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From Local Adaptation to Nature-Based Solutions in the Socio-Ecological Transformation of Sayung, Demak

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Abstract

The northern coastal region of Java Island has undergone rapid socio-ecological transformations due to tidal flooding, coastal abrasion, and land subsidence. This study examines the dynamics of the coastal ecotone in Sayung, Demak Regency, highlighting the shift from local adaptive strategies toward the implementation of Nature-Based Solutions (NbS). Field observations and direct interviews were conducted in two villages that are Wonorejo and Timbulsloko on September 20, 2025. The results indicate significant landscape changes, starting from rice fields that were converted into aquaculture ponds and eventually transformed into mangrove conservation areas. Local communities have developed various adaptation strategies, such as building floating settlements, elevating houses, and conducting mangrove rehabilitation. However, persistent environmental pressures have gradually exceeded the communities' adaptive capacity, leading to social and economic vulnerabilities. The findings emphasize the importance of integrating local knowledge with the NbS concept to enhance resilience and restore ecological functions in degraded coastal areas. Furthermore, this study contributes to understanding adaptive transformation processes in Indonesian coastal ecotones and supports the development of community-based coastal management frameworks.

Keywords: Coastal Ecotone; Sayung; Community Adaptation; Land Subsidence; Nature-Based Solutions

Cite This Article

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INTRODUCTION

Ecotones are transitional areas characterized by rapid ecological change between two distinct community types [1]. These zones are inherently dynamic and often unstable, functioning as buffer systems that absorb environmental disturbances and maintain equilibrium between adjacent ecosystems. Ecotones play essential ecological roles, including enhancing biodiversity, supporting nutrient cycling, and contributing to blue-carbon storage [2]. In coastal environments, ecotones commonly emerge between marine and mangrove ecosystems, seagrass beds and terrestrial landscapes, or agricultural lands and tidal flats [3]. In the case of Sayung, Demak Regency, the coastal ecotone represents a transition zone between mangrove forests, aquaculture ponds, and coastal settlements, shaped by both natural processes such as erosion and sedimentation and anthropogenic pressures including land reclamation and aquaculture expansion [4,5]. Continuous transformation of coastal ecotones is driven by sea-level rise, land subsidence, coastal erosion, and tidal flooding, which alter ecological boundaries [6].

The northern coast of Java, particularly Sayung, is recognized as a highly dynamic socio-ecological region due to severe environmental pressures such as tidal flooding, coastal abrasion, and land subsidence. These stressors have contributed to the formation of a highly sensitive coastal ecotone, where the interface between land and sea undergoes rapid transformation. Such dynamics are further intensified by global climate change, which significantly affects the stability of mangrove ecosystems and coastal environments [7]. The ecological importance of this coastal ecotone is reflected in its role in maintaining biodiversity, regulating nutrient flows, and supporting blue-green carbon storage [2].

Over the past two decades, Sayung has experienced marked landscape transformations. Spatial imagery indicates a progressive shift from rice fields (2003–2013) to aquaculture ponds, followed by the disappearance of these ponds after 2017 due to continuous abrasion and tidal inundation, eventually giving rise to emerging mangrove conservation zones. Field observations in Wonorejo and Timbulsloko on 20 September 2025 further substantiate these long-term transformations, revealing various local adaptation strategies such as elevating houses, constructing floating homes, and conducting mangrove rehabilitation. The transformation of the coastal landscape is strongly associated with tidal flooding, abrasion, and significant land subsidence. Indeed, substantial land subsidence has been recorded throughout the northern coastal region of Java, including the Semarang–Demak corridor, where high subsidence rates are linked to groundwater extraction and young alluvial soil characteristics [8]. These conditions accelerate land loss and expand areas of permanent inundation, directly affecting settlements and local livelihoods.

As environmental pressures intensify, local communities have continuously adapted through structural, spatial, and ecological strategies. However, the increasing severity of land subsidence reaching more than 10–20 cm per year in some areas combined with rising sea levels, persistent abrasion, and weak land-use governance has led to what can be described as societal fatigue in adaptation, where repeated adaptation efforts yield diminishing results. Recent literature emphasizes that Nature-based Solutions (NbS), particularly mangrove restoration, provide more sustainable and effective coastal protection compared to conventional hard-engineered structures [9,10]. Furthermore, the stability of coastal ecotones depends on biophysical factors such as sedimentation rates, vegetation succession, and salinity gradients, while edge effects significantly influence species distribution and carbon dynamics [11,12].

Given these complex socio-ecological transformations, integrating local ecological knowledge with adaptive NbS-based approaches is crucial for enhancing long-term coastal resilience in Sayung. This study therefore seeks to understand the dynamics of ecotone transformation, identify community-based adaptation strategies, and analyze the potential for NbS to strengthen environmental and social resilience in the region.

METHODS

Research Design

This study employed a descriptive qualitative approach aimed at explicitly understanding the dynamics of the coastal ecotone in a holistic manner, encompassing ecological, social, and spatial aspects. This approach was selected because the ecotone transformations in Sayung not only represent physical environmental phenomena but also involve complex social responses and evolving community adaptation patterns. Data collection was conducted through direct field observations, in-depth interviews with residents and community leaders, and spatial analysis using satellite imagery from 2003 to 2025 to identify land-use changes and shifts in coastal conditions over time.

The research was carried out on 20 September 2025 in two coastal villages in Sayung District, namely Wonorejo and Timbulsloko. Wonorejo was selected due to its function as a mangrove conservation area and its high level of coastal abrasion, while Timbulsloko was chosen as a representation of areas severely affected by tidal flooding and characterized by settlement adaptations such as the construction of floating houses. Both locations were considered to reflect the characteristics of a coastal ecotone undergoing continuous environmental pressure while simultaneously demonstrating community-driven adaptation innovations. These two locations are shown in Figure 1.

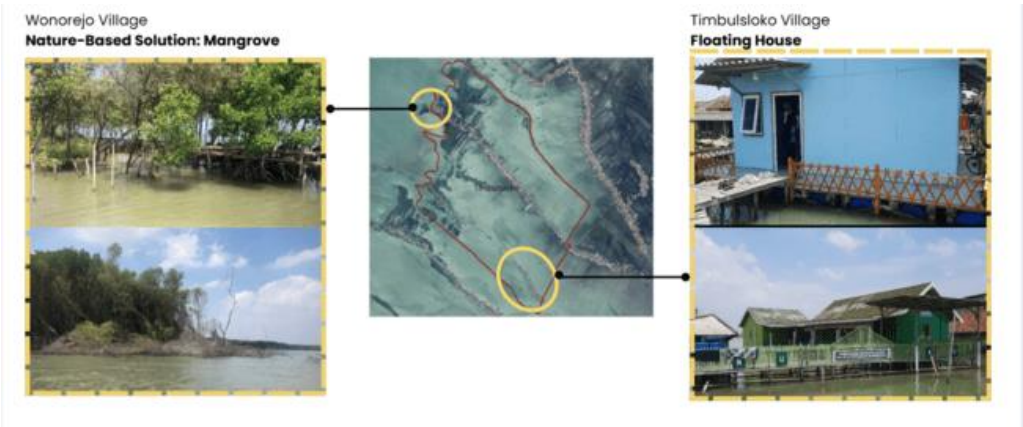

Figure 1. Research Location

Research Target/Subject

The research subjects consisted of various community groups who played important roles in coastal adaptation dynamics. Community leaders such as Mr. Mat Saeri, a resident of Wonorejo and the head of the local conservation community, served as key informants who provided insights into the historical development of land-use changes and mangrove rehabilitation efforts. In addition, youth representatives from Timbulsloko, such as Mr. Rony, contributed perspectives on youth-led initiatives related to environmental adaptation and sustainability. Other residents affected by tidal flooding, abrasion, and land subsidence were also interviewed to better understand their socio-economic conditions and the adaptation strategies employed in response to increasing coastal vulnerability.

Research Procedure

The research procedure began with direct observation of coastal morphology and settlement conditions to identify the physical changes occurring in the study area. This was followed by photographic documentation of environmental phenomena such as tidal flooding, coastal abrasion, land subsidence, floating houses, and mangrove rehabilitation zones. In-depth interviews were conducted to explore the historical timeline of land-use changes, community adaptation experiences, and local perceptions of environmental sustainability. The procedure then continued with a spatial analysis of land-use/land-cover (LULC) changes for the period 2003–2025, which served as the basis for examining the trajectory of coastal transformation. Finally, thematic analysis was carried out to synthesize findings related to environmental pressures, community adaptation patterns, and the potential application of Nature-based Solutions (NbS) in the study area. The flow of research is illustrated in Figure 2.

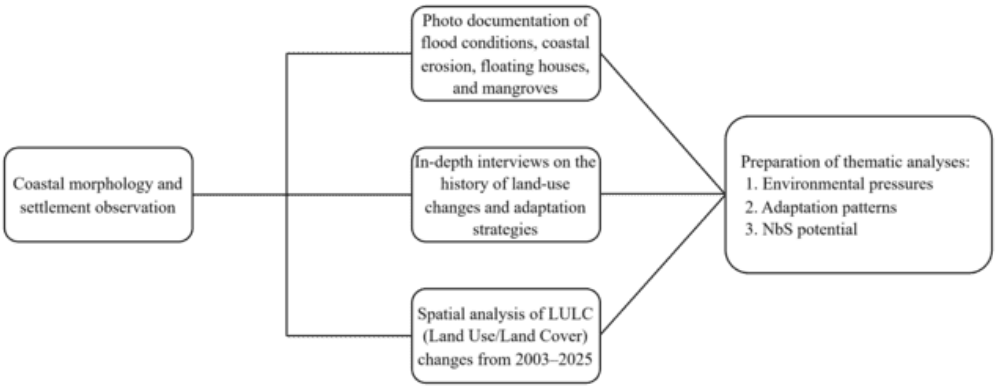

Figure 2. Research Flow

Instruments, and Data Collection Techniques

Data collection techniques included semi-structured interviews to obtain detailed information on community experiences and adaptation strategies. Photographic documentation was used to support field observations of tidal flooding, abrasion, and coastal morphological changes. Satellite imagery from available sources was utilized to analyze landscape transformations, particularly changes in land use and the loss of land due to abrasion. Additionally, a literature review was conducted to support the theoretical interpretation of coastal ecotones, abrasion dynamics, land subsidence, and concepts of coastal resilience and Nature-based Solutions.

Data analysis technique

The collected data were analyzed using content analysis to systematically interpret the results of interviews. Spatial analysis was employed to examine changes in land cover and coastal degradation processes over the past two decades. In addition, thematic analysis was carried out to identify community adaptation patterns in response to environmental pressures and their relationship to the socio-ecological transformation of the coastal ecotone. All field findings were then integrated with theoretical frameworks on coastal ecotones, adaptation, and Nature-based Solutions (NbS) to generate a comprehensive understanding of coastal dynamics in Sayung.

RESULTS AND DISCUSSION

Coastal Land Transformation

Multi-temporal satellite imagery of the Timbulsloko area (Figure 3) reveals a drastic transformation of the coastal landscape over more than two decades. In 2003, the region was still dominated by rice fields, indicating that terrestrial ecosystems remained relatively stable and supported agricultural activities. Between 2007 and 2009, these rice fields began to transition into aquaculture ponds. This shift reflects changes in community livelihoods toward aquaculture due to increasing seawater intrusion and greater economic incentives from fish and shrimp farming.

The most significant changes occurred during the 2013–2017 period. At this stage, most of the aquaculture ponds began to disappear because of repeated coastal abrasion, increasingly intense tidal flooding, and continuous land subsidence. The 2017 imagery shows that pond boundaries had been largely submerged, and the pattern of inundation indicates widespread land loss. Residential areas in several locations also appeared increasingly isolated from the mainland.

By 2025, the landscape transformation had reached a critical stage. Nearly all former pond areas had been converted into permanent water bodies, while the remaining settlements formed narrow strips surrounded by water. This pattern indicates severe and widespread land submergence, making the coastal area resemble small, fragmented islands.

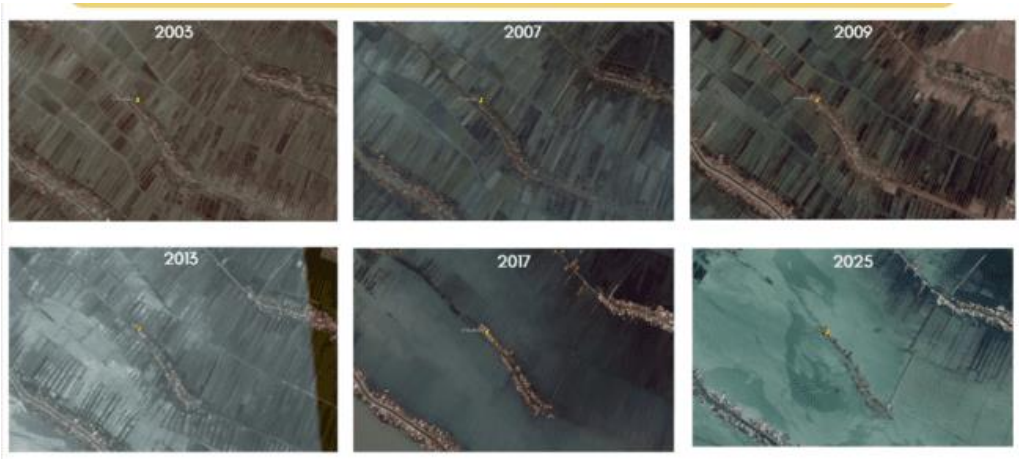

Figure 3. Coastal Land Transformation

This series of changes indicates that the transformation of the coastal ecotone in Sayung is not driven by a single factor, but rather by the cumulative interaction of multiple environmental pressures. Coastal abrasion continuously erodes the shoreline, while land subsidence which reaches more than 10–20 cm per year in several locations along the northern coast of Java accelerates the lowering of ground elevation and enlarges areas exposed to chronic inundation. Sea-level rise further exacerbates these conditions by increasing baseline water levels, making subsided areas increasingly vulnerable to permanent submergence. The combination of these three factors drastically alters ecological boundaries, submerging terrestrial land and driving the gradual transition from rice fields to aquaculture ponds, and ultimately to permanent water bodies.

Tidal Flooding

Tidal flooding is one of the dominant phenomena shaping coastal dynamics in Sayung. Figures 4 and 5 show that tidal flooding consistently inundates main roads and residential yards.

Figure 4. Evidence of Tidal Flooding Around the Main Road of Sayung

Figure 5. Permanent Inundation in the Sayung Village

This type of flooding is both daily and permanent; seawater does not only appear during certain tidal periods but remains for extended durations, resulting in persistent standing water. Such conditions disrupt local economic activities, hinder mobility between settlements, and severely limit the movement of residents. The continuous occurrence of

tidal flooding is the result of accumulated environmental pressures, including sea-level rise, land subsidence, and the declining effectiveness of both natural and built drainage systems.

Land Subsidence

Land subsidence in Sayung is one of the most critical factors contributing to the sinking of the region. Figure 6 visually illustrates houses that have subsided to the point where their roofs are nearly at the same height as an adult's head.

Figure 6. Evidence of Land Subsidence.

This condition reflects extreme ground-level lowering, consistent with subsidence rates recorded in northern Java. The severity of subsidence not only leads to structural deformation of buildings but also worsens flooding conditions, as the lowered terrain is unable to drain tidal water effectively. This phenomenon significantly impacts settlement safety, environmental health, and long-term habitability in the affected areas.

Welfare & Occupation Change

In response to increasing environmental pressures, the community of Sayung has developed various forms of local adaptation. One of the most common strategies is elevating houses and constructing wooden bridges to maintain connectivity between buildings, as shown in Figure 7. Residents of Timbulsloko have also implemented floating-house innovations to cope with permanent inundation. However, the loss of land has reduced the availability of public spaces, forcing children to play in the mosque area, which remains slightly elevated compared to the surrounding environment, as illustrated in Figure 8.

Figure 7. Evidence Of Permanent Inundation That Causes People to Build a Floating House

Figure 8. Kids Playing in The Mosque

From an ecological perspective, Wonorejo Village has adopted a Nature-based Solutions (NbS) approach through mangrove rehabilitation and the use of organic wave-breaking structures (ApO). Nevertheless, Figure 9 shows that strong coastal abrasion frequently damages young mangrove stands before they reach optimal growth. This highlights the vulnerability of biological restoration efforts in high-energy coastal environments.

Figure 9. Effect of Abrasion Such as Fallen Mangrove Trees and Destroyed Concrete

Environmental pressures have also influenced shifts in community livelihoods. Interviews with Mat Saeri reveal that residents have undergone multiple cycles of economic transition from rice farming to aquaculture, to losing their ponds due to submergence, and eventually shifting toward mangrove conservation activities. Interestingly, the peak of economic prosperity occurred during the aquaculture phase, prior to the point at which coastal degradation had reached a critical level.

Figure 10. Mat Saeri, The Head Of River Conservation Community and Rony, Leader Of Youth Movement In The Timbulsloko Village.

Root Causes

The complex environment and social problems observed in Sayung can't be separated from the region's historical and physical background. Better to understand the ongoing coastal transformations, it is essential to identify the root causes that have shaped the area's vulnerability over time. The following section elaborates on the key factors contributing to Sayung's coastal degradation, including geological history, soil characteristics, land management practices and coastal dynamics.

The area of Demak, Jepara, and part of Semarang was actually part of Java Sea in the past. Such research has been conducted by Wahyudi et al [14] by observing mollusc fossils that confirm marine life in the area. Furthermore, the soil type at this location is young alluvial soil that have limited water retention capabilities [13] and are susceptible to land subsidence.

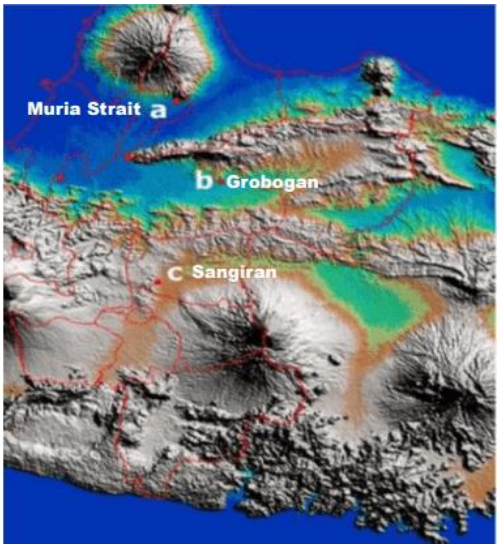

Figure 10. Historic Site of Muria Strait Based on Mollusc Fossil Sample [14]

Other than from the physical aspect, there are multiple socio-political factors that is also worsening the condition of the ecotone location. The strategic location of the Sayung creates an atmosphere of multilayered interest, such as from the government side through RTRW, the investors side through the industrialization, and the local people that is not aware about sustaibale practices [15]. This various stakeholders interest resulted in the different approach each party employed to resolve the issues. The government has instructed for a relocation, the industry does not give enough compensation for the communities affected by industrialization, and the environmentalist insisted that people should adapt to their new environment and using local potential to leverage their lives.

Emergence of Societal Fatigue

Although the community demonstrates a high capacity for adaptation, clear limits to resilience have begun to emerge through the phenomenon of "adaptation fatigue" or societal fatigue. Residents are required to continuously adjust both structurally and economically, such as by elevating houses, constructing wooden pathways, and undertaking self-initiated relocation efforts. However, these actions demand substantial financial resources, while coastal abrasion and tidal flooding persist without signs of stabilization. Houses continue to sink, access routes become increasingly difficult to navigate, and no formal relocation plan has been established to date. Figure 11 illustrates the cyclical nature of this process.

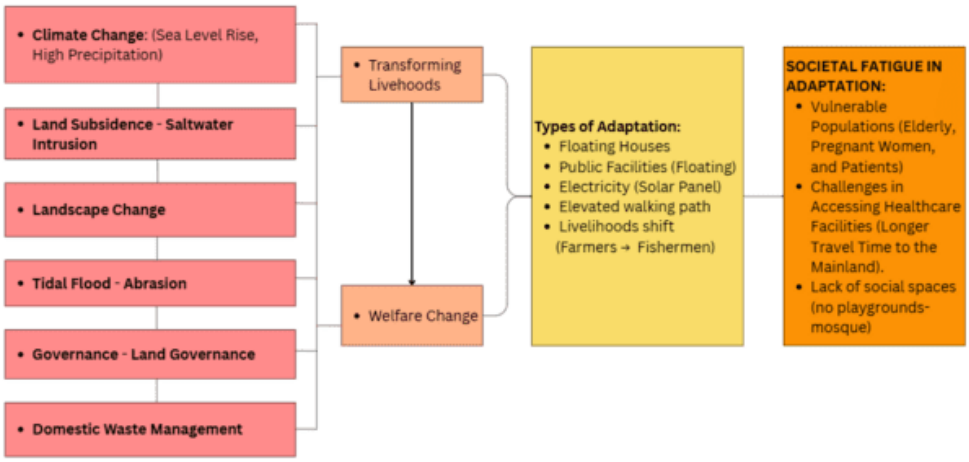

Figure 11. Schematic Representation of the Cyclical Process Leading to Societal Fatigue in Sayung's Coastal Community

Environmental pressures that escalate over time compel communities to repeatedly adapt, yet each adaptation is followed by the emergence of new stressors. This cycle eventually leads to a state of exhaustion in which the community's ability to cope becomes severely limited. Such conditions indicate that localized adaptation efforts alone are insufficient to address chronic coastal changes, highlighting the need for more integrated and systemic solutions.

Potential Transformation Toward Nature-Based Solutions (NbS)

In addressing the complex coastal challenges of Sayung, Nature-based Solutions (NbS) emerge as a more adaptive and sustainable alternative compared to conventional structural strategies such as seawalls and concrete breakwaters. Temmerman et al. [9] emphasize that NbS can restore the natural functions of coastal ecosystems, including wave attenuation, sediment trapping, and the enhancement of carbon storage. Mangroves, as a core component of NbS, play a vital role in reducing abrasion and improving shoreline

stability. However, the success of NbS is highly dependent on the region's biophysical conditions, sediment dynamics, and the long-term commitment of local communities to ecosystem management [7].

Several NbS strategies have strong potential to be implemented in Sayung, including multi-layered mangrove rehabilitation, the construction of living breakwaters, bio-shoreline engineering, and sediment-trapping interventions. Initial implementation in Wonorejo has shown promising results, with mangrove areas beginning to stabilize parts of the coastline. This approach offers an important opportunity to reduce community adaptation fatigue and enhance long-term coastal resilience.

CONCLUSIONS

The study concludes that the coastal ecotone of Sayung has undergone significant transformation due to land subsidence, abrasion, sea-level rise, and tidal flooding. These pressures have driven shifts in land use from rice fields to aquaculture ponds and eventually to permanently inundated areas while also disrupting community livelihoods. Local communities have adopted various adaptation strategies such as elevating houses, building floating structures, and restoring mangroves. However, continuous environmental pressures have led to societal fatigue in adaptation, as the capacity of residents to cope becomes increasingly limited.

Nature-based Solutions (NbS), particularly mangrove rehabilitation, offer promising potential to enhance ecological resilience. Future efforts should prioritize stronger governance support, improved monitoring of environmental change, and community-centered adaptation planning to sustain long-term coastal resilience.

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AUTHOR CONTRIBUTIONS

Conceptualization, R.S.D. and W.H.; Methodology, A.A.R. and A.W.; Validation, R.S.D., B.S.R., W.H., and A.R.; Formal Analysis, R.S.D., E.M., A.W., A.A.R., M.S.J; Investigation, R.S.D., E.M., A.W., A.A.R., M.S.J; Resources, R.S.D., E.M., A.W., A.A.R., M.S.J.; Data Curation, E.M., and M.S.J.; Writing – Original Draft Preparation, E.M., and M.S.J.; Writing – Review & Editing, E.M., and M.S.J.; Visualization, M.S.J., and A.W.; Supervision, R.S.D., B.S.R., W.H., and A.R.; Project Administration, A.A.R..

CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

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