

A GEOSPATIAL ASSESSMENT OF SHORELINE DYNAMICS AND COASTAL VULNERABILITY INDUCED BY THE SEMARANG–DEMAK SEA-TOLL ROAD INFRASTRUCTURE IN CENTRAL JAVA, INDONESIA

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ABSTRACT

The Semarang–Demak sea-toll road, a national strategic project in Central Java, Indonesia, was designed to enhance connectivity while simultaneously serving as a sea dike to mitigate tidal flooding and erosion. However, its construction within a subsiding and geomorphologically dynamic coastal environment raises concerns about long-term sustainability. This study assesses coastline change and coastal vulnerability after the toll road development using a GIS-based Digital Shoreline Analysis System (DSAS) and Coastal Vulnerability Index (CVI) frameworks that integrate nine geologic and oceanographic parameters. Results indicate pronounced spatial heterogeneity: North Semarang and Genuk exhibited high accretion rates (31.54 m/year and 51.64 m/year, respectively), whereas Sayung experienced extreme erosion, with retreat rates up to 654.09 m/year. CVI analysis revealed that 38.01% of the coastline falls under high vulnerability, particularly in the Sayung District, determined by factors such as sea-level rise, land subsidence (up to 8 cm/year), and extensive land use changes. The findings demonstrate that while the toll road enhances short-term protection and connectivity, it also intensifies long-term risks by disrupting sediment dynamics and degrading coastal ecosystems. Therefore, adaptive and ecosystem-based management is crucial to align infrastructure development with environmental resilience in rapidly subsiding deltaic regions.

Keywords: Coastal vulnerability; Shoreline change; Land subsidence; Semarang–Demak Toll Road; Indonesia

1. INTRODUCTION

Coastal zones, typically characterized by dense populations and vibrant economic activities, are inherently vulnerable to a range of natural and anthropogenic hazards, including flooding, coastal storms, sea-level rise (SLR), and erosion. Consequently, coastal vulnerability assessments have attracted substantial scholarly and policy attention (Dada et al., 2024; Kantamaneni et al., 2018; Tanim et al., 2022). Globally, shorelines exhibit diverse geomorphological characteristics that influence the development of trade, fisheries, maritime transport, tourism, and other coastal industries, thereby making significant contributions to national economies (De Vivo et al., 2022; Magnan et al., 2022). Coastal regions are home to approximately 40% of the world's population, and this proportion is projected to increase in the coming decades, intensifying pressures on coastal systems.

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The northern coast of Java, Indonesia, is of particular strategic importance due to its economic potential. Much of the coastline is of low relief and rich in both surface and groundwater resources, making it attractive for urban development. The region supports a wide range of socioeconomic functions, including industrial zones, government offices, seaports, marine tourism, fisheries, agriculture, settlements, mining, and public services such as roads, schools, hospitals, and markets (Solihuddin et al., 2021). However, as in many developing nations, low resilience and limited adaptive capacity within socio-ecological systems leave coastal communities, representing more than one-third of the global population, highly vulnerable to environmental change (Chai & Wu, 2023; Gu, 2019).

Climate change exacerbates these vulnerabilities by driving atmospheric warming and accelerating SLR, which in turn increases the frequency and severity of coastal flooding and erosion. In the Semarang–Demak coastal region of Central Java, tidal flooding (locally known as *rob*) and shoreline erosion are particularly acute, with the area experiencing the highest erosion rates in the province. Coastal flooding occurs regardless of rainfall events, with inundation depths ranging from 20 to 75 cm, largely driven by SLR and rapid coastal development (Salim et al., 2023). Sayung District, for instance, has experienced shoreline retreat rates of 0.6–1.15 m/year, categorizing it as a high-risk area (Rudiarto et al., 2020).

A major national strategic infrastructure project, the Semarang–Demak Toll Road, has been initiated to enhance regional mobility and logistics while also serving as a sea dike to mitigate tidal flooding and coastal erosion. This 27-km road traverses an area experiencing significant land subsidence (Chotimah et al., 2022), caused by geological cycles, continuous groundwater extraction, and the cumulative loading of urban infrastructure. While the toll road offers potential flood protection benefits, its construction in a subsiding and highly dynamic coastal environment raises questions regarding its long-term effectiveness and sustainability.

Globally, low-lying deltaic coasts represent some of the most vulnerable environments due to the combined pressures of SLR, land subsidence, and intensive human activity. The north coast of Java provides a quintessential example of these challenges, sharing similar characteristics with other subsiding megadeltas such as the Ganges–Brahmaputra, Mekong, and Mississippi, where rapid urban expansion coincides with geomorphological instability (Anderson et al., 2021; Dinh et al., 2012; Haque et al., 2024). Within this context, the Semarang–Demak region illustrates how coastal vulnerability intersects with infrastructure development, particularly through large-scale, dual-function projects such as toll roads that simultaneously act as sea dikes. Although the Coastal Vulnerability Index (CVI) has been widely applied to assess natural hazards and ecosystem sensitivity, few studies have employed it to evaluate the sustainability of infrastructure-based coastal defenses in subsiding deltaic environments. This study addresses this gap by integrating the CVI with the Digital Shoreline Analysis System (DSAS), extending conventional applications from general hazard assessment toward the quantitative evaluation of shoreline response and infrastructure effectiveness. This coupling enables a spatially explicit appraisal of how large-scale coastal structures influence sediment dynamics and ecosystem vulnerability. It is hypothesized that the sea-toll road induces a more stable coastline behind the structure, however, it causes exacerbated coastal erosion and vulnerability in the Sayung District as a result of hydrodynamic regime and sediment dynamic changes in the surrounding structures.

The findings of this study will provide a spatially explicit understanding of vulnerability patterns in the Semarang–Demak coastal zone, highlight priority areas for adaptive management, and offer insights into the integration of coastal protection measures within large-scale infrastructure planning. These outcomes will be relevant not only for Indonesia but also for other subsiding coastal megadeltas worldwide facing similar climate and development pressures.

2. STUDY AREA

The northern coastline of Java is underpinned by a diverse and relatively young geological framework, predominantly composed of unconsolidated and loosely compacted materials. These deposits include young volcanic products, extensive alluvial sediments, and coastal deposits that are highly susceptible to erosion and subsidence (Solihuddin et al., 2021). The Quaternary strata in this

area are largely made up of tuffaceous claystone, sand, silt, and clay, reflecting the combined influence of volcanic activity, fluvial processes, and marine sedimentation over the past several thousand years.

The Semarang–Demak Toll Road Project has emerged as a major National Strategic Project aimed at improving transportation efficiency and economic connectivity in Central Java. Spanning approximately 27 km, the toll road is designed to link industrial zones, ports, and key urban centers in Demak (**Fig. 1**), thereby facilitating the movement of goods and people while alleviating chronic traffic congestion. Beyond its transportation role, the project incorporates critical flood mitigation infrastructure, functioning as an integrated coastal defense system that combines a sea embankment, a polder network, and an upgraded drainage system to manage recurrent tidal inundation (Pamungkas, 2021).

Construction activities commenced in late 2019, with partial sections, particularly a 16 km stretch, temporarily opened during peak holiday travel periods to relieve traffic bottlenecks. Despite its potential socioeconomic benefits, the project has raised notable environmental concerns. The development is expected to result in the clearance of approximately 46 hectares of mangrove forest within the coastal zones of Semarang and Demak (Solahudin et al., 2024).

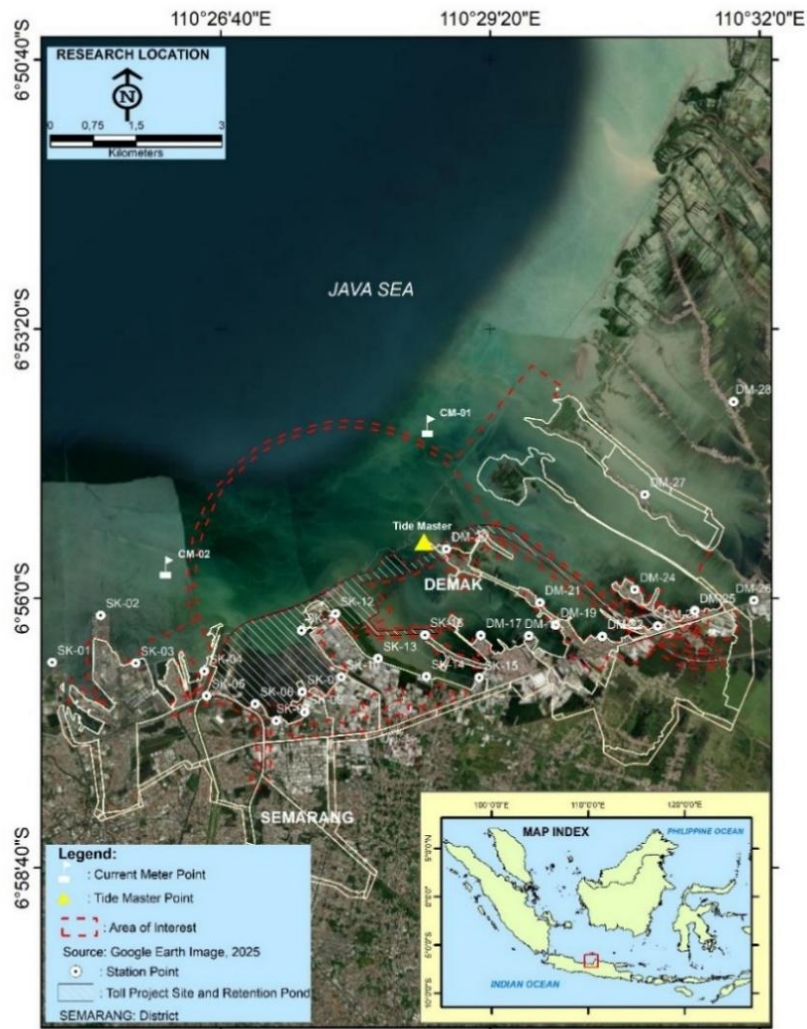


Fig. 1. Location of the Semarang–Demak sea-toll road development, field survey location, and *in situ* observation points.

3. DATA AND METHODS

3.1. Data acquisition

The Coastal Vulnerability Index (CVI) parameters used in this study comprise coastal relief, geomorphology, mean tidal range, shoreline change rate, relative sea-level change, mean wave height, slope, land subsidence, and land use. These parameters were chosen to capture the combined influence of geomorphology, hydrodynamics, relative SLR, and socio-economic exposure, factors that are particularly critical in low-lying, subsiding deltaic settings in the Semarang–Demak region. Data were obtained from multiple sources, including satellite imagery, digital elevation models (DEMs), tide gauge records, satellite altimetry, reanalysis datasets, and field surveys. The complete list of parameters, their sources, spatial/temporal coverage, and processing methods are summarized in **table 1**.

Table 1.

Data sources, resolution, and processing methods for CVI parameters

Parameter	Data source	Spatial resolution/coverage	Temporal coverage	Processing method
Coastal relief	SRTM DEM (USGS)	30 m	2000	Extracted coastal elevation profiles using GIS; reprojected to WGS 84 / UTM Zone 49S
Geomorphology	Sentinel-2 MSI (ESA); Field survey	10 m	2025	Visual interpretation and supervised classification; verified through ground-truthing
Mean tidal range	Tide gauge data (BIG); Tidal harmonic constituents	Point-based	2010-2025	Harmonic analysis and averaging of spring-neap cycles
Shoreline change rate	Landsat 5 TM, Landsat 7 ETM+, Landsat 8 OLI, Sentinel-2 MSI; DSAS v5.1	30 m (Landsat), 10 m (Sentinel-2)	1995-2025	Multi-temporal shoreline extraction and rate computation (EPR, LRR)
Relative sea-level change	AVISO+, Copernicus Marine Service (satellite altimetry); Local tide gauges	0.25° (altimetry)	1993-2025	Combined mean sea-level trends with local vertical land motion
Mean wave height	ECMWF ERA5 reanalysis	0.25°	1993-2025	Hourly data averaged to represent long-term wave climate
Slope	SRTM DEM (USGS)	30 m	2000	Derived nearshore slope using GIS terrain analysis tools
Land subsidence	Sentinel-1A/B (ESA) InSAR	20 m	2016-2021	InSAR time-series analysis using SNAP v12.0.0 & StaMPS v4.1 to estimate vertical displacement
Land use	Sentinel-2 MSI (ESA); ATR/BPN official maps	10 m	2025	Supervised classification validated with official land-use data and field checks

3.2. Digital shoreline analysis system (DSAS)

In this study, shoreline change analysis was conducted using the Digital Shoreline Analysis System (DSAS), a freely available add-in developed by the U.S. Geological Survey (USGS) for ArcGIS and QGIS platforms (Himmelstoss et al., 2021). DSAS enables the calculation of shoreline change rates by applying various statistical methods to multiple historical shoreline positions. Among these, the Linear Regression Rate (LRR) method was selected as it is widely regarded as one of the most robust approaches for estimating long-term shoreline change trends, particularly in large-scale coastal studies (Abdul Rahim et al., 2024; Nerves et al., 2024). The LRR method determines the slope of the best-fit line through all available shoreline positions along each transect, providing a statistically reliable rate of change. For this study, a reference baseline was established offshore, parallel to the general orientation of the coast. From this baseline, transects were automatically generated at 10 m intervals and oriented perpendicular to the shoreline. Historical shoreline vectors from different years were then compiled and processed within the DSAS framework to derive both net shoreline movement (NSM) and rate of change statistics. The NSM represents the total distance between the oldest and most recent shoreline positions, while the LRR expresses this movement as an annual rate by dividing the NSM by the elapsed time between the earliest and latest observations.

To ensure the reliability of the shoreline positions, uncertainty handling was explicitly incorporated in the analysis. The primary shoreline proxy used was the High-Water Level (HWL), extracted from atmospherically corrected multispectral satellite imagery. Tidal-stage normalization was performed using coincident tidal records to reduce temporal discrepancies among image acquisition dates. The total positional uncertainty (U_t) of each shoreline was estimated as the root sum of squares of image georeferencing error, spatial resolution, digitizing error, and tidal correction error. These cumulative uncertainties were integrated into DSAS to generate 95% confidence intervals for the calculated LRR values, ensuring statistically defensible estimates of shoreline change rates.

Shoreline datasets for this analysis were extracted from remote sensing imagery for four temporal snapshots (**Tab. 1**). This temporal resolution enables the assessment of both short-term variability and long-term trends, offering critical insights into the interplay between shoreline dynamics and coastal land-use transformations, as further examined in this study through supervised classification-based geospatial analysis.

3.3. Coastal vulnerability index (CVI) assessment

Coastal vulnerability mapping and assessment in this study were conducted using the Smartline methodology formulated by Sharples et al. (2009). This framework consists of three principal stages: (1) Indicative Mapping, which identifies coastal areas according to their geological and geomorphological characteristics, representing the fundamental determinants of vulnerability; (2) Regional Assessment, which integrates geomorphic coastal types with additional variables influencing vulnerability, including climate, wave regime, tidal range, and vertical tectonic movements; and (3) Site-specific Assessment, which examines in detail all geological, geomorphological, topographic, oceanographic, and climatic factors that influence the coastal system.

The parameters applied in this approach were not confined to observations and measurements taken parallel to the coastline but also extended to areas oriented perpendicular to the shore. All three Smartline mapping stages were implemented in this study with several modifications to the observed parameters, as summarized in **table 2**. The selection of the nine CVI parameters (coastal relief, geomorphology, mean tidal range, shoreline change rate (DSAS), relative sea-level change, mean wave height, slope, land subsidence, and land use) was guided by their direct relevance to the geomorphological instability and anthropogenic pressures characteristic of deltaic, subsiding environments. These parameters were subsequently processed and interpreted to produce a coastal vulnerability map classified into five categories: very low, low, moderate, high, and very high vulnerability. Since the original Smartline methodology does not provide a detailed quantitative procedure for generating vulnerability maps, the classification in this study was calculated using the Coastal Vulnerability Index (CVI) developed by Gornitz et al. (1992). The CVI calculation was performed after all parameters were first grouped into value intervals ranging from 1 to 5, where a

value of 1 indicates that the corresponding parameter is considered to have minimal susceptibility to coastal hazards. The CVI was then calculated as the geometric mean of the ranked variables, following the formula:

$$CVI = \sqrt[n]{a_1 x a_2 x a_3 x \dots x a_n} \quad (1)$$

where a_1 – a_n represent the rank values of the n selected parameters.

Equal weighting was assigned to all parameters to avoid subjective bias, though their relative influence was subsequently evaluated through a sensitivity analysis. This analysis examined the degree to which high-variance parameters, particularly land subsidence and shoreline change rate, dominated the composite CVI outcome. Results indicated that while subsidence exerted a significant local influence, the overall vulnerability pattern remained consistent across parameter weighting scenarios, demonstrating the model's stability.

Table 2.

Summary of indicative mapping parameter's scoring

Parameter	Very low (1)	Low (2)	Moderate (3)	High (4)	Very high (5)	References
Coastal relief (m)	> 30	21 – 30	11 – 20	6 – 10	0 – 5	(Shaw et al., 1998; Gornitz et al., 1991)
Geomorphology	Rocky, cliffed coasts, Fiords, Fiards; Plutonic, Volcanic, High-medium grade metamorphics	Medium cliffs, Indented coasts; Low grade metamorphics, Sand-stones and conglomerates, Metamorphic rocks	Low cliffs, Glacial drift, Alluvial plains; Most sedimentary rocks	Cobble beaches, Estuary Lagoon; Coarse, poorly sorted, unconsolidated sediments	Barrier beaches, Sand beaches, Salt marsh, Mud flats, Deltas, Mangroves, Coral reefs; Fine, consolidated sediment, Ice	(Gornitz et al., 1991)
Mean tidal range (m)	> 6.0	4.1 – 6.0	2.0 – 4.0	1.0 – 1.9	< 1.0	(Gornitz et al., 1991)
Shoreline change rate (m/year)	> 2.0	1.0 – 2.0	(-1.0)– (+1.0)	(-1.0) – (-2.0)	< -2.0	(Hammar-Klose et al., 2003; Gornitz et al., 1991)
Relative sea-level change (mm/year)	<-1.21	(-1.21) – (+0.1)	0.1 – 1.24	1.24 – 1.36	> 1.36	(Hammar-Klose et al., 2003)
Mean wave height (m)	< 1.1	1.1 – 2.0	2.0 – 2.25	2.25 – 2.6	> 2.60	(Hammar-Klose et al., 2003)
Slope (°)	> 10	7.5 – 10	5 – 7.5	2.5 – 5	≤ 2.5	(Reeder, et al. 2012)
Land subsidence (mm/year)	< -1.0	(-1.0) – (+1.0)	1.0 – 2.0	2.1 – 4.0	> 4.0	(Gornitz & White, 1992)
Land use	Dry land	Farm, Bush land	Vacant land with farm area	Sand area, Mangrove, plantation area	Building, Beach, Ponds degrade mangrove, Swamp, Aquaculture	(Romadhona, et al. 2020)

The final CVI values were classified into five vulnerability categories: very low, low, moderate, high, and very high, using natural breaks in the data distribution. Integrating the Smartline spatial framework with the quantitative CVI approach provided both geomorphological context and numerical precision, thereby enhancing the robustness, comparability, and reproducibility of the coastal vulnerability assessment. The spatial analysis framework in this study is illustrated in **figure 2**.

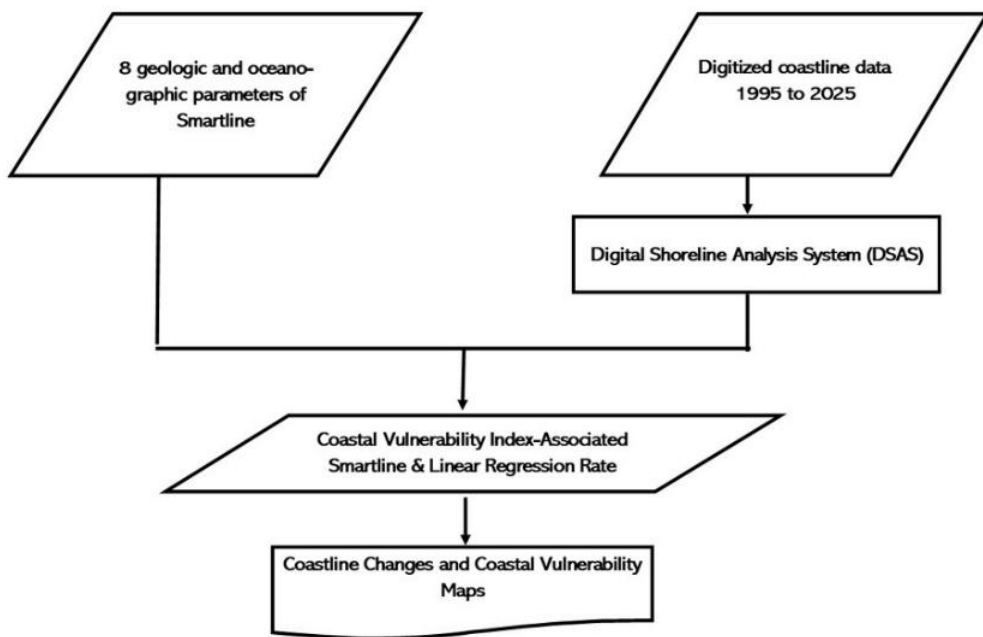


Fig. 2. Research framework of spatial analyses.

4. RESULTS AND DISCUSSIONS

4.1. Coastline change after the development of Semarang–Demak Sea-toll Road

The spatial distribution of shoreline change severity in the Semarang–Demak coastal zone is illustrated in **figure 3**. In the western sector, North Semarang was dominated by accretionary processes, ranging from moderate to severe accretion, with no significant erosion detected, indicating a relatively stable to advancing shoreline influenced by sediment deposition from local riverine inputs and coastal currents. Adjacent to this, Gayamsari exhibited a mixed shoreline change regime, where pockets of moderate accretion coexisted with severe erosion zones, suggesting localized erosional pressures likely driven by anthropogenic modification and changes in nearshore hydrodynamics.

Genuk recorded the most extensive accretion in the study area, encompassing severe to very severe accretion zones and contributing 60.1% of the total measured accretion, although certain segments experienced severe erosion, pointing to high sediment deposition rates counterbalanced by localized erosional forces. In stark contrast, the easternmost sector, Sayung, was overwhelmingly dominated by very severe erosion, accounting for 82.4% of the total very severe erosion recorded, with no evidence of accretion. The DSAS analysis identified the most extreme shoreline retreat in Sayung, reaching rates of 654.09 m/year between 2015 and 2021, underscoring the severe vulnerability of this area to coastal hazards (**Tab. 3**).

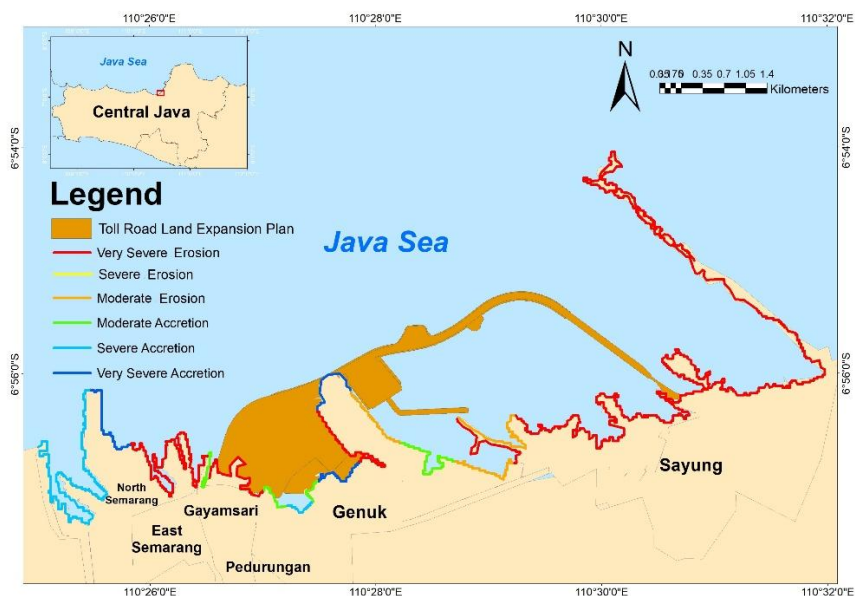


Fig. 3. Erosion and accretion status in the study area after the development of Semarang–Demak sea-toll road.

Table 3.

Summary of Coastline changes in the study area.

Zone	Erosion rate	Accretion rate	Category
North Semarang	-	31.54 m/year	Accretion
Gayamsari	18.01 m/year	2.75 m/year	Erosion
Genuk	55.65 m/year	51.64 m/year	Erosion-accretion
Sayung	654.09 m/year	-	Extreme erosion

4.2. Indicative mapping for CVI assessment

The indicative mapping of coastal vulnerability along the Semarang–Demak shoreline reveals pronounced spatial heterogeneity across the assessed parameters (**Fig. 4**). The coastal areas of Semarang City and Demak Regency are characterized by low relief and abundant water resources, both surface and groundwater, which historically made them favorable for urban development. The study area is also defined as a muddy coast. During low tide, the intertidal mudflats are exposed up to ± 2 km seaward, forming extensive tidal mudflat morphology. The geological condition of the study area is largely categorized as alluvial plains, except in Gayamsari District, which is classified as mudflats.

The observed tidal range along the coast varies between 2.5 m and 2.8 m, with the highest values recorded in Sayung District. The result also indicates that the rate of SLR in the study area ranges between 8 and 25 mm/year, making the study area categorized as a very high vulnerability (Figure 3). The highest rates (20–25 mm/year) are concentrated in Genuk and North Semarang Districts, while the lowest rates (8–10 mm/year) are found in parts of Sayung.

Analysis of shoreline change between 2015 and 2025 along the Semarang–Demak coast reveals five categories: severe accretion (13.0%), very severe accretion (5.4%), moderate accretion (19.4%), very severe erosion (54.4%), and moderate erosion (7.7%) (**Fig. 3**). On the other hand, based on measurements in the study area, subsidence rates are categorized into three groups: 70–100 mm/year

(31.9%), 50–70 mm/year (5.4%), and 60–80 mm/year (62.7%), with the latter dominating, particularly in Sayung and Genuk.

Land use patterns introduce additional complexity. Areas dominated by urban development and aquaculture ponds exhibit moderate to high vulnerability (81.5%), while some segments classified as low vulnerability (18.5%) correspond to remnant mangrove belts and green buffer zones, which still provide limited protection against coastal hazards.

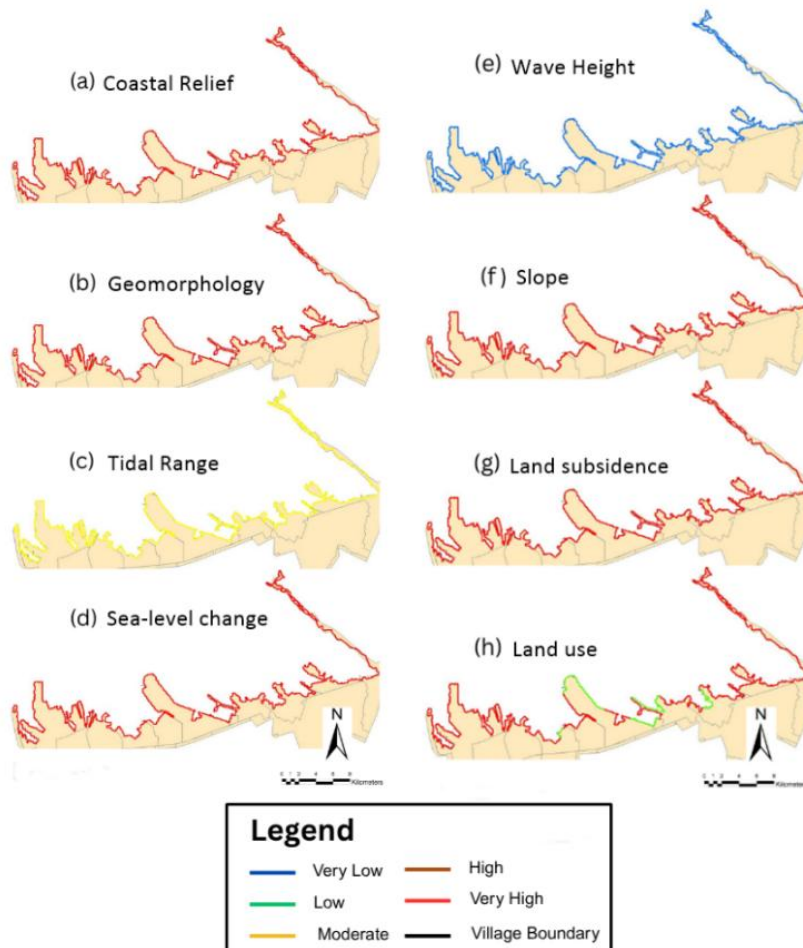


Fig. 4. The results of indicating mapping for CVI assessment, coastal relief (a), geomorphology (b), tidal range (c), sea-level change (d), wave height (e), slope (f), land subsidence (g), and land use (h).

4.3. Coastal vulnerability after the development of Semarang–Demak Sea-toll Road

The Coastal Vulnerability Index (CVI) analysis along the Semarang–Demak coastline after the development of the toll road revealed significant spatial variation across districts (**Fig. 5** and **Tab. 4**). In North Semarang, the coast is relatively less exposed, with only 2.2% categorized as highly vulnerable and 8.2% classified as low vulnerability. In Gayamsari, vulnerability increases slightly, with 4.4% of the coastline falling under high vulnerability and 2.0% under low vulnerability. A more complex distribution was observed in Genuk, where 8.9% of the shoreline is highly vulnerable, 11.9% moderately vulnerable, and 9.5% classified as low vulnerability.

By contrast, Sayung district exhibits the highest degree of coastal vulnerability, with 48.9% of its shoreline categorized as highly vulnerable and 4.0% as moderately vulnerable (**Tab. 4**), making it

the most critical hotspot along the study area. Overall, the CVI results highlight that coastal vulnerability increases eastward, with Sayung as the most threatened region compared to North Semarang, Gayamsari, and Genuk.

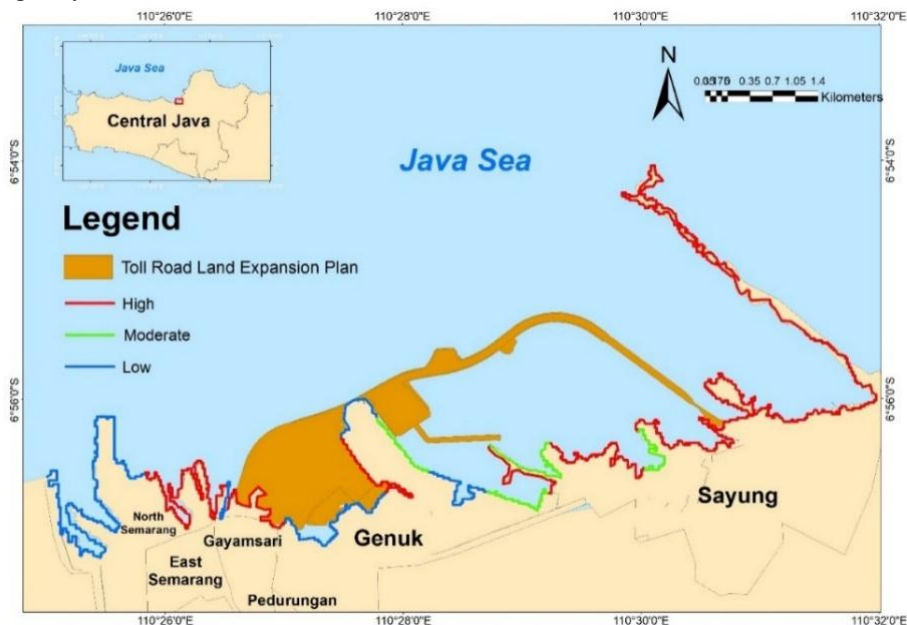


Fig. 5. Coastal vulnerability classification in the Semarang–Demak coastline after the development of sea-toll road.

Table 4.

Summary of CVI classification in each district impacted by the sea-toll road development.

District	Category	CVI percentage (%)
North Semarang	High vulnerability	2.2
	Low vulnerability	8.2
Gayamsari	High vulnerability	4.4
	Low vulnerability	2.0
Genuk	High vulnerability	8.9
	Moderate vulnerability	11.9
	Low vulnerability	9.5
Sayung	High vulnerability	48.9
	Moderate vulnerability	4.0

5. DISCUSSION

5.1. Sea-toll road impacts on coastal vulnerability

The Semarang–Demak sea-toll road represents a flagship example of dual-function infrastructure, designed simultaneously as a transport corridor and a coastal defense system. While such projects are promoted as strategic responses to the challenges of tidal flooding and transport connectivity in Java’s northern corridor (Wibowo et al., 2023), their long-term impacts on shoreline stability and socio-ecological systems are highly complex.

DSAS analysis highlights strikingly uneven outcomes: North Semarang experienced net accretion (31.54 m/year) and Genuk recorded even higher rates of accretion (51.64 m/year), whereas Sayung underwent extreme erosion of up to 654.09 m/year with no evidence of compensatory accretion. These results indicate that the construction of the toll road and associated sea dike likely affected littoral drift patterns and altered sediment transport dynamics, contributing to localized areas of accretion and erosion toward the eastern part of the coastline.

Field evidence and local reports reinforce these findings. Fishers have noted declining catches as aquaculture ponds have been transformed into open sea, while tidal flooding has intensified due to the impermeability of road surfaces and inadequate drainage design (Jamaludin & Mahdi, 2025; Aditiya & Ito, 2023).

Such impacts demonstrate that while the toll road has delivered short-term benefits by reducing tidal flooding in selected areas, its construction has simultaneously heightened long-term vulnerability in others, particularly in Sayung. Moreover, mangrove removal for infrastructure expansion has reduced natural shoreline protection, further amplifying erosion and wave exposure. These dynamics underscore the paradox of hard-engineering interventions: they offer immediate socio-economic benefits but can destabilize coastal systems in ways that ultimately undermine resilience.

5.2. Natural vs. anthropogenic drivers of shoreline change

The vulnerability of the Semarang–Demak coast cannot be understood without considering the interaction between natural coastal processes and human-induced pressures. From a natural perspective, the region's coastal relief is dominated by very low elevations (0–5 m) and flat slopes averaging 0.22°, making the coastline highly susceptible to inundation and storm surge intrusion (Handiani, 2019; Solihuddin et al., 2021). Geologically, the northern coast of Java is composed primarily of unconsolidated alluvial and lahar deposits, intersected by river systems draining into the Java Sea, which renders the area morphologically unstable (Handiani, 2019; Sagala et al., 2024). Geomorphological diversity includes sandy, muddy, coral, and deltaic coasts (Solihuddin et al., 2021), yet the study area is dominated by muddy tidal flats and degraded mangrove zones, both of which are highly vulnerable to erosion.

The tidal regime is characterized by mixed tides with diurnal dominance, and the mean tidal range falls into the mesotidal category, contributing to sediment redistribution but not providing the stabilizing effect of macrotidal environments (Handiani, 2019). Although wave energy is relatively low, the combination of flat relief and estuarine tidal dynamics contributes to shoreline instability. Meanwhile, long-term SLR, combined with local tectonic and anthropogenic subsidence, drives very high vulnerability scores across most of the coastline. Indeed, land subsidence is among the most critical anthropogenic drivers, with Semarang and Demak experiencing rates of up to 8 cm/year due to excessive groundwater extraction (Sidiq et al., 2021). Subsidence amplifies relative SLR and leads directly to tidal inundation, shoreline retreat, and land loss (Prasetyo et al., 2019; Sarah et al., 2022). In addition to the SLR factor, this study applied the relative sea-level change classification developed by Hammar-Klose et al. (2003). Since sea-level projections in areas near the equatorial region are generally higher than those in the northern hemisphere (Wisha et al., 2025), the threshold used to classify vulnerability levels based on this factor should be higher than that applied to the east coast of the United States. Consequently, the resulting scores indicate a very high level of vulnerability in the study area, even though SLR remains a significant and ongoing issue affecting the northern coast of Java.

On the other hand, land-use changes and rapid urbanization further exacerbate vulnerability. Industrial zones dominate North Semarang and Genuk, while settlements expand across Sayung despite recurring tidal flooding (Solahudin et al., 2024).

The loss of natural buffers through mangrove clearing and conversion of ponds for industry and settlements has removed critical ecosystem services, intensifying exposure to flooding and erosion. CVI assessments confirm that SLR, land subsidence, and geomorphological setting exert the greatest

influence on overall vulnerability (Mujabar & Chandrasekar, 2013). Thus, the interaction of natural drivers with anthropogenic stressors results in a compound risk scenario where infrastructure like the sea-toll road operates within a highly unstable deltaic system.

5.3. Implications for resilience and sustainability

The Semarang–Demak case highlights a broader paradox in deltaic adaptation: infrastructure-led interventions are often pursued as urgent responses to coastal hazards, yet their long-term effectiveness is constrained by geomorphological instability and human-induced pressures. The CVI results, showing that 38% of sites fall into the high vulnerability category, emphasize the fragility of the system even after the toll road was constructed. Rather than reducing risk, the project has in some cases shifted or intensified it, raising questions about its long-term sustainability. The coastal transformation along the Semarang–Demak corridor has also produced profound socio-economic and governance implications. Recurrent tidal flooding and shoreline retreat have displaced communities, disrupted aquaculture livelihoods, and reduced agricultural productivity, particularly in Sayung.

These findings align with global concerns over infrastructure-led adaptation in megadeltas, where subsidence, SLR, and erosion converge to undermine conventional engineering solutions (Han et al., 2022). The Semarang–Demak toll road demonstrates how such projects may provide immediate socio-economic and transport benefits but at the expense of ecological integrity and livelihood security. Sustainable resilience strategies must therefore integrate ecosystem-based approaches such as mangrove restoration, sediment management, and living shorelines, which can complement hard infrastructure by enhancing natural defenses (Nurhidayah et al., 2022). Furthermore, adaptive governance frameworks are essential, ensuring that coastal management integrates scientific modeling, geospatial monitoring, and local knowledge to adjust interventions as risks evolve.

Ultimately, the resilience of the Semarang–Demak coast depends not solely on the performance of a single project but on broader strategies that balance development and ecological protection. Without such integration, the sea-toll road risks entrenching a cycle of dependency on increasingly costly engineering solutions, while leaving local communities and ecosystems more vulnerable to the accelerating impacts of climate change and subsidence.

6. CONCLUSIONS

The Semarang–Demak coast is highly vulnerable due to its low-lying alluvial plains, muddy tidal flats, and unstable geomorphology. Shoreline change is spatially uneven, with extreme erosion in Sayung and localized accretion in Genuk and North Semarang, reflecting the combined influence of natural processes and anthropogenic pressures, including the Semarang–Demak Toll Road. Relative SLR, rapid land subsidence, and intensive land use further heighten risks to communities, infrastructure, and ecosystems. CVI results confirm that much of the coastline is in the high-vulnerability category, where socio-economic exposure compounds physical hazards. While the toll road offers short-term transport and flood protection benefits, its long-term effectiveness is uncertain. Building resilience will require integrated, ecosystem-based strategies that restore natural defenses, manage sediment dynamics, and embed adaptive planning into coastal development.

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