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MORALITY BEFORE KNOWLEDGE

The role of mangrove forests in socio-economic adaptation to coastal morphological changes: Community-based strategies for shoreline shifts and environmental degradation

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ABSTRACT

Background: The northern coast of Java, especially Demak Regency, is highly vulnerable to natural disasters and human-induced shoreline changes, leading to environmental degradation and direct impacts on local communities. Previous studies have not fully addressed the effects on populations or adaptation strategies. This study aims to assess the effects of shoreline changes on ecosystems and communities while identifying community-based adaptation strategies. **Methods**: A literature review was conducted, analyzing recent academic articles on shoreline changes and community adaptations. Data were selected based on relevance and analyzed qualitatively to explore the relationship between coastal changes and adaptation strategies. **Findings:** Shoreline changes are the primary driver of vulnerability in Demak, correlating with mangrove decline. Communities adapt by relying on mangrove ecosystems and implementing socio-economic and structural adjustments to cope with environmental shifts. **Conclusion**: Shoreline changes significantly affect coastal environments and local communities, necessitating integrated adaptation strategies. **Novelty/Originality of this article:** This study highlights the relationship between shoreline changes and community adaptations, emphasizing the critical role of mangroves in socio-ecological resilience.

KEYWORDS: shoreline change; coastal vulnerability; tidal flooding; adaptation; mangrove.

1. Introduction

Coastal areas are transitional zones between land and sea, characterized by rich biodiversity, natural features, and significant economic resources. These areas are often densely populated and widely utilized for settlements, industry, tourism, and regional development due to their abundant potential. Coastal regions form a complex ecosystem that supports various habitats but are also highly vulnerable to natural phenomena such as accretion, erosion, sedimentation, cyclonic storms, tidal movements, human activities, and the impacts of sea level rise (SLR) (Dewi & Bijker, 2020; Halder et al., 2022; Hussein et al., 2023; Laksono et al., 2022; Natarajan et al., 2021; Tsiakos & Chalkias, 2023). SLR, driven by global warming and climate change, accelerates changes in coastal ecosystems, causing land degradation and altering coastlines (Ankrah et al., 2022; Halder et al., 2022; Nijamir et al., 2023).

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The shoreline, which marks the boundary between the ocean and land, is directly influenced by tidal waves and serves as a key indicator for monitoring environmental changes in coastal regions. This dynamic geomorphological feature is constantly shaped by natural processes, climatic conditions, and anthropogenic factors such as coastal development, jetty construction, and tourism infrastructure expansion (Dewi & Bijker, 2020; Halder et al., 2022; Hossen & Sultana, 2023; Yum et al., 2023). Shoreline change is a critical concern in coastal management, requiring regular monitoring to understand the dynamics and spatial distribution of these changes for effective disaster prevention planning (Al-Zubieri et al., 2020; Halder et al., 2022; Mishra et al., 2020). Globally, the length of the coastline is estimated to be approximately 504,000 km, with over 50% of the world's population residing within 100 km of the coast (Toure et al., 2019).

Indonesia, an archipelagic nation, is among the countries with the longest coastlines, spanning approximately 95,181 km (Purwanti & Koestoer, 2024). This morphology, is highly vulnerable to sea-level rise (Azuga, 2021). The impacts of climate change became evident in the 20th century, with sea levels rising at an average rate of 4.6 mm per year during the 1993–2018 period, and this trend is expected to continue, with positive velocity values indicating ongoing sea-level rise (Handoko & Ariani, 2019). These changes have had detrimental effects on coastal communities, resulting in tidal flooding, shoreline shifts, and coastal erosion (Primasti et al., 2021).

The coastal regions of Central Java, particularly Demak Regency, are among the areas most affected by year-round tidal flooding, which has significant implications for residential environments and land-use planning. This has led to the reduction of mangrove forests, as well as the decline of pond and residential areas (Ardiyanto & Putrideta, 2024). In Demak Regency, ten villages in the Sayung Subdistrict are particularly vulnerable to tidal flooding, including Sriwulan, Bedono, Purwosari, Sidogemah, Gemulak, Tugu, Timbulsloko, Surodadi, Sidorejo, and Banjarsari (Kusuma et al., 2016).

Mangroves play a vital role in coastal ecosystems by preventing erosion, providing habitats for aquatic organisms, protecting coastal communities from extreme weather events, and serving as carbon sinks that mitigate global warming (Arceo-Carranza et al., 2024). The presence of mangrove vegetation in coastal areas is a key indicator of the physical health of these environments. Java Island, in particular, boasts the highest mangrove diversity in Indonesia, with 167 species recorded along its coastal waters. These mangroves thrive in areas such as estuaries and beaches with high sedimentation rates (Duryat et al., 2023).

Mangrove vegetation along the coastal area of Demak Regency has been significantly affected by tidal inundation, locally known as "rob," which has altered the land area in this region. This phenomenon has resulted in a reduction of 141.94 hectares of land in Demak's coastal zone (Ramadhani et al., 2021). Wicaksono et al., (2022) further reported that the land loss also contributed to the retreat of the coastline by approximately 2 kilometers, as seawater inundation encroached inland. This transformation has led to the conversion of formerly agricultural land into fishponds. In addition to the retreating coastline, the changes have also had a notable impact on the mangrove forests in Demak Regency.

According to Akbaruddin et al., (2020), the total mangrove land area decreased by 637.28 hectares between 2016 and 2019 due to these shifts in coastal morphology. Tidal flooding, or "rob," occurs when sea tides inundate coastal areas that lie below mean sea level. These inundations can last for several days or even a week, with the flood depth varying according to gravitational forces, as water flows to and fills the lowest areas (Kusuma et al., 2016). Tidal flooding results in muddy roads, obstructed drainage systems, saltwater intrusion into groundwater, and damage to building structures such as cracked or tilted floors, rotting foundations, and in some cases, the sinking of land due to soil subsidence (Bosserelle et al., 2022).

One of the primary causes of tidal flooding in the Sayung Subdistrict is the low land elevation, which falls below the highest sea level during peak tides. Residential areas near the coastline are particularly vulnerable to this flooding during high tides (Karmilah & Madrah, 2024). The phenomenon is further exacerbated by coastal abrasion and accretion, with significant annual changes in the shoreline. In addition to rising sea levels caused by climate change, coastal abrasion is driven by the reclamation of Marina Beach and the expansion of industrial zones in Semarang, which borders Sayung Subdistrict. These reclamation activities push seawater further inland (Marfai, 2012). Accretion, on the other hand, is caused by the deposition of sediments carried by rivers in Demak Regency (Muskananfola et al., 2020). Tidal flooding in Demak Regency, which affects various areas, has significant implications for the residential environment. One contributing factor to this issue is land subsidence (Ardiyanto & Putrideta, 2024).

The coastal area of Sayung Subdistrict is currently experiencing severe environmental degradation, primarily due to coastal abrasion and tidal flooding. These processes have resulted in the submersion of fish ponds and residential areas, with some areas being lost entirely (Muskananfola et al., 2020). In 2016, the length of the coastline changed by 32.138 km (Utami et al., 2017), and the extent of coastal abrasion totaled 116.48 hectares, with the greatest impact observed in Timbulsloko Village and the least in Sriwulan Village (Ramadhani et al., 2021).

To mitigate the impact of coastal disasters, it is crucial to assess the vulnerability of affected areas. One approach is through the Coastal Vulnerability Index (CVI), which evaluates the physical condition of coastal areas. CVI is a relative ranking method based on physical parameters such as geomorphology, shoreline change, elevation, tides, sea-level rise, and wave height (Kasim et al., 2012).

In 2016, Demak Regency had a coastline stretching 72.14 km, from Sayung Subdistrict to Wedung Subdistrict (Dinas Kelautan dan Perikanan Kabupaten Demak, 2016). The regency's mangrove forests, located along the coast and in pond areas, serve a vital physical function by retaining sediment and promoting the formation of new land. As of 2015, the mangrove area covered 2,021.28 hectares, distributed across four coastal subdistricts, though not all villages in these areas have mangroves. Inland fisheries and fishponds are also prominent in Demak Regency's coastal regions.

According to the Central Bureau of Statistics, a total of 9,724 hectares of land were utilized for fishponds or state forests (Badan Pusat Statistik, 2016). The use of Sentinel-2A satellite imagery, through composite channels and guided classification, allows for the precise determination of the extent of mangrove forests and pond areas. This data is intended to raise awareness among local residents about the importance of preserving mangrove forests to reduce the risk of coastal erosion and mitigate shoreline changes, while also helping to sustain livelihoods in the coastal region (Akbaruddin et al., 2020).

In Java, coastal flooding impacts several areas, posing serious risks to residential environments. One major contributing factor is land subsidence. In Bedono Sayung Village, residents have adopted various adaptation strategies to reduce the effects of tidal flooding, including raising house foundations. In nearly all villages affected by tidal flooding, many residents have been forced to elevate the foundations of their homes, often multiple times, as land subsidence and tidal flooding continue to worsen each year. However, this adaptation comes at a significant cost, which is borne by the residents without government assistance. Not all families can afford these repairs, leaving some households vulnerable to daily tidal flooding (Ardiyanto & Putrideta, 2024).

Consistent shoreline changes along the coast of Sayung Subdistrict have significant implications for the local community, particularly in their efforts to adapt to these changes. Adaptation refers to actions taken to address environmental changes, both reactively and proactively, by adjusting to current conditions (Sagala et al., 2024). This approach emphasizes the importance of adjusting to changing circumstances in order to sustain life and maintain settlements in coastal areas (Pinuji et al., 2023).

Understanding the impacts of these coastal changes is crucial for identifying the level of vulnerability and projecting future risks to coastal areas. The Coastal Vulnerability Index (CVI) serves as a valuable tool for spatially assessing coastal vulnerability and estimating how these conditions may evolve over time. As such, a comprehensive analysis of coastal vulnerability in Demak Regency is necessary to inform coastal management and mitigation strategies, reducing the risks associated with the dynamic coastal environment (Primasti et al., 2021).

The Sayung area is highly vulnerable to disasters due to its coastal location. Specifically, Morosari Hamlet in Bedono Village, which is situated directly adjacent to the sea, faces an elevated risk of disaster events. According to the multi-disaster risk map, Morosari Hamlet is classified as a high-risk area, particularly prone to severe coastal abrasion and tidal flooding, primarily due to its proximity to the sea (Rif'an & Wenan Tyawati, 2020).

Coastal communities, as the first to experience the direct impacts of disasters, must respond and adapt to the changing environment. In terms of adaptive responses, communities often focus on familiarizing themselves with disaster conditions and adjusting their behaviors accordingly (Ardiyanto & Putrideta, 2024). Based on this context, the present study aims to analyze shoreline changes in Sayung Subdistrict from 2000 to 2020, as well as investigate how coastal communities in Sayung are adapting to these ongoing environmental changes.

2. Methods

Coastal communities, as the first to experience the direct impacts of disasters, must respond and adapt to the changing environment. In terms of adaptive responses, communities often focus on familiarizing themselves with disaster conditions and adjusting their behaviors accordingly (Ardiyanto & Putrideta, 2024). Based on this context, the present study aims to analyze shoreline changes in Sayung Subdistrict from 2000 to 2020, as well as investigate how coastal communities in Sayung are adapting to these ongoing environmental changes.

This research adopts a literature review approach aimed at identifying, analyzing, and synthesizing studies on community adaptation to shoreline changes. This method allows for the exploration of up-to-date, relevant secondary data sources, specifically peer-reviewed scientific journal articles from academic databases. These sources discuss the phenomenon of shoreline change and the adaptive responses of coastal communities. The selection criteria for the literature were based on relevance to key topics, including shoreline changes due to natural and anthropogenic factors, the social and environmental impacts of these changes, and the various forms of community adaptation, whether social, economic, or physical.

The data collection process involved identifying and compiling relevant journal articles related to the research topic. The steps were as follows: literature search, literature selection, and data organization. Literature searches were conducted using pre-defined keywords in academic search engines and journal databases. Articles were then selected based on their relevance to shoreline changes and community adaptation. Studies that were not pertinent or did not meet the selection criteria were excluded. In the data organization stage, the selected studies were categorized according to main themes. These articles were then analyzed to identify key findings, patterns of adaptation, and factors contributing to the success or failure of adaptation efforts.

A qualitative content analysis method was employed to analyze the data, identifying patterns, themes, or trends across different studies. The analysis process consisted of data coding, grouping, and interpretation. Each article was coded based on major themes related to community adaptation and shoreline changes. The coded data were further categorized into adaptation aspects (social, economic, and environmental) and the influencing factors. These grouped data were then interpreted to understand how coastal communities respond to shoreline changes and the factors that shape the adaptation process.

The articles analyzed included studies using Sentinel-2A imagery and the Coastal Vulnerability Index (CVI) to assess shoreline changes. Observations and interviews were employed to examine patterns of community adaptation. Landsat 5 and Landsat 8 satellite data, retrieved from the USGS website (https://earthexplorer.usgs.gov/) under Path 120 and Row 65, were used in the analysis. To ensure clear data processing, images with minimal cloud cover were preferred. The selected data included Landsat 5 imagery from 2000, 2005, and 2010, and Landsat 8 imagery from 2013 and 2020. These images were processed using Er Mapper 7.0 and ArcGIS 10.2 software.

The coastal impacts of shoreline changes were examined to spatially identify the level of coastal vulnerability and to project future changes. The Coastal Vulnerability Index (CVI) was used to assess vulnerability levels and to estimate future coastal changes. The analysis of community adaptation to shoreline changes was focused on the residents of Sayung Subdistrict, particularly in relation to land reduction.

3. Results and Discussion

The analysis focused on four villages in the coastal area of Sayung District, namely Bedono, Timbulsloko, Surodadi, and Sriwulan (Table 1). Landsat 8 satellite imagery was employed to digitize the coastline from 2013 to 2020. The digitized coastlines for each year were then overlaid into a single layer, facilitating the observation of coastline changes over time.

Table 1. Change in area of each village

Village	Accretion (ha)	Abrasion (ha)
Surodadi	11.72	16.75
Bedono	1.74	89.78
Timbulsloko	9.01	25.24
Sriwulan	9.72	14.15

These changes included both seaward and landward shifts of the shoreline. Over the eight-year period, significant alterations were observed, with shoreline retreat being the dominant trend, primarily driven by coastal abrasion. The visual impact of these changes is depicted by Ramadhani et al., (2021) in Figure 1 and Figure 2, which illustrate the gains and losses in coastal areas within Sayung Subdistrict between 2013 and 2020.

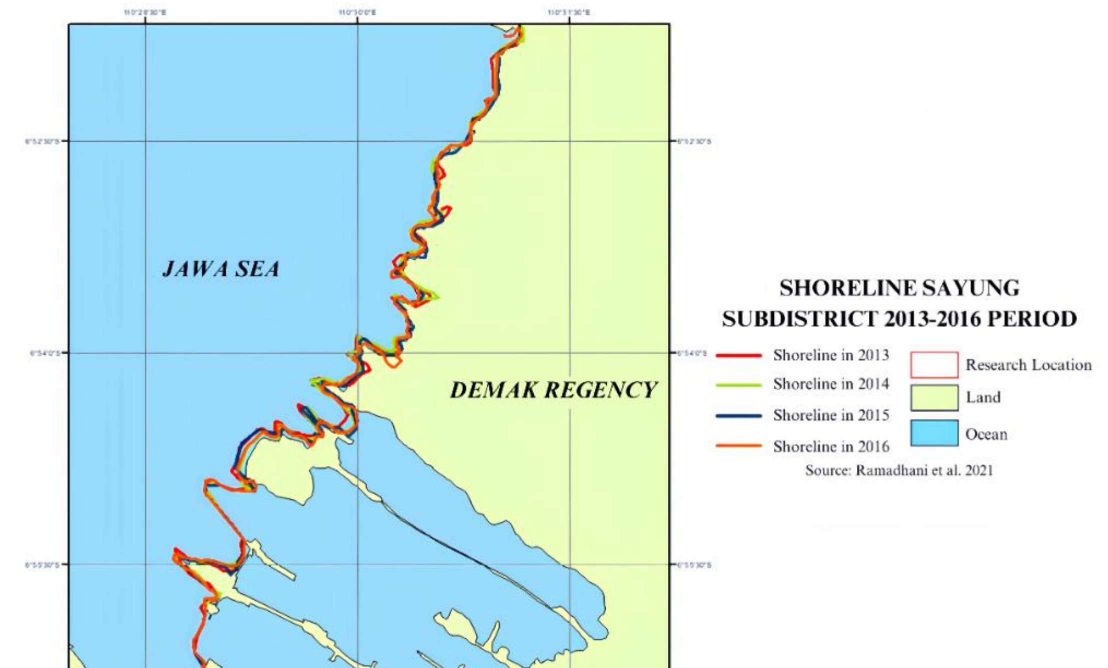

Fig. 1 Map of coastal shoreline changes in sayung subdistrict 2013-2016 (Ramadhani et al. 2021)

The analysis of Landsat 8 imagery using the Digital Shoreline Analysis System (DSAS) revealed significant coastal changes in the administrative area of Sayung Subdistrict between 2013 and 2020. Over this period, the coastline, which spans 20,953.59 meters, experienced substantial modifications. A total of 141.49 hectares were lost due to coastal abrasion, while accretion contributed to a gain of 36.61 hectares.

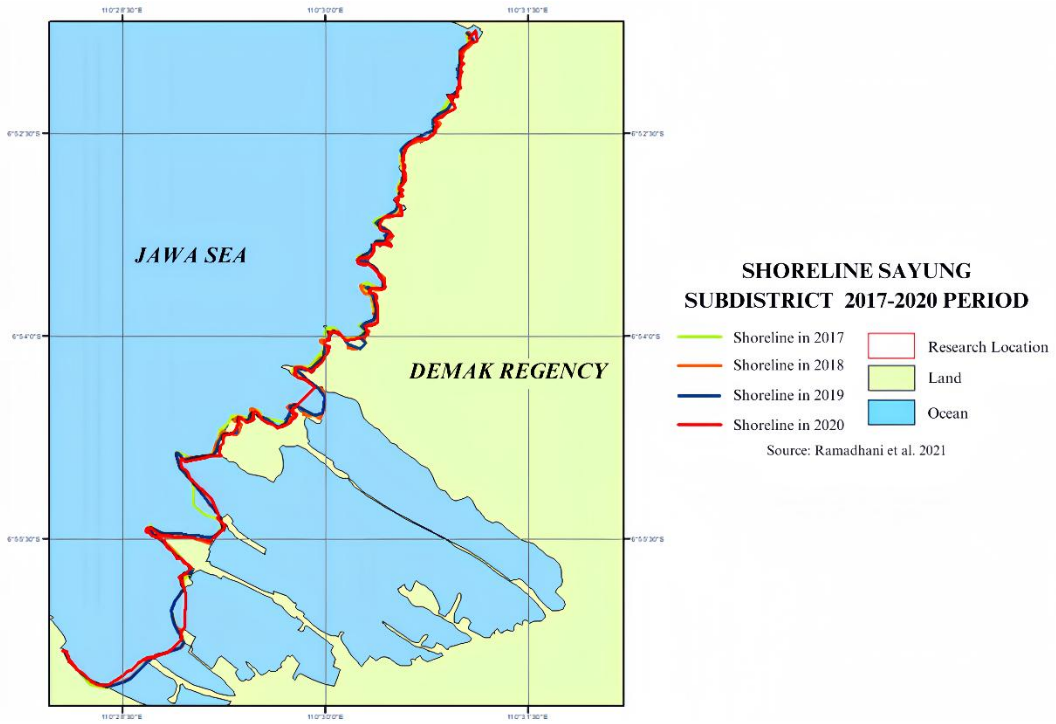

Fig. 2 Map of coastal shoreline changes in sayung subdistrict 2017-2020 (Ramadhani et al. 2021)

Surodadi Village saw 16.75 hectares affected by abrasion and 11.72 hectares gained through accretion. Bedono Village experienced the most severe abrasion, losing 89.78 hectares, with only 1.74 hectares gained from accretion. Timbulsloko Village recorded 25.24 hectares of abrasion and 9.01 hectares of accretion, while Sriwulan Village lost 14.15 hectares to abrasion and gained 9.72 hectares through accretion. Overall, coastal changes in Sayung Subdistrict during the 2013–2020 period were predominantly driven by abrasion, which accounted for 82% of the total changes in land area, while accretion made up only 18% (Figure 3).

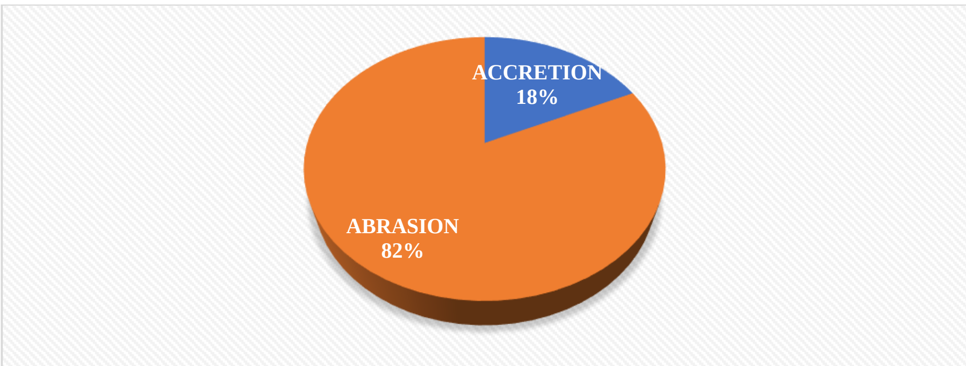

Fig. 3 Percentage of area change in the coastal area of sayung subdistrict 2013-2020 Period

The research findings indicate that the coastline of Timbulsloko Village has shoreline changes, primarily driven by the processes of erosion and accretion. However, from 2000 to 2017, erosion was the dominant force shaping the coastal area. The most severe erosion occurred between 2005 and 2010, causing extensive damage to the coastal region (Table 2).

Table 2. Timbulsloko Village Shoreline Length

Year	Length of Shoreline (km)	Change Rate (km)
2000	2.69	0
2005	2.58	(-0.11)
2010	7.33	(+4.75)
2015	5.12	(-2.21)
2017	5.36	(+0.24)

(Purba et al., 2019)

Erosion was also observed during the periods of 2000–2005, 2010–2015, and 2015–2017, although its intensity was less severe compared to the 2005–2010 period. The ongoing effects of erosion have led to significant damage to pond areas and land in Timbulsloko Village, posing a serious threat to vital coastal resources that are crucial to the local economy and environment. Abdullah et al. (2023) support the finding that the coastline in Demak, particularly in Timbulsloko Village, has been eroding since 2002, with significant losses observed in the remaining pond areas. This region, originally a mangrove forest, has experienced erosion rates of up to 900 meters over a decade. The erosion pattern in Timbulsloko closely follows the layout of the existing ponds. Despite the land loss caused by erosion, Timbulsloko Village also witnessed land gain through accretion. The most significant accretion occurred between 2015 and 2017, thanks to the collaborative efforts of the local community and support from Wetlands International. During this period, Hybrid Engineering technology was implemented to reinforce the shoreline, coupled with a sustainable mangrove planting and maintenance initiative. These efforts played a crucial role in restoring the coastal ecosystem in Timbulsloko Village.

Table 3 illustrates that all villages in the coastal Sayung Sub-district have experienced significant shoreline changes, primarily driven by abrasion. Bedono Village experienced the highest degree of shoreline loss due to abrasion, with an average retreat of 142.81 meters and an abrasion rate of 19.87 meters per year. Despite this, Bedono Village also recorded the highest accretion, with an average shoreline gain of 66.82 meters and an accretion rate of 9.30 meters per year. In contrast, Sriwulan Village experienced the least abrasion, with an average shoreline retreat of 45.59 meters and an abrasion rate of 9.81 meters per year. Surodadi Village, on the other hand, recorded the lowest accretion, with an average shoreline increase of 35.13 meters and an accretion rate of 6.09 meters per year. These figures demonstrate the varied coastal dynamics across the villages, where both abrasion and accretion have different impacts on shoreline changes.

Table 3. Calculation results of shoreline change 2013-2020

Villages	Shoreline Change Distance (m)				Shoreline Change Rate (m)				Description
	Highest	Lowest	Average +	Average -	Highest	Lowest	Average +	Average -	
Surodadi	104.54	-117.11	35.13	-58.08	14.92	-16.30	6.09	-7.25	Abrasion
Timbulsloko	184.86	-456.76	59.1	-110.56	25.72	-63.56	8.22	-15.38	Abrasion
Bedono	251.08	-476.49	66.82	-142.81	34.94	-66.31	9.30	-19.87	Abrasion
Sriwulan	439.87	-216.4	37.32	-49.59	36.7	-30.11	9.27	-9.81	Abrasion

(Ramadhani et al. 2021)

The preliminary Coastal Vulnerability Index (CVI) analysis compared six variables to assess their individual contributions to coastal vulnerability at the selected sites. This analysis provides insight into specific conditions contributing to vulnerability, informing management strategies to mitigate these risks. CVI and Mangrove Vulnerability Index (MVI) were calculated by assigning equal weight to each variable across three areas. For example, shoreline change values indicated that negative values represent erosion (ranked as moderate, high, or very high vulnerability), while positive values signify accretion (ranked as very low or low vulnerability). The geomorphological analysis revealed that 60 of the 78 grids in Demak Regency, covering approximately 60 km^2 (76.9%), were classified as highly vulnerable. The Demak coastline has experienced significant erosion due to land-use changes and seawater intrusion, with geomorphology characterized by sandy coastal and alluvial plains. Between 2000 and 2020, erosion dominated the study area with an average shoreline change rate of -8.96 m/yr across the Demak coast. The maximum erosion rate was 153.9 m/yr, while accretion was recorded at +116.78 m/yr. A majority (86%) of Demak's coast displayed negative shoreline change (<0 m/yr), classifying 66 grids (95.19 km) as high vulnerability (Figure 4).

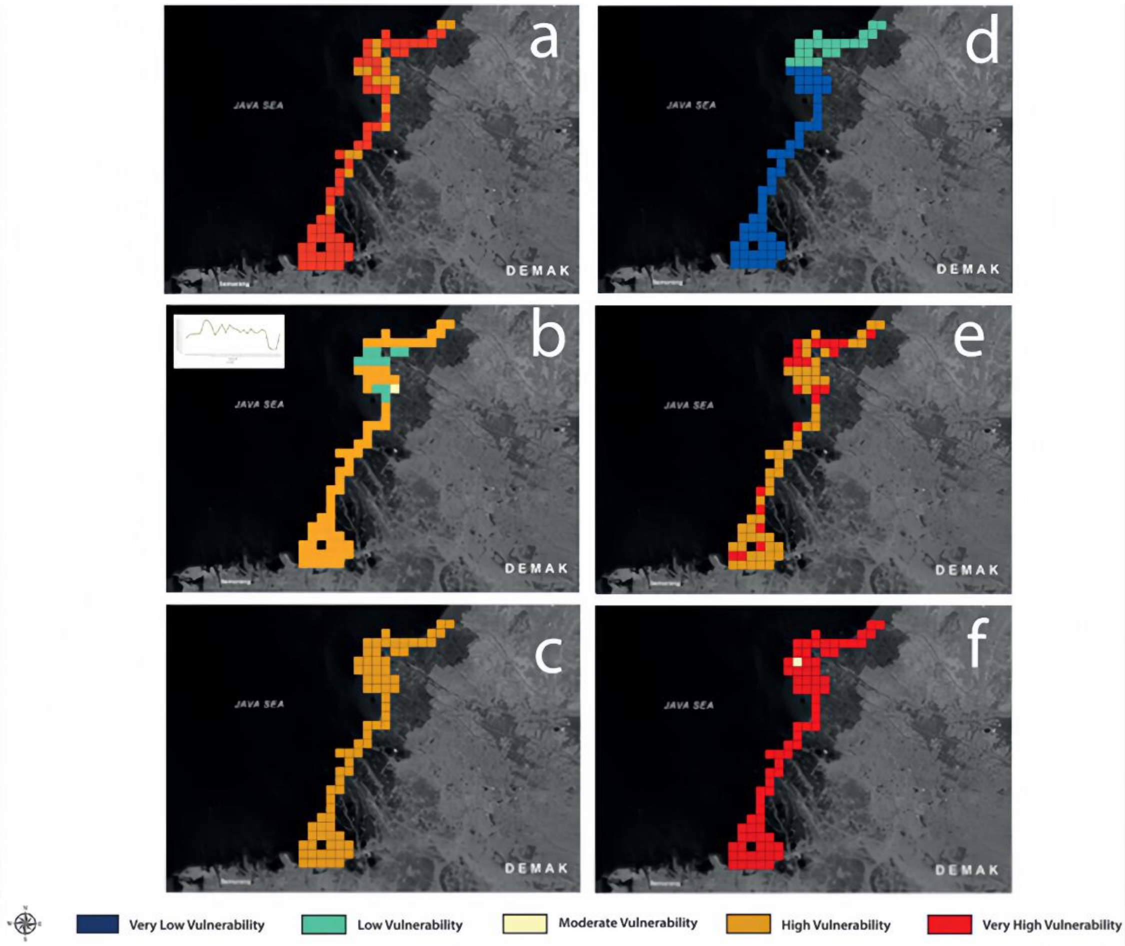

Fig. 4 Vulnerability ranking in Demak of variables respectively: a) geomorphology; b) shoreline change rate; c) rate of sea level rise; d) significant wave height; e) coastal slope; f) bathymetry (Sagala et al., 2024)

The analysis also highlighted that sea-level rise significantly contributes to coastal degradation in Demak Regency. Between 1993 and 2016, historical sea-level change rates exceeded 3.0 mm/yr, with an annual mean sea-level trend between 5.8 and 6.2 mm/yr (covering 78 grids or 78 km^2). Mean significant wave heights ranged from 0.2 to 1.0 m, with 21 grids (27% or 21 km^2) classified as low vulnerability. Demak's gentle slopes and lowlying plains make it susceptible to coastal hazards such as flooding. Specifically, 71.79% of the coastal area (56 grids or 56 km) falls into the high vulnerability category, and 28% (22 grids or 22 km) is classified as very high vulnerability, with slopes between 0 and 6 degrees. Across Demak Regency, 87.99 km (80%) were identified as high vulnerability and 22.30 km (20%) as very high vulnerability. Regarding bathymetry, approximately 99% (77 km^2) of Demak's coast fell into very high vulnerability, while 1% (1 km^2) was categorized as moderate vulnerability.

Table 4. Mangrove area change 2016-2019

Year	Mangrove Area Change (Ha)		
	Increased Area	Decreased Area	Fixed Area
2016-2017	407.4	422.82	984.48
2017-2019	561.73	476.89	902.51
2016-2019	569.30	673.28	748.07

(Akbaruddin et al., 2020)

Changes in mangrove coverage involve both expansion along the shoreline and within pond areas. This expansion is primarily due to the natural sediment-trapping function of mangroves, which gradually leads to the formation of new land. However, mangrove area loss also occurs along the shoreline, driven by strong wave energy that accelerates coastal abrasion and results in a reduction of mangrove coverage.

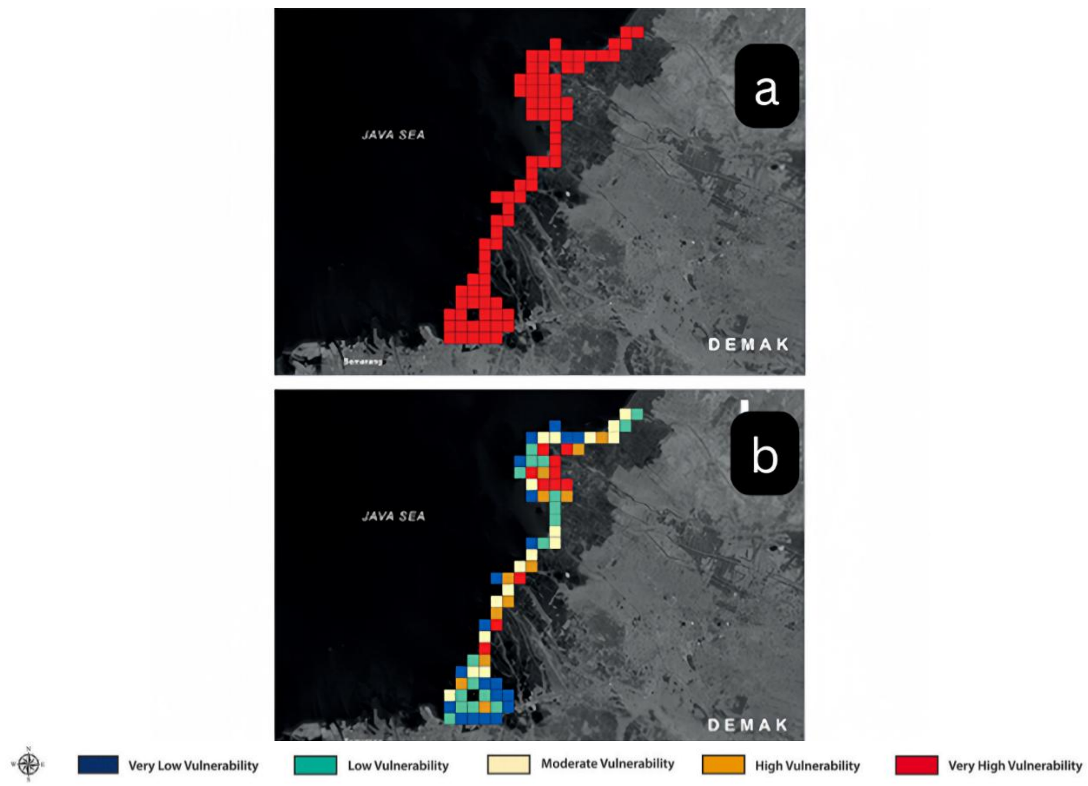

Fig. 5 a) Mean Tidal Range and b) Mangrove Density of Sayung Demak
(Sagala et al., 2024)

The mangrove area in the coastal villages of Demak Regency has fluctuated over recent years, with a total of 1,429.48 hectares in 2016, 1,405.72 hectares in 2017, and 1,475.98 hectares in 2019. Changes in mangrove area during these years are detailed in Table 4. Between 2016 and 2017, the mangrove area experienced an addition of 407.51 hectares, a reduction of 422.84 hectares, and an unchanged area of 984.6 hectares. From 2017 to 2019, the changes included an increase of 561.78 hectares, a decrease of 476.94 hectares, and an unchanged area of 902.6 hectares. Over the period from 2016 to 2019, there was a total increase of 569.37 hectares, a decrease of 476.94 hectares, and 884.6 hectares of mangroves that remained stable.

The tidal range in Demak Regency was found to be inversely related to vulnerability, where a higher tidal range indicated lower vulnerability, and vice versa. The mean tidal ranges along the Demak coastlines, measured at 0.5 m and 1 m, place these areas in the very high vulnerability category. Over the past few decades, the Demak coast has experienced substantial mangrove loss. Approximately 51% (40 km^2) of the study grids along the Demak coast were categorized as having moderate, high, or very high vulnerability. These areas are particularly susceptible to natural factors and anthropogenic pressures, including land-use changes. Low to very low vulnerability areas were primarily those with limited mangrove presence, often growing in specific estuarine conditions or in isolated patches.

The Mangrove Vulnerability Index (MVI) was computed using eight variables, as applied in the study by Mondal et al. (2022), which calculated mangrove vulnerability zones based on a combination of physical and anthropogenic factors. In this study, mangrove vulnerability reflects the combined effects of these eight variables and suggests management zones for mangrove conservation based on MVI scores and rankings. The findings aim to evaluate the resilience of mangrove ecosystems to various hazards and to provide insights into the current vulnerability conditions of mangrove forests. Overall, Demak Regency continues to have the largest percentage of area and coastline length classified as highly vulnerable, affecting 46% of the total area and 43% of the coastline length. These high-vulnerability zones are predominantly concentrated in Sayung, with no grids categorized as low-vulnerability across the study area. The results of the coastal vulnerability analysis highlight the emergence of new adaptation patterns among coastal communities in Demak Regency, developed as strategies to ensure their survival amidst changing environmental conditions.

The government of Demak Regency has implemented various protective adaptation measures to mitigate the impacts of environmental changes in coastal areas. These efforts include hard structure technologies such as coastal walls (revetments), breakwaters, and Hybrid Engineering Technology, alongside soft structure approaches like mangrove restoration and rehabilitation through conservation and replanting initiatives. These actions are undertaken not only by the local government but also with active participation from community members.

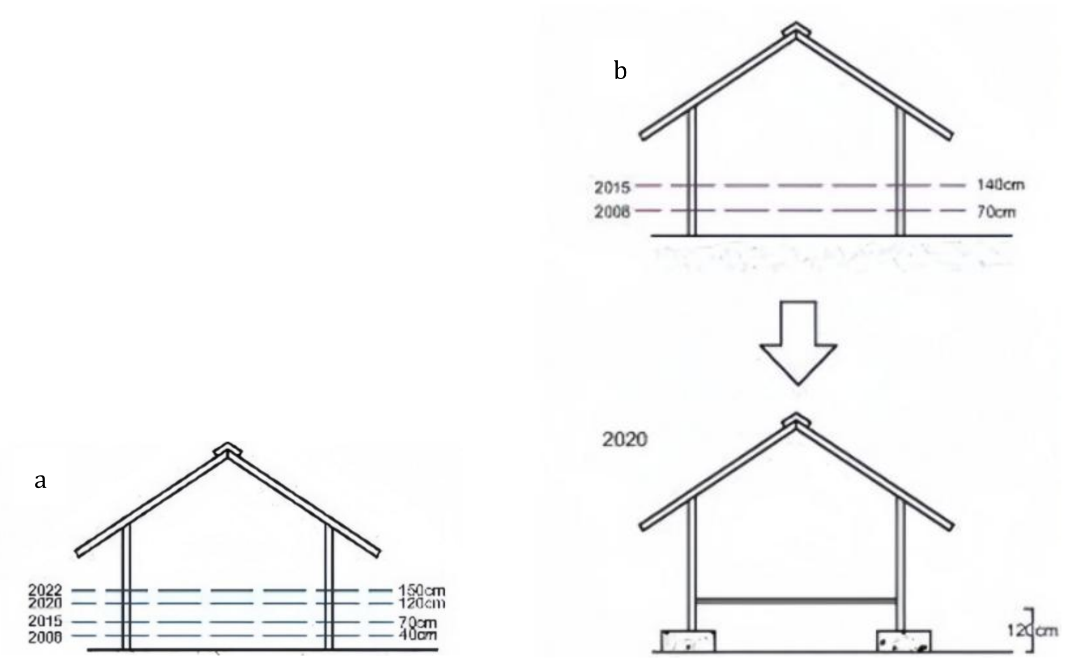

Fig. 6 (a) Sea water rise level; (b) Changes in house structure with building elevation level of house a (Ardiyanto & Putrideta, 2024)

In Sayung Subdistrict, physical protective adaptations by the community include the use of coastal walls (37.21%) and mangrove planting (44.19%). Mangrove planting is preferred due to its greater effectiveness in protecting the environment compared to hard structures. Additionally, 4.56% of the community combines both hard and soft structural technologies, using coastal walls alongside mangrove plantations. The community also employs physical accommodation adaptations to counteract land reduction and preserve residential areas. These adaptations include renovating and modifying homes, repairing roads and bridges, and improving environmental drainage systems. House renovations involve a variety of strategies, such as raising house floors using materials like wood, bricks, or cement; constructing stilt houses with elevated structures using either wood or bricks; combining polished cement or ceramic floors with elevated house foundations.

A case study of four tidal-affected houses in Sayung Subdistrict illustrates long-term adaptation efforts. For instance, House A experienced 40 cm of tidal flooding in 2008, prompting gradual elevation of the kitchen and front room floors to 70 cm. However, by 2015, tidal levels rose to 70 cm above the new floor level, necessitating further elevation. In 2018, the terrace was embanked to allow activities during floods (Figure 6). Despite these efforts, tidal waters reached disruptive levels again in 2020, forcing the demolition of House A. The demolished materials were repurposed as soil reinforcement, and the house was reconstructed using the government-provided RISHA (*Rumah Instan Sederhana Sehat*) modular stilt house technology, featuring a durable concrete structure designed for flood resilience. This case demonstrates the dynamic and continuous nature of adaptive strategies employed by both the government and the community to address the challenges of coastal environmental changes.

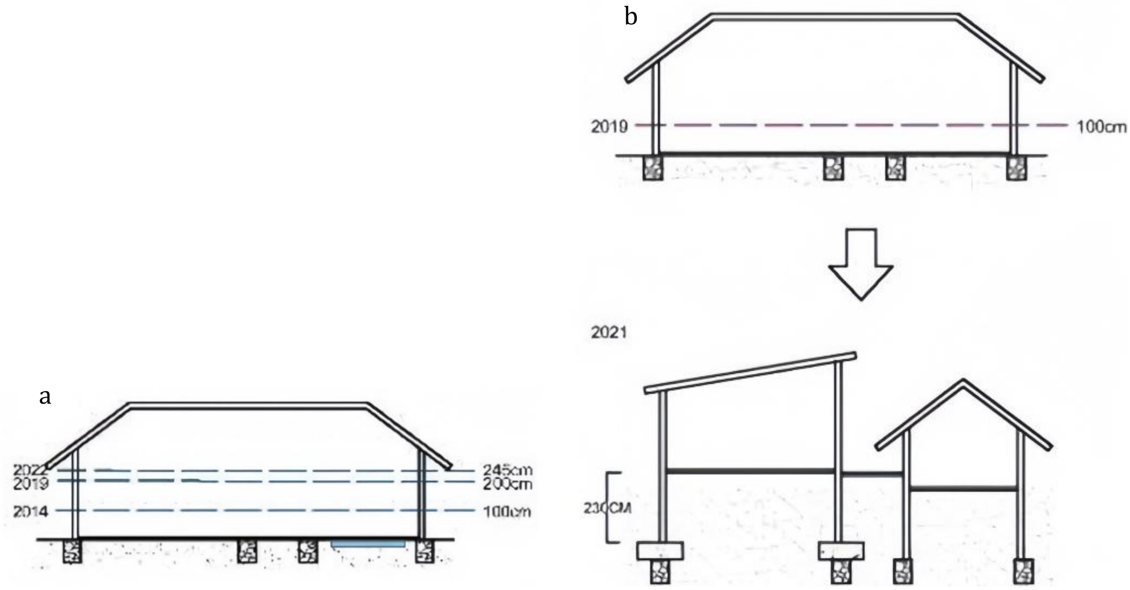

Fig. 7 (a) sea water rise level; (b) changes in house structure with building elevation level of house b (Ardiyanto & Putrideta, 2024)

In 2014, the House B experienced tidal flooding with water levels reaching 100 cm. Despite this, the homeowner continued to reside in the building without making any significant structural changes, such as elevating or embanking the property. By 2019, the flooding had worsened, with water levels rising to 200 cm, severely disrupting daily activities and restricting access to the house. This prompted the homeowner to plan for the construction of a new house in 2020. In 2020, the homeowner constructed a new house, repurposing materials from the original structure, which had become entirely submerged, to form the foundation of the new building. By 2022, the footpath leading to the house was buried under 100 cm of sediment, providing a natural elevation that prevented tidal flooding from affecting the property throughout the year (Figure 7).

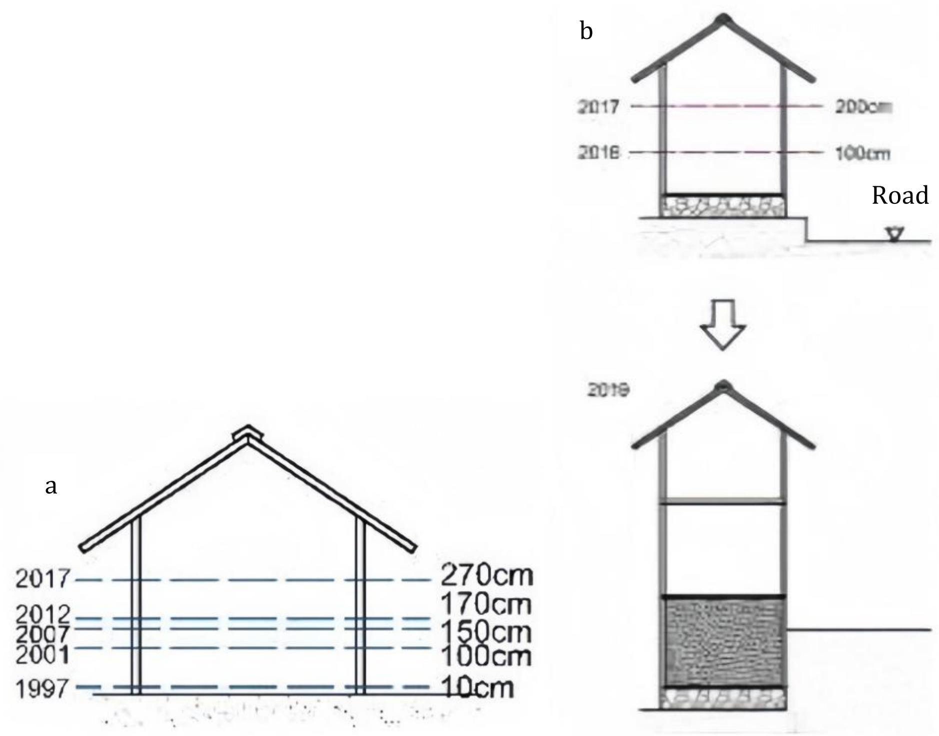

Fig. 8 (a) sea water rise level; (b) changes in house structure with building elevation level of house c (Ardiyanto & Putrideta, 2024)

In 1997, House C began experiencing tidal flooding, with water levels reaching 10 cm above the floor. To address this, in 2002, the homeowner raised the house by 150 cm and constructed a road embankment for additional protection. However, by 2007, tidal water levels rose to 150 cm above the house floor. In response, the house was elevated an additional 100 cm above the tidal water level as a precautionary measure. In 2012, tidal water levels further increased to 170 cm, prompting the homeowner to raise the house by another 50 cm. Finally, in 2017, the owner undertook a complete reconstruction of the property (Figure 8). The existing house floor was retained as the foundation for the new structure, while the remainder of the original building was demolished.

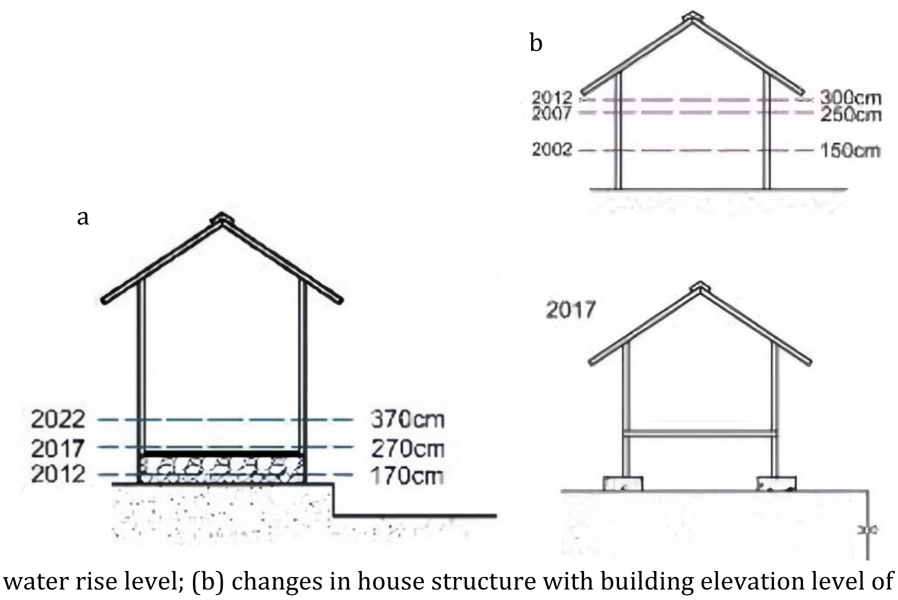

Fig. 9 (a) sea water rise level; (b) changes in house structure with building elevation level of house d (Ardiyanto & Putrideta, 2024)

In 2015, the footpath outside D’s house was raised by 100 cm; however, the house itself was not yet affected by flooding or structural issues. By 2016, the house began to experience impacts, prompting the owner to backfill the property to 100 cm above the road level. In 2018, both the road and the house were further backfilled, each raised by an additional 100 cm. In 2019, the homeowner addressed the persistent challenges by constructing a second floor. This modification did not involve an overhaul of the house’s foundational structure or walls, as the existing two-story design provided sufficient structural integrity. The new construction included the addition of a perimeter sloof above the roof wall to enhance stability. By 2022, the house's elevation was adjusted further to align with subsequent backfilling of the surrounding access road, maintaining accessibility and mitigating flood impacts.

Munawaroh & Setyaningsih (2021) explained, prior to adaptation efforts, all sample houses shared similar structural and material characteristics, featuring concrete structures and red brick walls. However, the recurring tidal flooding prompted significant changes in building materials and construction methods. Three of the four sample houses were reconstructed into stilt structures with footplate foundations. Stilt houses effectively prevent capillarization, which occurs when tidal water seeps into walls, causing dampness and wetness. By replacing brick walls with wooden ones, residents can more easily elevate or modify their homes every five years to accommodate rising water levels. Wooden materials are particularly advantageous as they can be reused, exemplified by House A's risha design, which employs a knock-down system for flexibility. The structural evolution of houses in the area reveals a shift from river stone foundations and brick walls to stilt houses with concrete footplate foundations, constructed with either wooden or brick walls. With tidal water levels rising approximately 100 cm every decade, or an average of 10 cm annually, residential environments have undergone continuous transformation. Many residents undertake backfilling every five years, raising their floors by 50–100 cm to safeguard their homes from inundation. Building stilt houses has become a common strategy among those whose original house structures were not adapted to tidal flooding. Stilt houses allow water to flow beneath the house, reducing the risk of overflow into adjacent areas. Local road improvements in Sayung Subdistrict involve physical adaptations such as concreting, elevating roads with compacted fill, or constructing wooden pathways. The choice of road adaptation is influenced by village policies, budgets, and environmental conditions. For instance, in frequently inundated areas like Tambaksari Hamlet, roads are built using wood. Planned road concreting projects in Bedono Village include areas such as Mondoliko, Pandansari, and Bedono Hamlets. In addition, drainage systems, including residential ditches and rivers, are elevated to mitigate tidal inundation. This involves increasing the capacity of sewers and raising riverbanks. Mangrove planting along riverbanks complements these measures, helping stabilize the ecosystem and reduce flooding impacts.

Economic adaptation in Bedono Village includes shifts in livelihoods, changes in pond land use, altered spending priorities, and innovations in home-based agriculture. Abrasion and land reduction have significantly affected local livelihoods; before the events, 65.12% of the population worked in fisheries, but this figure dropped to 44.19% post-land loss. Conversely, the percentage of self-employed individuals rose from 6.98% to 32.56%. Social adaptation strategies include adjustments in education and healthcare. For instance, residents in Dukuh Bedono, the area most affected by tidal flooding, rely on alternative sea transportation, such as boats, to access schools. In terms of health, the community faces increased risks of diseases such as diarrhea, skin irritation, vomiting, typhoid, and colds due to land degradation. To address this, residents keep basic medicines at home and benefit from government programs such as the Healthy Indonesia Card and free mobile healthcare services. These adaptations illustrate the community's resilience and proactive efforts to mitigate the social, economic, and environmental impacts of tidal flooding in Sayung Subdistrict. Community gatherings, such as yasinan activities, family welfare empowerment meetings, and other communal events in Bedono Village, have adapted to the recurring tidal floods by learning the patterns of tidal behavior. This knowledge allows residents to anticipate flood times and utilize elevated public facilities, such as flats in Dukuh Bedono, worship facilities, or community houses with high construction, as venues for their activities. For special occasions like weddings or circumcisions, the community has adopted flexible accommodation strategies. Those with sufficient financial resources rent alternative venues within Bedono Village, while households with limited means organize celebrations on makeshift wooden stages built in areas submerged by seawater.

In Sayung Subdistrict, retreat adaptation has become a significant response to tidal flooding, involving the relocation of residential areas to safer locations. This adaptation impacts various aspects of the community's life, particularly land ownership. Before retreating, most residents owned their land. However, after relocating, 93.94% of households now reside on government-owned land, often repurposing irrigation land to secure a safer location. This relocation increases the distance of homes from the sea. Prior to the adaptation, 90.91% of the community lived within 500 meters of the coastline. Following the retreat, 84.85% moved to areas more than 1.5 kilometers from the sea, reducing exposure to coastal hazards. Retreat adaptation also brings significant changes in access to essential services such as education and healthcare. Before relocating, residents struggled to reach these facilities due to damaged roads caused by ongoing tidal flooding. Post-relocation, improved access to these services has positively impacted the community, demonstrating the broader benefits of retreat adaptation in mitigating the challenges posed by tidal flooding.

4. Conclusions

The study provides a comprehensive analysis of shoreline changes in Sayung Subdistrict, Demak Regency, from 2013 to 2020, revealing significant coastal dynamics driven by abrasion and accretion processes. Over this period, abrasion was the dominant trend, accounting for 82% of the total coastal changes, resulting in a net loss of 141.49 hectares of land. The analysis highlights Timbulsloko and Bedono as the most severely affected villages, where erosion has caused substantial damage to aquaculture ponds and residential areas. Conversely, localized accretion was observed, facilitated by community-driven initiatives such as Hybrid Engineering technology and mangrove restoration, showcasing the potential of ecosystem-based solutions to counteract coastal degradation.

The findings contribute to a nuanced understanding of the interplay between natural processes and anthropogenic factors in shaping the coastline. Through the application of the Digital Shoreline Analysis System (DSAS) and the Coastal Vulnerability Index (CVI), the study underscores the spatial variability of coastal vulnerability in Demak Regency. Factors such as sea-level rise, geomorphology, wave energy, and bathymetry emerged as critical contributors to the high vulnerability of the region. Mangrove ecosystems were identified as both highly susceptible to degradation and pivotal in mitigating coastal hazards, emphasizing their role in adaptive coastal management strategies.

This study's contributions extend beyond mapping and analysis, offering valuable insights into community and governmental adaptation practices. These include physical measures like mangrove planting and elevated infrastructure, as well as socio-economic adjustments in livelihoods and education. The innovative use of modular stilt houses and dynamic land-use practices illustrates the resilience of coastal communities facing environmental challenges. Furthermore, the research highlights the importance of integrating scientific findings with local knowledge to inform sustainable coastal management policies.

However, the study faces limitations, including the reliance on Landsat imagery with moderate spatial resolution, which may overlook finer-scale changes in coastal features. Additionally, while the analysis provides robust insights into shoreline dynamics, it does not fully account for long-term climatic trends or socio-economic variables influencing adaptation strategies. Future research should explore higher-resolution satellite data, longitudinal studies on climate impacts, and the integration of ecosystem services valuation. These approaches can enhance the understanding of coastal system resilience and inform targeted interventions to safeguard vulnerable coastal zones.

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Author Contribution

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