Jurnal Geografi Gea 26 (1) (2026) 14-28

Jurnal Geografi Gea

Journal homepage: https://ejournal.upi.edu/index.php/gea

Central Java's North Coast Shoreline Dynamics (1999-2023): An Empirical Basis for the "Giant Sea Wall"

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ABSTRACT

The phenomenon of shoreline retreat toward the mainland has become a serious issue along the northern coast of Java Island. This study analyzes shoreline changes along the northern coast of Central Java to identify priority locations for coastal protection structures, including the planned Giant Sea Wall. A quantitative remote sensing and GIS approach was applied using multi-temporal Google Earth Pro (1999–2023). Shorelines were interpreted and digitized in ArcMap, and analyzed using DSAS v5 with the Net Shoreline Movement (NSM) method. The results indicate widespread and severe erosion, with the highest retreat observed along the Semarang–Demak coast. This area is therefore recommended as a priority site for the Giant Sea Wall due to its strategic importance as a residential and industrial zone.

ARTICLE INFO

Article History:
Submitted/Received 02 June 2025
First Revised 04 August 2026
Accepted 21 April 2026
First Available online 29 April 2026
Publication Date 30 April 2026

Keyword:
Shoreline retreat,
Shoreline changes,
Giant Sea Wall,
Net shoreline movement

1. INTRODUCTION

Coastal zones, dynamic interfaces between terrestrial and marine environments, are shaped by intricate geomorphological processes (Woodroffe et al., 2023). This inherent dynamism, however, renders these vital regions highly susceptible to a spectrum of risks (Malhouni, Y et al., 2025; Roukounis and Tsihrintzis, 2022; Rocha et al., 2023). At the heart of these transformations, erosion and sedimentation are pivotal in instigating significant alterations to the shoreline (Short, 2013 ; Bird, 2011).

Coastal erosion, particularly abrasion driven by wave action, currents, and tidal fluctuations, is a highly dynamic process (Davidson-Arnott, 2019; Anthony et al., 2016; Hauser et al., 2023). Globally, this phenomenon shows an escalating trend, causing substantial shoreline retreat and becoming a key concern in sustainable coastal management (Ghosh et al., 2015; Andreadis et al., 2021; Dong et al., 2024; Bianchini, A et al., 2019). While accretion, land expansion through sedimentation, has also increased globally, (Mentaschi et al., 2018) highlight that global land loss from abrasion (approximately 28,000 km^2) is twice the land gain from accretion (around 14,000 km^2), indicating a net global coastline retreat.

Historically, coastal regions have attracted human settlement, leading to high population concentration and resource density (Neumann et al., 2015; Kummu et al., 2016; MacManus et al., 2021). With approximately 2.1 billion people globally residing near coastal zones—898 million in low-elevation areas, a figure projected to rise significantly (Reimann et al., 2023) their vulnerability to shoreline changes is profoundly exacerbated. Key socioeconomic transformations, including increasing population density, rapid urbanization, extensive migration to coastal areas, and improper development, amplify impacts due to heightened human presence and unsustainable reliance on coastal resources (Mohd et al., 2018; Zhang and Hou, 2020; Noor and Maulud, 2022). These changes render coastal communities highly susceptible to hazards such as coastal flooding, locally known as 'banjir rob,' which can lead to significant infrastructure damage and economic losses as observed in other Indonesian coastal cities (Hanif et al., 2021).

As an archipelagic nation, Indonesia exemplifies this coastal dependency, with around 150 million (55% of its population) residing in coastal areas (Rudiarto et al., 2018). Central Java Province shows a pronounced trend, with approximately 15 million residents (41%) inhabiting coastal regions. Low-lying northern coastal cities like Semarang, Kendal, and Demak host significant populations whose livelihoods depend on marine resources and coastal economic sectors (Suadi et al., 2021; Insani et al., 2022; Wasik et al., 2024). Abrasion and accretion along Central Java's northern coast have already induced substantial shoreline changes, damaging public infrastructure, tourism areas, agricultural land, and settlements (Marfai, 2011; Marfai, 2014; Prihatanto et al., 2014). These changes are aggravated by growing populations in vulnerable urban coastal centers, leading to irreversible loss of natural habitats and degradation of vital coastal ecosystems.

Scholarly investigations have explored Central Java's coastal dynamics. For example, (Irsadi et al., 2022) analyzed abrasion and land loss in Sayung, Demak, while (Setiadi et al., 2023) mapped shoreline shifts in Jepara (2001-2020) using DSAS, linking them to economic losses from sea-level rise. (Solihuddin et al., 2021) noted a general erosion trend (1998-2018) influenced by mangrove conversion and hard structures across the north coast. Panjaitan and Maulana (2024) identified dominant abrasion in Pemalang (2007-2022) via DSAS, attributing it to beach slope and land use. (Setyowati et al., 2021; Youssef et al., 2021) highlighted

DOI: https://doi.org/10.17509/gea.v26i1,%20April.97852
p-ISSN 1412-0313 e- ISSN 2549-7529

challenges in community-led disaster mitigation in Rembang. In the broader Central Java context, (Alwi et al., 2023) used DSAS to map shoreline change in Karimunjawa Islands, revealing accretion in some segments and emphasizing small island vulnerability. While these studies offer valuable insights into specific local areas or shorter periods, a comprehensive, long-term analysis of shoreline dynamics across the entire northern coast of Central Java Province from 1999 to 2023 remains underexplored.

This comprehensive understanding of shoreline dynamics is critical given the Indonesian government's major strategic initiative: the "Giant Sea Wall" across Java's northern coast. Designated a new National Strategic Project (PSN) under Presidential Regulation No. 12 of 2025, this mega-infrastructure, overseen by the Ministry of Public Works (PU), aims to address severe coastal hazards including land subsidence, tidal flooding (rob), and erosion. Land subsidence, exacerbated by overburdened buildings and groundwater extraction, particularly amplifies tidal flooding in cities like Semarang (Hadi et al., 2020). While initial phases focused on Jakarta, the project's long-term vision extends 946 km from Cilegon to Gresik, with integrated developments already underway in Central Java (e.g., Semarang-Demak and Semarang Harbour Toll Roads) to prevent inundation and reduce groundwater reliance (Hadi et al., 2020). This phenomenon of subsidence driven by intensive groundwater extraction is a critical concern across rapidly urbanizing Indonesian coastal areas, as evidenced by studies in cities such as Bandar Lampung (Anggara et al., 2024). However, the complex environmental and social implications, including hydrodynamic changes within protected bays and impacts on local communities, remain crucial considerations (Al Hakim et al., 2024; Wiryomartono, 2020). Our study, by quantitatively analyzing two-and-a-half decades of shoreline change across the Northern Coast of Central Java, seeks to provide crucial empirical data to inform the strategic prioritization and optimal placement of this massive coastal protection infrastructure, enhancing its effectiveness and sustainability.

To quantitatively and temporally analyze these complex shoreline changes across such a broad and dynamic region, the DSAS, a GIS-based software, is widely adopted. DSAS facilitates precise calculation of shoreline change rates from multi-temporal spatial data, offering a robust methodological foundation for statistical analyses of erosion and accretion (Thieler et al., 2009). Building upon these techniques and addressing the identified knowledge gap, this study aims to comprehensively quantify and analyze the spatiotemporal shoreline dynamics along the entire northern coast of Central Java Province (1999-2023). This will provide crucial updated insights into regional patterns of erosion and accretion and their implications for sustainable coastal management.

2. THEORETICAL FRAMEWORK

This study's analysis of shoreline dynamics along Central Java's Northern Coast is guided by established theoretical constructs in coastal geomorphology and human-environment interaction.

Coastal Morphodynamics and Sediment Budget Theory

Shoreline evolution is understood through coastal morphodynamics, which posits mutually interdependent and constantly adjusting coastal forms and processes (Anthony, 2020). Central to this is the coastal sediment budget concept, where shoreline changes directly manifest the balance between sediment inputs (e.g., fluvial delivery, offshore transport) and outputs (e.g., aeolian transport, longshore drift divergence) within a defined coastal cell (Bird, 2011; Alberti, 2022). A positive budget leads to accretion, while a negative budget results in

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p-ISSN 1412-0313 e- ISSN 2549-7529

erosion. Hydrodynamic forces like wave action, currents, and tidal fluctuations primarily drive this sediment budget, dictating energy for sediment transport and deposition (Davidson-Arnott, 2019; Anthony et al., 2016). Our investigation quantifies these net changes, reflecting the cumulative impact of natural processes on Central Java's northern coast.

Coupled Human-Natural Systems and Coastal Vulnerability

Beyond natural forces, this framework acknowledges the significant influence of anthropogenic activities on coastal systems, viewed as coupled human-natural systems (Liu et al., 2007; Dee et al., 2018). Human interventions, including coastal urbanization, infrastructure development (ports, seawalls), and land-use change (e.g., mangrove deforestation), directly modify natural sediment pathways and alter coastal protection, often exacerbating erosion or inducing localized accretion (Zhang and Hou, 2020; Amini, 2024; Noor and Maulud, 2022). These actions imbalance the natural sediment budget and heighten coastal vulnerability, which encompasses not just physical exposure but also the susceptibility of socio-economic systems reliant on coastal resources (Mohd et al., 2018; Betzold, C et al., 2019). Studies employing the Coastal Vulnerability Index (CVI), which integrates multiple physical and socio-economic parameters like geomorphology, shoreline change rates, and sea level rise, have effectively quantified this vulnerability, classifying areas such as Pekalongan on the northern coast of Java as having 'very high' vulnerability largely influenced by human activities and sedimentation characteristics (Wahyuni et al., 2024). Our analysis implicitly considers how these human modifications may have contributed to observed long-term shoreline dynamics in the study area.

Quantitative Geomorphological Analysis

To empirically assess these theoretical constructions, this study employs quantitative methodologies. The Digital Shoreline Analysis System (DSAS), integrated within a GIS environment, provides a robust framework for measuring historical shoreline positions and calculating rates of change (Thieler et al., 2009). This tool allows for the objective quantification of Net Shoreline Movement (NSM) and End Point Rate (EPR), translating erosion and accretion concepts into measurable spatial and temporal data. This quantitative approach is essential for identifying patterns and magnitudes of shoreline change across Central Java's Northern Coast, allowing inferences regarding dominant processes and their implications.

3. METHODS

This study employed quantitative remote sensing and GIS techniques to analyze shoreline dynamics along the Northern Coast of Central Java Province **(Figure 1)**. The research utilized multi-temporal Google Earth Pro imagery (Maxar Technologies), spanning from 1999 to 2023. Given the nature of the data and the study's objectives, all analyses were performed using remote sensing and GIS techniques, and no fieldwork or ground-truthing surveys were conducted. This imagery was selected for its high spatial resolution and extensive historical archive, providing consistent data coverage across the broad study area for the specified 25-year period.

DOI: https://doi.org/10.17509/gea.v26i1,%20April.97852
p-ISSN 1412-0313 e- ISSN 2549-7529

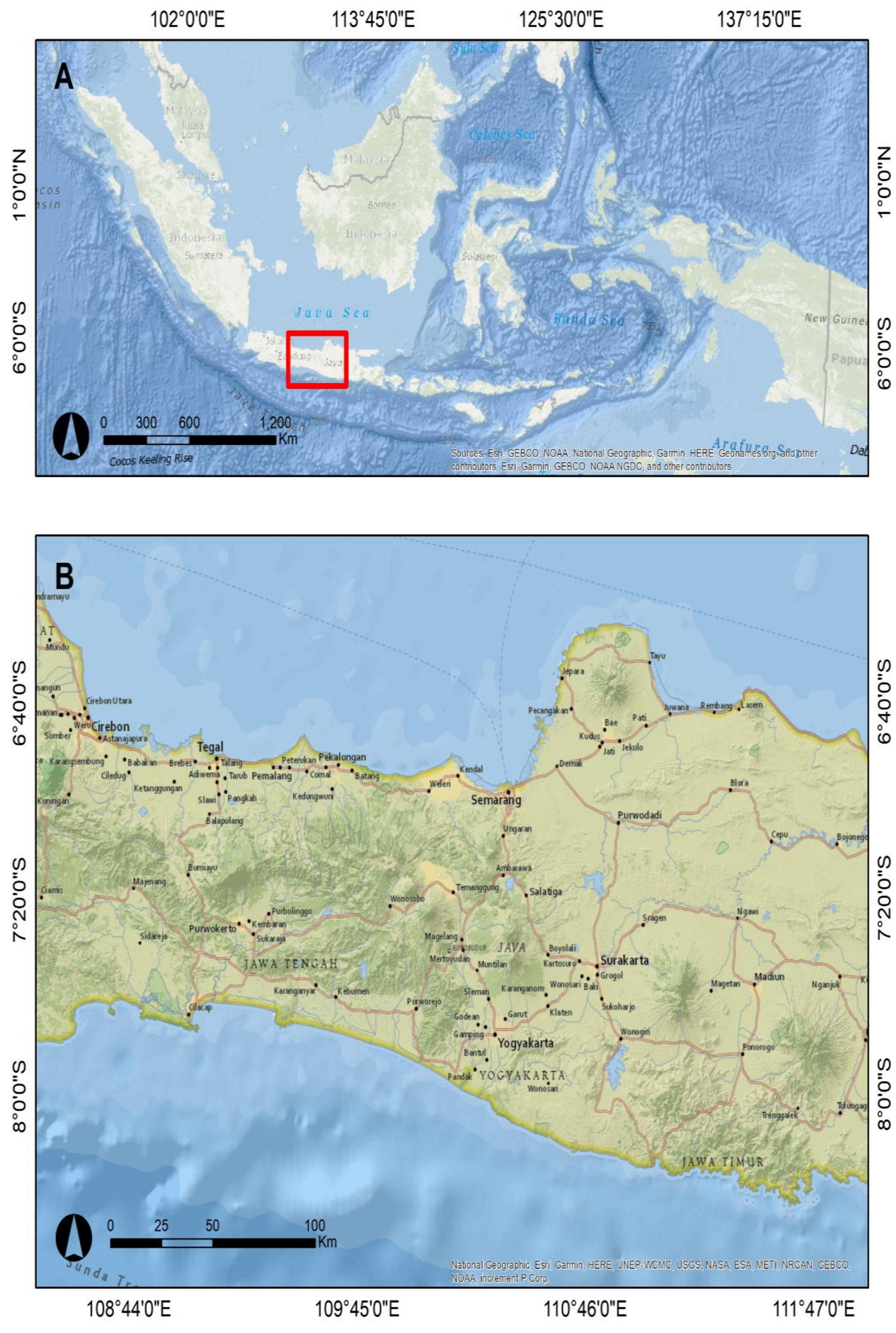

Figure 1. Study Area: Central Java Province, Indonesia.

Data Acquisition and Shoreline Delineation

High-resolution Maxar Technologies imagery, accessed via Google Earth Pro, served as the primary data source. Shoreline positions for selected years between 1999 and 2023 were visually interpreted and manually digitized using ArcMap software (version 10.4). This process involved careful delineation of the instantaneous shoreline, defined as the wet/dry line or the vegetation line where present, to ensure consistency across different time periods. All digitized shoreline data were then converted into georeferenced vector datasets.

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p-ISSN 1412-0313 e- ISSN 2549-7529

Shoreline Change Analysis using DSAS

Shoreline change analysis was conducted using the DSAS add-in version 5 within ArcMap software (version 10.4). This method requires two main input datasets

Shoreline Feature Class: All delineated shorelines (from 1999 to 2023) were compiled into a single feature class. Each shoreline was attributed with its respective acquisition date and an uncertainty value. The uncertainty value accounts for potential inaccuracies in image georeferencing and visual digitization, aiding in robust intersection point determination (Arjasakusuma et al., 2021; Himmelstoss et al., 2021).

Baseline Feature Class: A non-intersecting baseline was established landward of all historical shorelines. The oldest shoreline (1999) was used as a guide for creating this baseline to ensure it served as a consistent reference point (Marfai et al., 2022; Mutaqin, 2017). The baseline was attributed with unique IDs and grouping information as required by DSAS (Himmelstoss et al., 2021).

Following input preparation, transects were cast perpendicular to the baseline at a uniform spacing of 1000-2000 m along the entire study area. A maximum search distance of 20000 m was applied to ensure all shoreline segments intersected the transects (Himmelstoss et al., 2021).

Shoreline change rates were then calculated for each transect using the NSM statistic. The NSM was selected due to its effectiveness in calculating changes between two specific points in time (the oldest and most recent shoreline), providing a clear rate of change for each shoreline segment (Lazuardi et al., 2022; Marfai et al., 2022). A negative NSM value indicates erosion, while a positive value denotes accretion **(Table 1)**. The resulting patterns and magnitudes of shoreline change across the Northern Coast of Central Java were then spatially visualized and statistically summarized. The overall research workflow is illustrated **in Figure 2**.

Table 1. Category of Shoreline Changes Based on NSM Value

No.	Category	NSM Value (m/year)
1	Very high erosion	< -2
2	High erosion	-1 to -2
3	Moderate erosion	0 to -1
4	Stable	0
5	Moderate accretion	0 to +1
6	High accretion	+1 to +2
7	Very high accretion	> +2

Source: *Nassar et al. (2018)* and *Alwi et al. (2023)*

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p-ISSN 1412-0313 e- ISSN 2549-7529

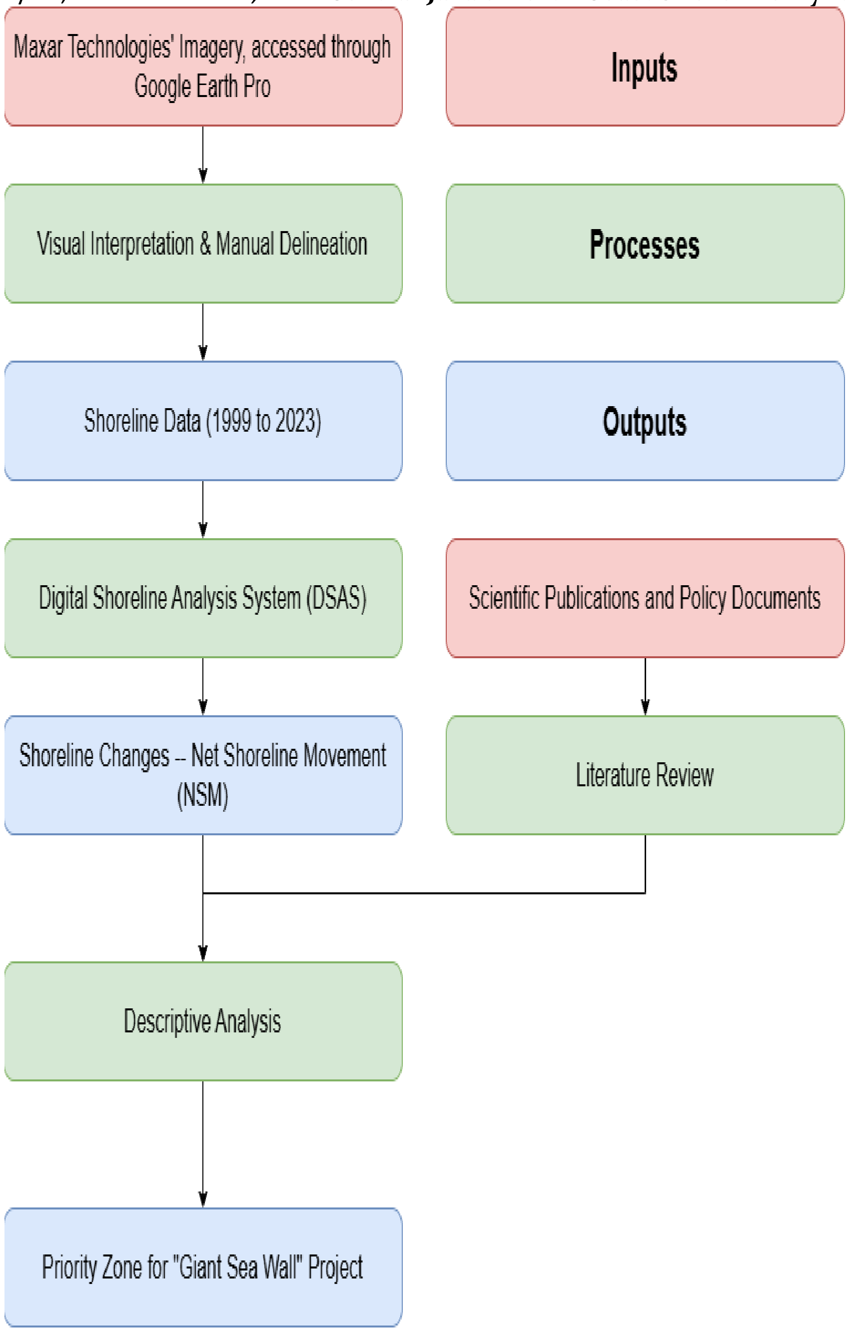

Figure 2. Research Framework

4. RESULTS AND DISCUSSION

The findings of this study reveal that the majority of coastal areas along the northern coast of Central Java are subject to severe erosion, classified within the highest category of erosion intensity **(Table 1 and Figure 3)**. In particular, the coastal areas of Demak and Semarang exhibit critically high erosion levels, as evidenced by a landward retreat of the shoreline exceeding 2 meters or more **(Figure 4)**. These results are also supported by several modeling studies in the same area by (Muskananfola et al., 2020; Sagala et al., 2024). According to Muskananfola (2020), the coastline in the region receded by nearly 600 meters from 1994 to 2018. Conversely, (Sagala et al., 2024) stated that the Demak coastline is moving inland at 8.96 m/year between 2000 and 2020.

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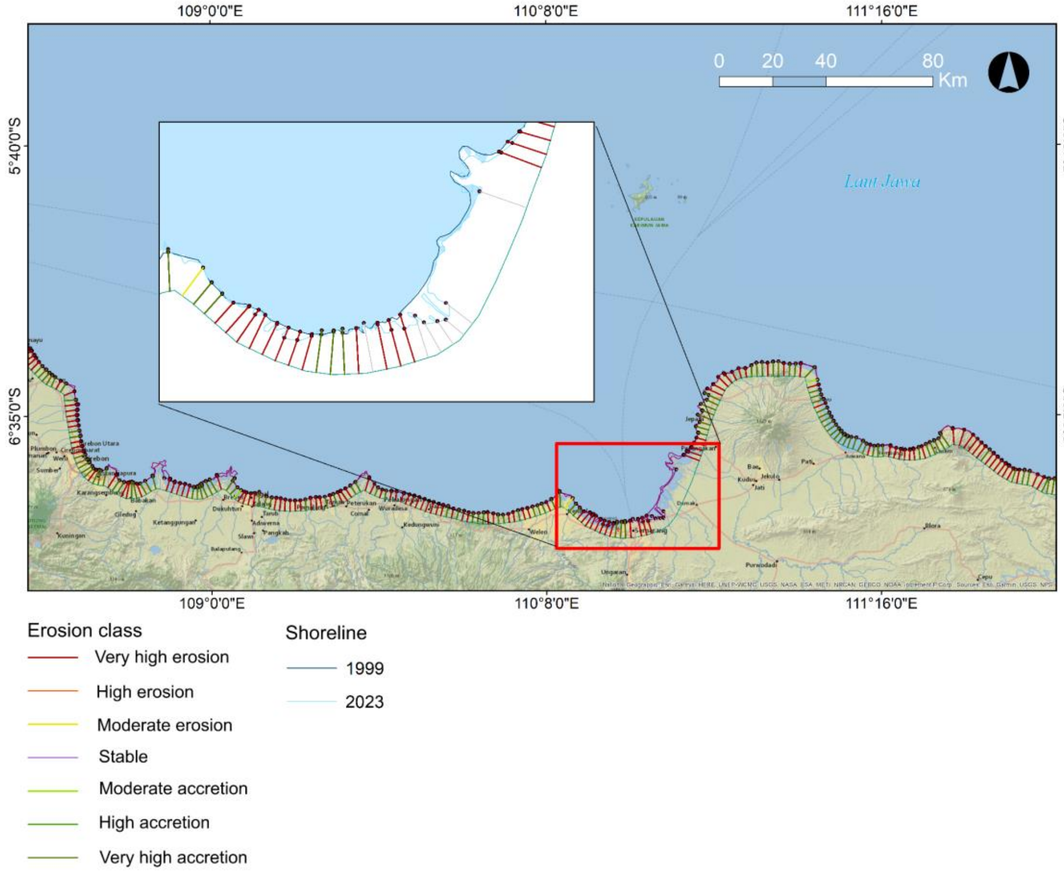

Figure 3. Map of spatial distribution of shoreline changes in the northern coastal area of Central Java Province.

The severe coastal erosion observed along Central Java's northern coast, particularly in the Semarang-Demak area, underscores a critical imbalance in the coastal sediment budget, as highlighted by the coastal morphodynamics theory (Bird, 2011; Komar, 1998). A negative sediment budget, where sediment outputs exceed inputs, directly manifests as the shoreline retreat quantified in this study. This erosion is driven by a combination of natural hydrodynamic forces such as wave action, currents, and tidal fluctuations—and exacerbated by significant anthropogenic activities. As recognized by the coupled human-natural systems framework (Liu et al., 2007), human interventions like extensive coastal urbanization, infrastructure development, and changes in land use (e.g., mangrove deforestation) have altered natural sediment pathways and reduced inherent coastal protection, intensifying the region's vulnerability to erosion (Zhang and Hou, 2020; Noor and Maulud, 2022).

In response to this escalating issue, the proposed Giant Sea Wall project is conceptualized as a major coastal protection measure. Its primary purpose, consistent with principles of coastal engineering, is to physically block wave energy and limit further shoreline retreat, thereby protecting vulnerable land and infrastructure. For a region experiencing rapid and substantial land loss, such as Semarang-Demak, a large-scale hard structure like a sea wall aims to re-establish a stable boundary where natural processes have failed to maintain one. By providing a fixed barrier, the Giant Sea Wall directly intervenes in the coastal morphodynamics, attempting to shift the local sediment budget equilibrium by preventing the removal of sediment from the landward side and reducing the erosive impact of incoming

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p-ISSN 1412-0313 e- ISSN 2549-7529

waves. This aligns with the prioritization strategy of intervening in areas with the most immediate risks to coastal communities and infrastructure (Bianchini, A., 2019).

(a)

(b)

Figure 4. Shoreline position in Demak and Semarang coastal area between: a) 1999 and b) 2023.

Following the quantitative analysis of shoreline change rates using the DSAS and the classification, this study contributes to the prioritization of zones for the strategic implementation of the proposed Giant Sea Wall project along the northern coast of Central Java. Based on the findings, it is recommended that the Giant Sea Wall should not be constructed along the entire northern shoreline of Central Java. Instead, priority should be given to the coastal area between Semarang and Demak, which has exhibited the highest rate of shoreline erosion during the study period.

This area holds strategic importance, as it encompasses residential settlements, aquaculture facilities (e.g., fish ponds), and the Jatengland Industrial Park Sayung (JIPS)—a key industrial zone for Central Java Province. Furthermore, as predicted by (Sirait et al., 2024), the increasing occupancy of this industrial area is likely to intensify the complexity of land use and reduce accessibility, thereby heightening the urgency for protective infrastructure to mitigate future shoreline-related hazards. This situation mirrors challenges in other rapidly developing Indonesian regions where intense economic growth intersects with escalating flood risks and environmental degradation (Agustina, 2021).

The prioritization strategy proposed in this study aligns with the principle that regions undergoing rapid and substantial land loss represent the most immediate risks to coastal communities, infrastructure, and ecosystems, and thus demand urgent intervention (Bianchini, A., 2019).

It is worth noting that a toll road, which also functions as a seawall, is currently planned for development. According to a report by Muazam and Fahmi (2025), this structure will extend from Tanjung Mas Village in Semarang to Kadilangu in Demak. However, this planned development does not encompass the entirety of the affected coastline. Several northern coastal areas such as Bedono, Timbulsoko, and Surodadi Villages are expected to remain unprotected and vulnerable to ongoing shoreline retreat **(Figure 5)**. This highlights the fragmented nature of current and planned coastal protection efforts and emphasizes the need for a more comprehensive and strategically targeted approach, such as the focused implementation of the Giant Sea Wall as recommended by this study, to address the widespread and severe erosion across the northern coast.

Figure 5. The Location of Sea Wall Toll Road.

5. CONCLUSIONS

The findings of this study indicate that the northern coastal region of Central Java, particularly in Demak and Semarang, is experiencing severe shoreline erosion, posing significant socio-economic and environmental risks. While existing protective measures offer partial relief, the continued shoreline retreat in these critical zones highlights an urgent need

DOI: https://doi.org/10.17509/gea.v26i1,%20April.97852
p-ISSN 1412-0313 e- ISSN 2549-7529

for comprehensive intervention. The quantified spatiotemporal patterns of erosion, particularly in the highly vulnerable Demak-Semarang corridor, strongly suggest that this region is a prime candidate for large-scale coastal protection initiatives, such as the proposed Giant Sea Wall, to safeguard key assets and prevent further losses. Future planning and implementation of such measures would benefit from more accurate and refined data to ensure precision and effectiveness in addressing shoreline change. In addition, future planning should take into account the sediment balance in the surrounding area as well as the socio-economic conditions of the people living near the area.

6. RECOMMENDATIONS

It is recommended that future researchers and relevant authorities prioritize further investigation and mitigation efforts in the critically eroded coastal zones between Semarang and Demak. Given the strategic significance of this area, which includes densely populated settlements, aquaculture operations, and the Jatengland Industrial Park Sayung (JIPS), immediate protective interventions are needed to prevent further land loss and socio-economic disruption. Future research should refine shoreline change assessments by addressing data processing limitations within the Digital Shoreline Analysis System (DSAS) to ensure accurate spatial representations.

6. ACKNOWLEDGMENT

The author gratefully acknowledges the support provided by Irene Renika and Anugrah Jorgi Firmansyah during the writing process. Appreciation is also extended to the anonymous reviewers whose valuable feedback contributed to the improvement of this study.

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