flat coastal plains. Several residential and agricultural areas are exposed, with floodwater extending inland in a fan-like pattern. The flood gradient suggests a gradual decrease in depth from the shoreline, influenced by surface roughness and elevation derived from DEM data.

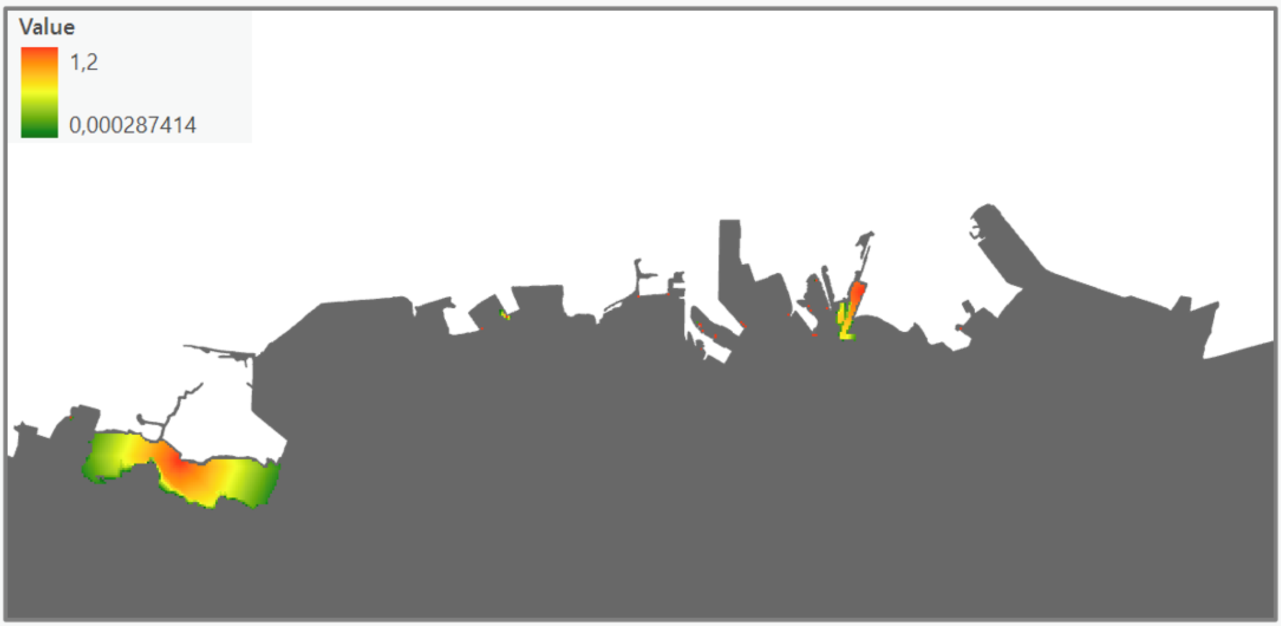

Figure 8. Semarang City Inundated Area

While Semarang displays a complex inundation pattern due to its combination of urban development, river systems, and coastal topography. The most severe flooding appears in the northern coastal subdistricts such as Genuk and Tugu. Inundation reaches densely populated neighborhoods, indicating a high-risk scenario under extreme tide conditions. The flood depth reaches its peak along the harbor and industrial coastal strip. The extent of the inundated area in Pantura is summarized in Table 3.

Table 3. Inundation-affected Area per Districts

Administrative Area	Inundation-affected Area (ha)
Tegal Regency	0
Pemalang Regency	15.46
Pekalongan Regency	17.15
Tegal City	0.98
Semarang City	513.17
Pekalongan City	0.31
Kendal Regency	3,744.91
Brebes Regency	2,880.58
Batang Regency	6.45

However, as can be seen from the inundation results in Figures 6, Figure 7, and Figure 8, the inundation pattern appears circular rather than closely following the natural topographic contours of the coastal landscape due to the limitations of the study. This effect arises from the simplified modeling approach, in which a uniform water surface elevation (based on the HHWL from tidal processing) was applied across the study area. In reality, the extent and shape of tidal flooding are controlled by local topography, drainage patterns, land subsidence, and coastal geomorphology, which create irregular, contour-following inundation zones. However, in this simplified framework, such spatial variability is not captured. The absence of hydrodynamic simulation means that processes such as water flow direction, accumulation in depressions, and amplification in low-lying channels are not represented. Thus, the circular inundation shape should not be interpreted as a literal prediction of flood geometry. Instead, it represents the theoretical maximum inland extent under a static water level scenario.

Conclusions

Based on the results of a study on tidal inundation simulations, assuming the sea surface height corresponds to the Highest High Water Level (HHWL) of 1.2 meters along the northern coast of Java (Pantura), nearly all districts directly bordering the Java Sea are affected by inundation. The area with the most severe inundation is Kendal Regency, with an inundated area of 3,744.91 hectares, followed by Brebes Regency and Semarang City. Other regions along the Pantura coast are also impacted, although to a lesser extent compared to these three areas.

It is important to emphasize that this model adopts a simplified representation of inundation, where a uniform water surface elevation based on tidal processing is applied across the study area. Consequently, the simulation does not account for storm surge effects, spatial variation in water level, or hydrodynamic processes such as water flow direction, current velocity, and drainage interactions. This simplification can also cause the inundation patterns to appear circular or concentric, rather than following the natural topographic contours of the coastal area. In reality, tidal flooding is strongly influenced by local topography, land subsidence, and coastal geomorphology, which create irregular, contour-following inundation zones.

Therefore, the inundation maps generated in this study should be interpreted as a baseline or worst-case scenario under tidal forcing, not as an exact depiction of real-world conditions. Nevertheless, the findings highlight the vulnerability of Pantura's coastal districts, where any additional contribution from storm surge or extreme weather would significantly worsen the impacts. These results underscore the urgency for policymakers and local governments to integrate adaptation measures, spatial planning, and future hydrodynamic modeling with high-resolution topographic data in order to reduce the risk of economic, social, and environmental losses caused by tidal flooding.

Acknowledgment

The author would like to express sincere gratitude to fellow colleagues from the Civil Engineering Department of the University of Jember (UNEJ) for their valuable assistance and support throughout this research. Their contributions in data collection and technical discussions were instrumental in the successful completion of this study. The collaborative spirit and dedication shown during this research process are deeply appreciated.

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