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Coastal Vulnerability Assessment Using CVI in Kedung and Tahunan

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ABSTRACT

Coastal areas are increasingly exposed to environmental pressures, such as erosion, shoreline change, and sea-level rise, which threaten the sustainability of coastal systems and human activities. This study aimed to assess coastal vulnerability in the Kedung and Tahunan subdistricts using the coastal vulnerability index (CVI). The analysis integrated physical and socioeconomic parameters, including shoreline change, geomorphology, wave conditions, sea-level rise, tidal range, coastal slope, land use, population density, sex ratio, age structure, and poverty rate. Data were obtained from field surveys, secondary sources, and Landsat 8 imagery and processed using geographic information systems (GIS) and the digital shoreline analysis system (DSAS). The results showed clear spatial variations in vulnerability at the village level. Panggung exhibited the highest CVI value (25.5), indicating high vulnerability, whereas Kedungmalang (6.81), Bulakbaru (5.11), Semat (6.14), and Telukawur (6.14) fell into the moderate category. Kalianyar (4.09), Surodadi (3.06), Tanggultlare (0.68), and Tegalsambi (3.07) showed lower vulnerability levels. These differences were influenced by the interaction between physical coastal conditions and socioeconomic characteristics, particularly population density, demographic structure, and poverty levels. The findings demonstrate that the CVI approach provides a comprehensive representation of coastal vulnerability and offers a useful basis for spatially informed coastal management and risk reduction strategies.

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1. INTRODUCTION

Coastal regions represent highly dynamic environments in which terrestrial and marine processes interact intensively. These areas are directly influenced by sea-level variations, tidal processes, and broader oceanographic dynamics, including those operating across the continental shelf (Rachman & Arifki, 2023). In addition, coastal zones are increasingly exposed to climate-related pressures, such as changing wind regimes, shifts in ocean circulation, shoreline instability, and sea-level rise (Sanjoto et al., 2016). These interacting pressures render coastal systems particularly vulnerable, especially in areas with high human activity and development intensity.

The coastal zone of Jepara Regency is highly exposed to marine processes and shoreline instability. The coastline extends approximately 77.962 km facing north and northwest, and is strongly influenced by ocean dynamics, such as waves, tides, and sediment transport (Nugroho et al., 2019). Along the western coast of Jepara, shoreline dynamics are shaped by the interaction of wave energy, tidal forcing, longshore and cross-shore currents, and anthropogenic pressure. These combined processes have contributed to severe coastal abrasion, particularly in the Kedung and Tahunan subdistricts. Shoreline changes occur through sediment movement along and across the littoral zone and are controlled by topography, geological characteristics, waves, tides, and wind (Darmiati et al., 2020).

Coastal abrasion in Jepara has caused significant environmental and socioeconomic impacts. Erosion has damaged houses, fishponds, roads, tourist facilities, and fish auction sites, while also reducing the productive land area. Mangrove conversion and unstructured coastal development have intensified these pressures along with the natural dynamics of the Java Sea. It is estimated that 938 ha of land has been lost in Jepara Regency, with approximately 460 ha located in Kedung and Tahunan subdistricts, and abrasion rates reaching 30–50 m per year (Nugroho et al., 2019). These conditions have affected the livelihoods of fishers, fish farmers, and farmers who depend on coastal resources. Historically, the Kedung coastline has shifted by approximately 2 km since the 1970s, forcing relocation in 1980, including Tanggultlare and Bulakbaru villages, with Bulakbaru being relocated twice in 1980 and 1983 (Ismiyanti & Buchori, 2021). In Tahunan Subdistrict, coastal development continues to increase, particularly in tourism areas such as Teluk Awur, Semat, and Tegalsambi (Deviana et al., 2019; Safira et al., 2022).

Existing approaches to coastal management have not fully addressed the complexity of coastal vulnerability. Most interventions tend to focus on visible impacts, such as erosion control or infrastructure damage, while the interaction between physical exposure and socioeconomic sensitivity is less systematically evaluated. This limitation is critical because vulnerability is shaped not only by environmental conditions but also by social and economic characteristics that influence how communities respond to coastal hazards.

The coastal vulnerability index (CVI) offers a structured framework for assessing coastal vulnerability by integrating multiple indicators. Within this framework, vulnerability is understood as a spatial condition reflecting the degree of exposure and sensitivity of coastal systems to hazards, such as erosion, coastal storms, flooding, and sea-level rise (Bevacqua, 2018). In its application, the CVI typically incorporates parameters such as geomorphology, elevation, sea-level rise, shoreline change, wave conditions, tides, and land use. However, many CVI-based studies remain dominated by physical indicators, and the integration of socioeconomic variables at the local scale is still limited or insufficiently explained.

A more integrated approach is required to capture spatial variations in coastal vulnerability at the local level. This need is particularly evident in Kedung and Tahunan, where severe shoreline change occurs alongside variations in settlement patterns, demographic structure, poverty levels, and land use pressure. In such contexts, vulnerability cannot be adequately interpreted using physical parameters alone. Therefore, this study contributes by integrating physical coastal parameters and village-level socioeconomic indicators within a CVI-based spatial assessment in Kedung and Tahunan, Jepara.

This study assessed coastal vulnerability in the Kedung and Tahunan subdistricts using the coastal vulnerability index (CVI). Specifically, it identified the physical and socioeconomic factors associated with spatial variations in coastal vulnerability and evaluated the degree of exposure of coastal areas to abrasion, shoreline change, and sea-level rise based on CVI results. The analysis focused on vulnerability as the primary outcome, and the implications for community adaptation were cautiously discussed without directly measuring resilience.

2. METHOD

This study was conducted through four main stages: literature review and problem identification, data collection, parameter processing, and integrated coastal vulnerability analysis. The literature review and issue identification served as the basis for determining the coastal vulnerability parameters. Data collection involved both primary and secondary sources obtained from government agencies, scientific publications, field surveys, remote sensing data, and supporting documentation.

The data were then prepared and processed based on parameter groups. Coastal physical parameters were analyzed using 30 m Landsat imagery, the Digital Shoreline Analysis System (DSAS), ArcGIS 10.8, and Microsoft Excel to identify shoreline change, coastal geomorphology, coastal slope, wave conditions, tidal range, sea-level rise, and land use. Socio-economic parameters were analyzed using Microsoft Excel and ArcGIS 10.8 to assess population density, sex ratio, vulnerable age ratio, and poverty rate.

All parameters were subsequently analyzed in an integrated manner using scoring and vulnerability classification. The overlay process among the parameter layers produced a coastal vulnerability map, which served as the basis for the analysis and discussion of the results. The overall workflow of this study, from data collection to analysis and interpretation, is presented in Figure 1.

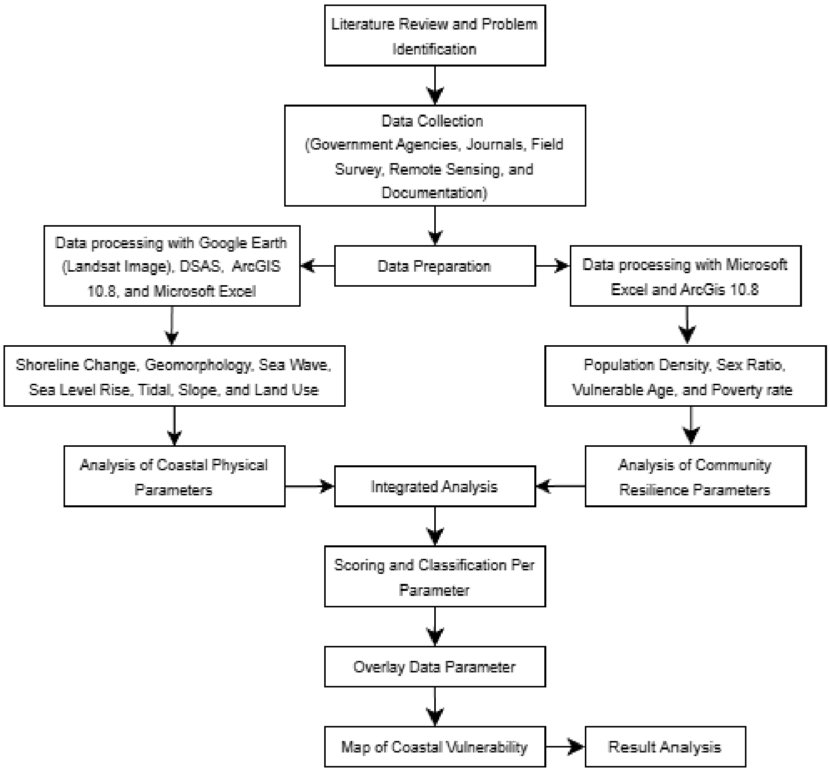

Figure 1. Flowchart of Data Processing

2.1. Coastal Vulnerability Indeks

Coastal vulnerability refers to the reduced ability to cope with external pressures that threaten human life, livelihoods, natural resources, infrastructure, and human well-being. When the relationship between hazards and vulnerability is not properly managed, it can generate substantial risks (Dhiauddin et al., 2017; Batzakis et al., 2024).

To evaluate coastal vulnerability, this study used the coastal vulnerability index (CVI), which integrates indicators representing both the physical environment and socioeconomic conditions of coastal communities. The physical parameters describe the exposure of coastal areas to geomorphological and oceanographic processes, including shoreline change, coastal landforms, wave conditions, sea-level rise, tidal range, coastal slope, and land use. Generally, shoreline erosion, unconsolidated coastal landforms, gentle coastal slopes, and intensive built-up land use are associated with higher vulnerability.

Socio-economic parameters were included to represent population pressure and social vulnerability. Areas with higher population density, demographic imbalance, and a higher vulnerable age ratio tend to experience greater socio-economic pressure because of increased exposure and more limited adaptive resources. All parameters were standardized and combined to produce the CVI, which was then classified into four categories: not vulnerable, moderate, vulnerable, and highly vulnerable.

The analysis incorporated 11 parameters, consisting of seven physical and four socioeconomic parameters. The CVI was calculated using the following formula:

$$CVI = \sqrt{\frac{AxBxCxDxExFxGxHxIxJxK}{11}} \quad (1)$$

where A = shoreline change, B = coastal geomorphology, C = wave height, D = sea level rise, E = tidal range, F = coastal slope, G = land use, H = population density, I = sex ratio, J = vulnerable age ratio, and K = poverty rate.

All parameters were classified into five ordinal scores, ranging from 1 (very low vulnerability) to 5 (very high vulnerability). The classification of each parameter is listed in Table 1.

Table 1. Classification of CVI Parameters

Parameter	Very Low (1)	Low (2)	Moderate (3)	High (4)	Very High (5)
Shoreline Change (m)	> 2.0	1.0–2.0	-1.0 to 1.0	-2.0 to -1.0	< -2.0
Geomorphology	High cliff	Medium cliff	Low cliff/ plain	Estuary /lagoon	Sandy/ mudflat/ mangrove
Wave Height (m)	< 0.5	0.5–1.0	1.0–1.5	1.5–2.0	> 2.0
Sea-Level Rise (mm)	< 1.8	1.8–2.5	(verify)	3.0–3.4	> 3.4
Tidal Range (m)	< 0.5	0.5–1.0	1.0–1.5	1.5–2.0	> 2.0
Coastal Slope (%)	> 45	25–45	15–25	8–15	< 8
Land Use	Natural	Semi-natural	Aquaculture/ agriculture	Infrastructure	Built-up/ industrial
Population Density (people/km²)	< 500	500–667	667–833	833–1000	> 1000
Sex Ratio (%)	95–100	106–110	111–115	116–120	> 120
Vulnerable Age (%)	< 20	20–30	30–40	40–50	> 50
Poverty (%)	< 10	10–15	15–20	20–25	> 25

Sources: (Hammar-Klose et al., 2003; Dwi et al., 2018; Ferreira et al., 2023; Ramieri et al., 2011, as cited in Mutmainah & Putra, 2017; Azzahra et al., 2025; Sanjoto et al., 2025; Diniati et al., 2025).

The calculated parameter scores were analyzed and grouped according to predetermined vulnerability classes. The CVI classification used in this study is presented in Table 2.

Table 2. Coastal Vulnerability Index Classes

CVI Value	Vulnerability Class
< 4.75	Not vulnerable
4.75–10.64	Moderate
10.65–19.66	Vulnerable
> 19.66	Highly vulnerable

Source: (Radhwarana, 2023)

The coastal vulnerability index results were analyzed through map overlay to integrate 11 parameters using ArcGIS 10.8. All parameter maps were combined into a single layer to identify the interrelationships among the assessed variables affecting coastal vulnerability. This process produced a coastal vulnerability map that shows the spatial pattern of vulnerability levels based on the combined influence of all physical and socioeconomic parameters.

3. RESULTS AND DISCUSSION

3.1. Coastal Vulnerability Parameter Conditions in Kedung and Tahunan Subdistricts

3.1.1. Shoreline Change

Shoreline change exhibited strong spatial variations across the study area. An analysis based on the endpoint rate (EPR) derived from DSAS using multi-temporal Landsat imagery (2005–2025) shows that the Kedung coastal sector is dominated by negative values, indicating persistent shoreline retreat. In contrast, the Tahunan coastal sector shows relatively stable shoreline conditions, with EPR values close to zero and occasional accretion.

The highest abrasion rates were observed in Kedungmalang, followed by Kalianyar, Surodadi, Panggung, Bulakbaru, and Tanggultlare. Semat, Telukawur, and Tegalsambi showed more stable shoreline behavior. This spatial pattern confirms that shoreline change is one of the most influential parameters in differentiating coastal vulnerability among villages, as it reflects the cumulative effects of marine processes and local coastal conditions (Hammar-Klose et al., 2003; Rocha et al., 2020).

The spatial distribution of shoreline change is shown in Figure 2, which clearly shows the concentration of erosion in the Kedung coastal sector.

Figure 2. Spatial Distribution of Shoreline Change in Kedung and Tahunan Subdistricts]

3.1.2. Coastal Geomorphology

Coastal geomorphology indicates a uniformly high level of physical susceptibility across all villages. The coastal environment is dominated by sandy landforms, with localized mangrove and swamp areas in Kedungmalang and mixed geomorphology in Tanggultlare. Under the classification framework, all villages were assigned the highest vulnerability score.

As this parameter showed no spatial variation, it did not contribute to the differentiation among villages. Instead, it defined the baseline physical fragility of the coastal system. This is consistent with CVI applications, in which geomorphology acts as a background exposure parameter rather than a spatial discriminator (Ramieri et al., 2011, as cited in Mutmainah & Putra 2017).

3.1.3. Wave Height

Wave conditions varied temporally but were relatively uniform spatially. The average significant wave height (SWH) of 1.37 m places the study area in the moderate vulnerability class. Peak wave conditions occurred in 2015, whereas the other years showed moderate to low values.

As wave height is applied as a regional parameter, it does not explain village-level differences in the data. Instead, it represents a common forcing factor that influences the entire coastal system (Bevacqua, 2018).

3.1.4. Sea-Level Rise

Sea-level rise represents a significant regional pressure that affects the study area. The recorded rate of 4.8 mm/year places this parameter in the very-high vulnerability class.

This parameter does not vary spatially across villages and, therefore, does not directly contribute to differentiation. However, it amplifies the effects of shoreline retreat and low coastal slope, reinforcing the overall vulnerability of the coastal system (Hammar-Klose et al., 2003).

3.1.5. Tidal Range

The tidal regime is relatively uniform, with an average tidal range of 0.99 m, classified as having low vulnerability. The mixed, mainly diurnal tidal type indicates moderate hydrodynamic influence. Owing to its limited variation, the tidal range contributes minimally to spatial differentiation. Its role is primarily to characterize the broader marine setting rather than local variability (Rocha et al., 2020).

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3.1.6. Coastal Slope

All villages exhibited very gentle coastal slopes (0.50%–0.72%), resulting in uniformly high vulnerability scores. Such low-gradient coastal areas are more susceptible to flooding and shoreline instability. Although this parameter does not differentiate villages, it reinforces the overall exposure of the study area to coastal hazards (Bevacqua, 2018).

3.1.7. Land Use

Land use shows clear spatial variations and plays a significant role in differentiating vulnerability. Areas under natural or less intensive land uses exhibit lower vulnerability, whereas built-up areas and intensive coastal uses show higher vulnerability.

The spatial distribution of land use is presented in Figure 3, which illustrates the concentration of built-up areas and aquaculture zones along the coast of the island. This pattern highlights the interaction between human activity and coastal hazard exposure, which is a key component of vulnerability assessment (Azzahra et al., 2023; Untulangi et al., 2016; Azzahra et al., 2025).

Figure 3. Land Use Distribution in Kedung and Tahunan Subdistricts

3.1.8. Population Density

Population density varies considerably among villages and contributes to differences in socio-economic pressure. Villages such as Tegalsambi and Telukawur show higher values, while Kalianyar and Tanggultlare are relatively lower.

This parameter is one of the main contributors to spatial differentiation in the CVI, as higher population concentrations increase exposure to coastal hazards (Diniati et al., 2025). However, the unit inconsistency between this section and the Methods (people/km² vs. percentage) must be corrected to ensure methodological clarity.

3.1.9. Sex Ratio

The sex ratio showed minimal variation across the villages, with most values close to balance. This resulted in low vulnerability scores. This parameter contributes limited analytical value and should not be interpreted as a direct indicator of social vulnerability, as demographic balance does not necessarily reflect adaptive capacity (Maulana et al., 2025; Prathanazal et al., 2021; Putiamini et al., 2022; Bevacqua, 2018).

3.1.10. Vulnerable Age Ratio

The vulnerable age ratio exhibited significant variations across villages. Most villages fell within the low-vulnerability category, while Panggung showed an extremely high value (89.5%), placing it in the very high category. This value strongly influenced the CVI result for Panggung and required verification because of its outlier nature. In composite indices, extreme values can disproportionately affect final scores, especially when other parameters show limited variation (Ibrahim et al., 2023; Joesidawati, 2016).

3.1.11. Poverty Rate

The poverty rate shows a relatively low variation among villages. Most values fall within the very low to low vulnerability classes. Although it contributes to the socioeconomic dimension of vulnerability, it is not a dominant differentiating factor in this study.

3.2. Coastal Vulnerability Index of Kedung and Tahunan

The spatial distribution of the coastal vulnerability index (CVI) highlights the variations in vulnerability across villages. Although several physical parameters indicate uniformly high exposure, the final CVI values are primarily driven by spatially variable parameters, such as shoreline change, land use, population density, and vulnerable age ratio.

Table 3. Coastal Vulnerability Index Calculation Results

Village	Parameter Scores												
	EPR	Geomorphology	Slope	Tidal	Wave	SLR	Land Use	PopulatioDensity	Sex Ratio	Vulnerable Age	Poverty Rate	CVI	Classification
Kedungmalang	5	5	5	2	3	5	1	5	2	1	2	6,81	Moderate
Kalianyar	5	5	5	2	3	5	3	1	2	1	2	4,09	Not Vulnerable
Surodadi	5	5	5	2	3	5	3	3	1	1	1	3,06	Not Vulnerable
Panggung	5	5	5	2	3	5	3	5	1	5	1	25,5	Highly Vulnerable
Bulakbaru	5	5	5	2	3	5	3	5	1	1	1	5,11	Moderate
Tanggultlare	5	5	5	2	3	5	1	1	1	1	2	0,68	Not Vulnerable
Semat	3	5	5	2	3	5	3	5	1	1	2	6,14	Moderate
Telukawur	3	5	5	2	3	5	3	5	1	1	2	6,14	Moderate
Tegalsambi	3	5	5	2	3	5	3	5	1	1	1	3,07	Not Vulnerable

The spatial pattern of CVI is shown in Figure 4, which reveals that high vulnerability is concentrated in specific locations, particularly in Panggung.

Figure 4. Spatial Distribution of Coastal Vulnerability Index (CVI)

Panggung has the highest CVI value (25.5) and is classified as highly vulnerable. This result is strongly influenced by the combination of high physical exposure and the extreme vulnerable age ratio. However, this interpretation should be treated with caution until the demographic value is verified.

Kedungmalang, Bulakbaru, Semat, and Telukawur were classified as being in the moderate category, whereas Kalianyar, Surodadi, Tanggultlare, and Tegalsambi were classified as being not vulnerable.

These results indicate that coastal vulnerability is not determined solely by physical conditions but by the interaction between environmental exposure and socioeconomic characteristics. This finding aligns with integrated vulnerability frameworks, in which vulnerability emerges from the combination of exposure and sensitivity factors (Hammar-Klose et al., 2003; Bevacqua, 2018).

Lower CVI values should not be interpreted as evidence of higher resilience. The CVI measures relative vulnerability based on selected parameters and does not directly assess adaptive capacity or recovery ability. Therefore, the results should be used for spatial prioritization and coastal management planning rather than as a direct indicator of resilience (Handiani et al., 2022; Himmelstoss et al., 2018).

4. CONCLUSIONS

This study shows that coastal vulnerability in the Kedung and Tahunan subdistricts is shaped by the interaction between physical coastal conditions and socioeconomic characteristics at the village level, as follows: Within the CVI framework used in this study, shoreline change, land use, population density, and vulnerable age structure contribute more clearly to village-level variation than parameters that remain relatively uniform across the study area, such as geomorphology, coastal slope, tidal range, and sea-level rise. The results confirm that village-level coastal vulnerability cannot be interpreted from physical exposure alone, but must also consider socioeconomic pressure within the assessed coastal system.

The CVI results identified clear spatial differences in vulnerability among villages. Panggung recorded the highest vulnerability level, while Kedungmalang, Bulakbaru, Semat, and Telukawur fell into the moderate category, and Kalianyar, Surodadi, Tanggultlare, and Tegalsambi were classified as not vulnerable under the adopted classification thresholds. These findings indicate that the integrated CVI approach is useful for distinguishing relative vulnerability among villages and for identifying locations that require greater attention in coastal management.

However, the findings should be interpreted within the limits of the index design. The CVI developed in this study assesses relative coastal vulnerability based on selected physical and socioeconomic parameters; however, it does not directly measure resilience, adaptive capacity, or post-impact recovery. Therefore, the main contribution of this study is to provide a spatially structured assessment of relative coastal vulnerability in Kedung and Tahunan that can support priority setting for monitoring, planning, and further coastal risk assessment.

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