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RESTORATION OF THE INTERTIDAL ZONE AND MITIGATION OF COASTAL EROSION DISASTERS IN SAYUNG

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ABSTRACT: Sayung District, Demak, is a muddy alluvial coastal ecosystem that has experienced severe ecological pressure due to the massive conversion of mangrove land into ponds, which has damaged the natural function of *the intertidal zone* as a wave buffer and biota habitat. This study aims to: (1) Analyse changes in the coastline and loss of intertidal habitat during the period 1994–2025 using *the Digital Shoreline Analysis System* (DSAS); (2) Simulate land area dynamics until 2050 using *System Dynamics*; and (3) Assess the potential for ecosystem restoration for community economic sustainability. The simulation results show that the Hybrid Scenario (integration *of* mangrove *greenbelts* and permeable structures) provides the highest effectiveness, drastically reducing the rate of abrasion to 9.65 Ha/year by 2025. This intervention is projected to save 595.71 Ha of land from the threat of permanent submersion compared to the *Business as Usual* scenario. In addition to stabilising the coastline after 2030, this ecosystem restoration restores environmental services that are crucial for supporting sustainable aquaculture (*silvofishery*), carbon sequestration potential (*Blue Carbon*), and ecotourism, offering a holistic adaptation solution for coastal community resilience.

Keywords: Intertidal Zone, Erosion, System Dynamics, Silvofishery, Sayung.

1. INTRODUCTION

Indonesia, as the largest archipelagic nation, possesses an extensive and dynamic coastline. This coastal region provides crucial ecosystem services, one of which is through the existence of mangrove forests that function as *natural barriers* or protectors of the coast from wave energy and storms. Mangrove forests naturally break waves and trap sediment, maintaining the stability of the coastline from the threat of erosion [1]. However, high anthropogenic pressure often ignores these ecological functions for short-term economic gain.

One of the areas experiencing the most extreme coastal degradation on the island of Java is Sayung District, Demak Regency. Historically, this area was a dense mangrove ecosystem. However, drastic changes occurred in the 1980s and 1990s with *the boom* in tiger prawn and milkfish commodities. The community massively converted *the land*, turning the mangrove green belt into a fish pond area [2]. The loss of this protective vegetation triggered an ecological crisis in the form of severe abrasion, exacerbated by the characteristics of soft alluvial soil and the phenomenon of *land subsidence*.

The impact of mangrove loss and erosion has been devastating. Research shows that environmental damage in Sayung has resulted in the loss of thousands of hectares of productive land, the submergence of settlements, and the destruction of vital infrastructure due to tidal flooding or tidal waves [3]. The phenomenon of "land destruction" in the villages of Bedono and Sriwulan is clear evidence of how ecological imbalance can permanently destroy the socio-economic assets of a community [4]. This crisis is exacerbated by changes in ocean currents from reclamation in the surrounding area (Semarang), which shift wave energy eastward, hitting the Sayung coastline that has lost its natural protection [5].

To mitigate this disaster, an approach is needed that not only looks at current conditions but also projects future conditions. Previous studies have generally focused on static spatial analysis. This study offers something new by integrating historical spatial analysis using *the Digital Shoreline Analysis System* (DSAS) to map the rate of change in the coastline from 1994 to 2025 [6], which is then used as input in dynamic modelling (*System Dynamics*). This integration aims to simulate abrasion mitigation scenarios until 2050, comparing the effectiveness of vegetative (mangrove) approaches, purely civil approaches, and hybrid approaches (sea walls and mangroves) in maintaining coastal land area.

2. METHOD

2.1. Study Area

This research was conducted in the coastal area of Sayung Subdistrict, Demak Regency, Central Java

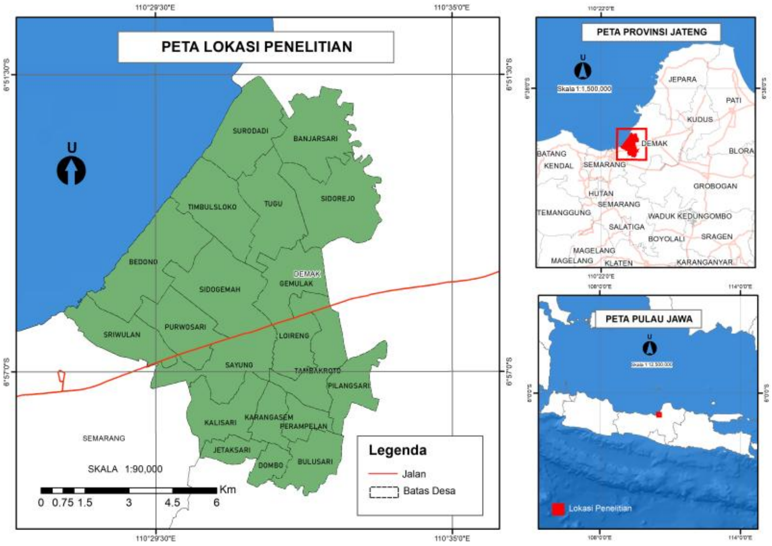

Fig 1. Map of Location Research

Geographically, this area is a low-lying alluvial plain directly bordering the Java Sea to the north. This location was chosen because of its complex hydro-oceanographic problems, namely extreme abrasion and the highest land subsidence on the north coast of Java, which have a significant impact on coastal line changes and the loss of productive land for the community [4].

2.2. Data Acquisition

Multi-temporal analysis of coastline changes was conducted using satellite imagery data that recorded coastal conditions over a 31-year period (1994–2025). The satellite data used consisted of Landsat 5 Thematic Mapper (TM) imagery for historical data and Sentinel-2 MultiSpectral Instrument (MSI) imagery for current condition data. the selection of image acquisition dates was based on the availability of data with minimum cloud cover (<10%) to ensure optimal visibility of land-water boundaries. Detailed specifications of the satellite image data are presented in Table 1.

Table 1. Specification of Satellite Imagery Used

No	*Satellite Sensor*	*Acquisition Date*	*Resolution (m)*	*Path/Row / Tile*	*Source*
1	Landsat 5 TM	20 June 1994	30	120/065	USGS
2	Landsat 5 TM	11 February 2011	30	120/065	USGS
3	Sentinel-2 MSI	11 July 2025	10	T49MCM	ESA/Copernicus

Source: Results of data analysis, 2025.

Data pre-processing includes geometric correction to ensure inter-temporal position consistency (*co-registration*) and radiometric correction (*Top of Atmosphere/TOA reflectance*) to correct pixel values due to atmospheric interference.

2.3. Shoreline Extraction using NDWI

To improve accuracy in separating land and water bodies, this study uses a water index transformation method, namely the Normalised Difference Water Index (NDWI) developed by McFeeters [6]. NDWI was chosen for its ability to suppress noise from vegetation and soil, allowing wet shoreline boundaries to be identified automatically and objectively.

The NDWI formula is applied to the *Green* and Near-Infrared (*NIR*) bands with the following equation:

$$NDWI = \frac{(Green - NIR)}{(Green + NIR)}$$

Where:

- For **Landsat 5 TM**: *Green* is Band 2 and *NIR* is Band 4.
- For **Sentinel-2 MSI**: *Green* is Band 3 and *NIR* is Band 8.

The NDWI calculation results in values ranging from -1 to +1. The thresholding process is carried out by setting a threshold value of zero (0), where values >0 are classified as water, and values <0 are classified as land. This binary raster result is then converted into shoreline vector data for further analysis.

2.4. Shoreline Change Analysis (DSAS)

The shoreline vectors extracted from NDWI in 1994, 2011, and 2025 were analysed using Digital Shoreline Analysis System (DSAS) software version 5.0 [7]. DSAS works by creating perpendicular transects from the baseline on land towards the sea.

In this study, transects were created at 50-metre intervals along the Sayung coastline. Shoreline change statistics were calculated using two main parameters:

1. **Net Shoreline Movement (NSM):** The total distance of shoreline displacement between the oldest (1994) and most recent (2025) years for each transect (unit: metres).
2. **End Point Rate (EPR):** The annual rate of shoreline change by dividing the distance of shoreline displacement (NSM) by the time span between years (unit: metres/year). A negative EPR value indicates abrasion, while a positive value indicates accretion [8].

2.5. System Dynamics Modelling

Future coastal land area projections were simulated using the System Dynamics approach with the assistance of Powersim Studio 10 software. This method was chosen for its ability to model complex and non-linear system behaviour through Stock (level) and Flow (rate) structures and feedback loops [9].

The model was constructed with *a* simulation *time horizon* of 25 years (2025–2050). The average rate of change (EPR) obtained from the DSAS results was used as the basic input to calibrate the model. Three mitigation scenarios were developed: (1) *Business as Usual*, (2) *Moderate* (Mangrove Rehabilitation), and (3) *Optimistic* (Hybrid: Sea Dikes & Mangroves).

3. RESULTS AND DISCUSSION

3.1. Spatiotemporal Shoreline Dynamics (1994–2025)

The dynamics of coastal morphological changes in Sayung over the last three decades have been clearly recorded through *multi-temporal* remote sensing observations. As presented in Fig. 2, a visual comparison between historical Landsat 5 TM data (1994, 2011) and current Sentinel-2 MSI data (2025) shows massive *landward retreat*. In Fig. 2a (1994), the coastline still juts out into the sea with dense vegetation, but in Fig. 2b (2025), the area has been completely inundated by open water. This landscape transformation did not occur naturally, but was triggered by the loss of the mangrove green belt that previously served as *coastal defence* [1].

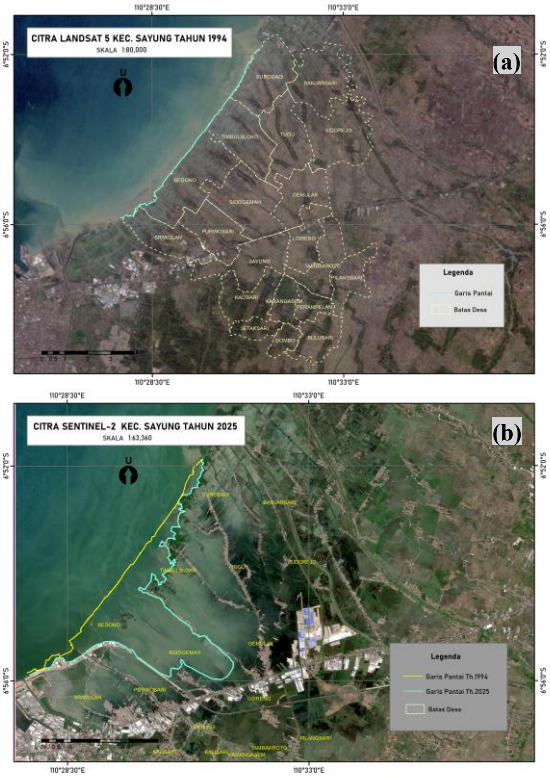

Fig 2. Comparison of Multi-temporal Satellite Images: (a) Landsat 5 TM 1994, (b) Sentinel-2 MSI 2025

Given the high sedimentation that causes turbidity in coastal waters in Sayung, the identification of land-water boundaries is often biased if it relies solely on *true colour* composites. Therefore, this study applies *Normalised Difference Water Index* (NDWI) spectral transformation for more precise coastline extraction, as shown in Fig. 3. This index effectively separates water pixels (positive values) and land pixels (negative values), allowing accurate mapping of intertidal zone changes.

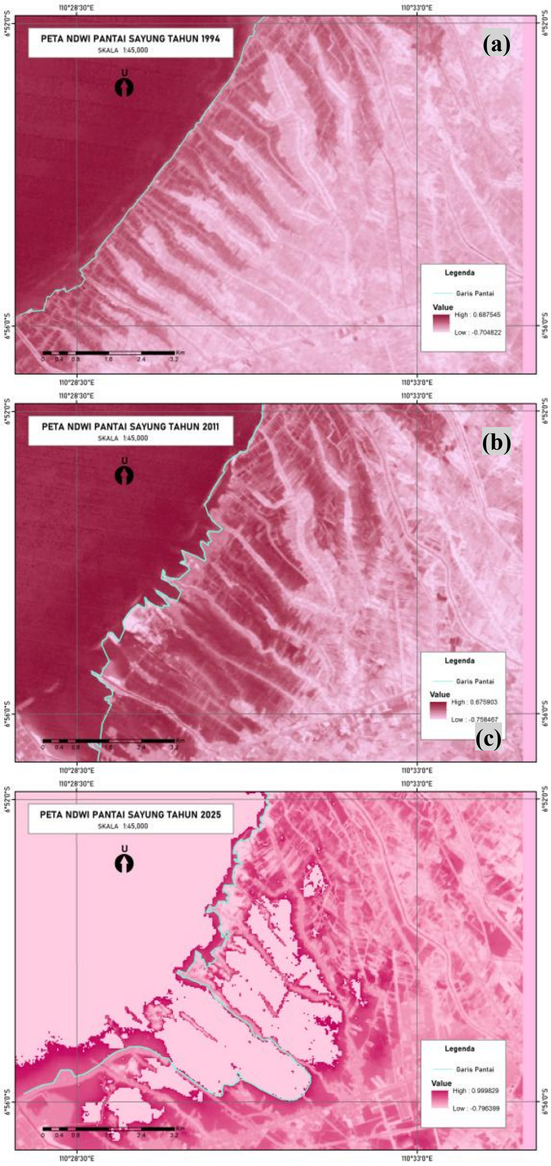

Fig 3. Spatial distribution of NDWI for land-water boundary delineation: (a) 1994, (b) 2011, and (c) 2025

Based on statistical calculations *of Net Shoreline Movement* (NSM) from the extracted coastline, the total area of land lost due to permanent abrasion over a period of 31 years reached **1,181.55 hectares**. Meanwhile, the natural accretion phenomenon was only identified in an area of 216.58 ha, most of which was fluctuating (appearing and disappearing). Thus, the average rate of land loss (*End Point Rate*) in Sayung Subdistrict was recorded at 38.30 ha/year.

The phenomena visualised in Fig. 2 and Fig. 3 indicate the loss of a crucial *intertidal zone*. In 1994 (Fig. 2a), satellite imagery recorded the existence of extensive mudflats and mangrove vegetation. However, in the 2025 imagery, this productive zone has disappeared. The loss of this tidal zone correlates directly with historical data on intensive pond conversion in the 1990s [2]. Without an intertidal *buffer zone*, ocean wave energy directly hits the soft alluvial soil structure, accelerating the rate of erosion and causing permanent flooding in residential areas [3].

3.2. Future Projection of Coastal Resilience

The *System Dynamics* model simulation projects three contrasting future trajectories for the sustainability of the Sayung region. This model was developed based on *feedback* loops that connect physical subsystems (hydro-oceanography) and human intervention subsystems. The structure of the interrelationships between these variables is visualised in *the Stock Flow Diagram* (SFD) in Fig. 4.

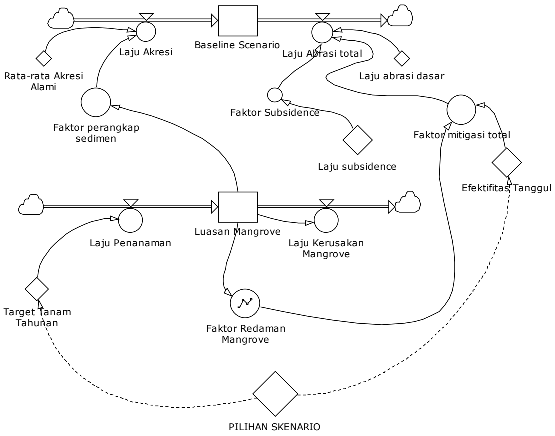

Fig. 4. Stock Flow Diagram (SFD) of Sayung Coastal Dynamics Simulation

As shown **in Fig. 4,** this **model** has two main *Stock* (Level) variables, namely Coastal_Land_Area and Mangrove_Area. The dynamics of land area change are determined by the *rate* of competition between the Rate_of_Accretion (Inflow) and the Rate_of_Total_Abrasion (Outflow). The novelty of this model lies in the integration of the *Land Subsidence* variable as a multiplier factor for bottom abrasion. Given the soft characteristics of Sayung's alluvial soil, the rate of land subsidence—estimated to reach 10-13 cm/year—significantly exacerbates the impact *of relative sea level rise* [9].

In the model mechanism **(**Fig. 4), the Subsidence_Factor works to increase the abrasion coefficient each year, so that the wave energy hitting the coast becomes more destructive than in stable coastal conditions. To offset this rate of damage, human intervention variables are included through mitigation scenarios. The Mangrove_Area variable functions as a natural regulator that increases *the Wave_Attenuation_Factor*. Empirical evidence shows that increased mangrove density reduces wave energy and traps sediment, ultimately slowing the rate of abrasion [10]. Additionally, in the optimistic scenario, hard structural interventions (sea walls) are activated as *auxiliary* variables that provide instant protection against extreme wave impacts [11].

A. Scenario 1: Business as Usual (BAU) The first scenario simulates *Business as Usual* (BAU) conditions, assuming no significant policy changes or structural or vegetative interventions from the current conditions. The projected dynamics of Sayung coastal land area until 2050 are presented and visualised through a trend graph in Fig. 5.

As seen in Fig. 5, the simulation results graph shows a persistent and cumulative trend of land area decline. This is confirmed by simulation data, where the rate of abrasion remains high, moving from 38.30 Ha/year in 2025 and continuing to reach 39.58 Ha/year in 2050. Although there is no drastic increase in the rate, the consistency of this land loss indicates that environmental pressure is not abating.

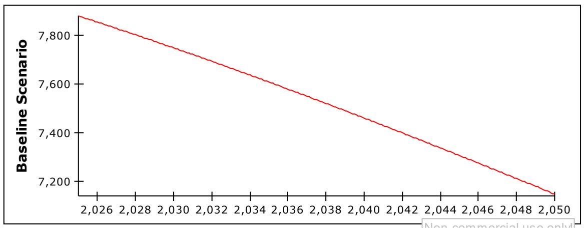

Fig 5. Simulation graph of coastal land area decline in Sayung (2025–2050) in the Baseline Scenario.

The decline curve in Fig. 5 indicates that environmental damage is occurring systematically (sustained loss). This phenomenon is exacerbated by the variable of *land subsidence*, which acts as *a reinforcing loop* (positive feedback) in the system. Continued ground subsidence causes tidal flooding to spread further inland, changing the characteristics of previously dry soil to soft (water-saturated) soil, thereby drastically reducing its resistance to wave energy and maintaining a high average abrasion rate of ~39 Ha/year [9].

If this unmitigated trend continues, the model projects that by 2050, Sayung District will experience an accumulated land loss of nearly 1,000 hectares, equivalent to the loss of a significant portion of the current productive coastal area. The spatial consequence of this projection is the submergence of vital infrastructure and densely populated settlements currently located on the *coastline* frontline. This condition leads to what is known as *permanent inundation*, which has the potential to trigger a wave of forced migration (*climate migration*) [4].

B. Scenario 2: Moderate (Mangrove Rehabilitation)

The moderate scenario with mangrove planting intervention covering an area of 20 hectares per year is projected to begin slowing the rate of abrasion in the fifth year of the simulation (2030). Theoretically, increased vegetation density increases the *hydraulic* roughness coefficient, which serves to reduce wave energy.

However, the simulation results show that in 2050, the erosion rate will remain high at 38.10 hectares per year. This indicates that mangrove intervention alone (*standalone*) is not strong enough to counteract the combination of erosion forces and extreme *land subsidence* rates in Sayung. The effectiveness of planting is hampered because young mangrove seedlings often drown due to relatively rapid sea level rise, before their root systems are strong enough to trap sediment and stabilise the soil.

C. Scenario 3: Optimistic (Hybrid Engineering)

The hybrid scenario, which integrates the construction of effective permeable sea walls by 2030 with the restoration of a mangrove green belt, shows the most significant environmental response with a drastic reduction in the rate of abrasion to 9.65 Ha/year by 2025. This success is based on the *Building with Nature* principle, where hard structures function to break waves (*wave diffraction*) to create *calm water* zones that reduce bottom shear stress [11], conditions that allow the mangrove root system to grow optimally and trap sediment to trigger vertical accretion [12]. In contrast to the *Business as Usual* (BAU) scenario, which is projected to destroy thousands of hectares of , this hybrid intervention has the potential to save 595.71 hectares of land from the risk of permanent submersion by 2050, providing crucial protection for high-value economic assets [10]. After 2030, the simulation graph shows land stabilisation (*levelling off*) and a positive trend in new land formation, confirming that a combination of engineering and ecosystems is the most sustainable coastal adaptation strategy in the face of sea level rise [13].

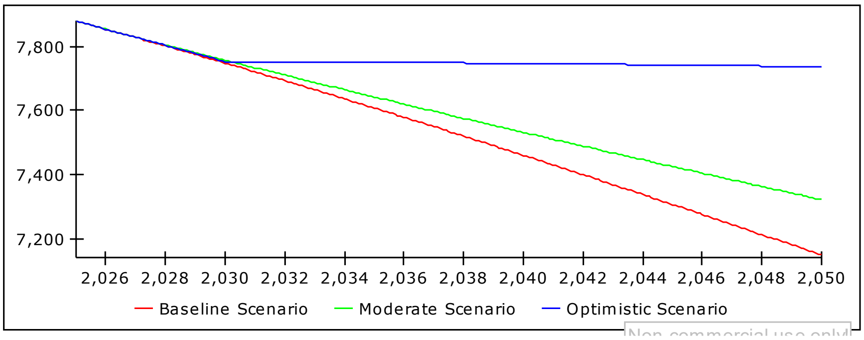

Fig 6. Simulation graph of coastal land area reduction in Sayung (2025–2050) under the Optimistic Scenario.

3.3. Revitalisation of the Intertidal Zone and the successful implementation of the Optimistic Scenario is not limited to the physical preservation of the coastline, but extends to the restoration of the ecological function of the *intertidal* zone. Habitat restoration in areas protected by hybrid structures opens up opportunities for sustainable economic transformation for affected communities, turning threats of vulnerability into productive assets through three main mechanisms:

1. **Wanamina-based Sustainable Aquaculture (*Sustainable Silvofishery*)**

The restoration of the intertidal ecosystem creates a foundation for the implementation of environmentally friendly aquaculture or *silvofishery* systems. Unlike conventional intensive pond practices that often degrade the environment, this model harmoniously integrates aquaculture ponds among mangrove stands [14]. Ecologically, decomposed mangrove leaves become detritus that serves as natural feed, while improving water quality through natural biofiltration [15]. Studies show that this system can reduce the operational costs of artificial feed and increase the *survival rate* of commodities such as milkfish and tiger prawns, making it a resilient economic adaptation strategy for farmers in flood-prone areas [16], [17].

2. ***Blue Carbon Sequestration* Environmental Services**

Mangrove restoration on the Sayung coast has high economic valuation potential through the *Blue Carbon* scheme. Tropical mangrove ecosystems are known to have a carbon storage capacity per hectare that far exceeds that of terrestrial forests, both in above-ground biomass and carbon reserves in sediments [18], [19]. With the global carbon market framework increasingly developing, this conservation area can be registered in *voluntary carbon market* mechanisms or REDD+ schemes, which will provide direct financial incentives to coastal villages as compensation for emission absorption services [20].

3. **Eco-Edutour*ism***

Restored coastal areas have high aesthetic and educational value that can be developed into *Eco-Edutourism* destinations. The narrative of community resilience in the face of sea level rise ("Resilient Coastal Village") combined with mangrove forest tours offers a unique tourist experience [21]. Diversification of livelihoods into *community-based tourism* has proven effective in reducing excessive exploitation of fishery resources [22]. In addition to economic impacts, the development of educational tourism also strengthens local conservation awareness and ensures the long-term sustainability of green belt maintenance [23].

4. CONCLUSION

This comprehensive analysis confirms that the Hybrid Scenario is the only intervention pathway capable of providing a holistic solution to the Sayung coastal crisis. A significant reduction in the rate of abrasion to below 10 Ha/year in the initial phase and the potential for *land reclamation* after 2030 prove the superiority of *the Building with Nature* approach over conventional methods.

More than just physical defence, the integration of permeable structures and mangrove restoration offers *a multiplier effect* in the form of local economic revival through wanamina, carbon trading, and ecotourism. Therefore, accelerating the implementation of this scenario before the ecological tipping point is reached must be a top priority for regional development policies, supported by cross-sector collaboration to ensure ecological sustainability and the social welfare of coastal communities.

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