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Analysis of Shoreline Changes Using the One-Line Model at Batu Karas Beach, Pangandaran, Indonesia

Subiyanto[1*], Defania Saqina Ramadhanti[1], Umar Abdurrahman[1]

[1]*Department of Marine Science, Faculty of Fishery and Marine Science, Universitas Padjadjaran, Sumedang, Indonesia*

**Corresponding author email: subiyanto@unpad.ac.id*

Abstract

This study aims to analyze and quantify shoreline changes along Batu Karas Beach, located in Pangandaran Regency, using a numerical modeling approach based on the one-line theory. The objective is to understand the spatial distribution of coastal erosion (abrasion) and sediment deposition (accretion), which are primarily driven by wave dynamics and longshore sediment transport. The simulation employs the finite difference method to discretize and solve the governing equations of shoreline evolution, enabling the projection of shoreline position over time in a simplified one-dimensional form. Key input parameters such as wave height, direction, and coastal morphology were integrated into the model to enhance prediction accuracy. The results show that shoreline retreat (abrasion) occurs predominantly in the western and eastern segments, with an average rate of 35.94 meters per year, while shoreline advancement (accretion) is concentrated in the central zone, with an average of 34.32 meters per year. These findings underscore the utility of numerical modeling in supporting sustainable coastal planning, particularly in identifying high-risk zones, evaluating potential mitigation strategies, and informing regional development and conservation policies in the face of increasing coastal pressures.

Keywords: Accretion, Erosion, Finite difference method, One-line model, Shoreline change

1. Introduction

The coastal zone is a highly dynamic transition area between land and sea, naturally influenced by various oceanographic processes such as waves, currents, and tides, as well as increasing human activities. One key indicator of coastal dynamics is shoreline change, which occurs in the form of erosion or accretion and can significantly impact coastal ecosystems, infrastructure, tourism, and spatial planning (Fauzie, 2017; Subiyanto et al., 2024). In recent decades, climate change-driven factors such as sea-level rise and the increasing frequency of extreme weather events have intensified these processes, particularly along sandy coastlines (McInnes et al., 2024).

To address these challenges, various methods have been developed to analyze shoreline changes, including observational and numerical approaches. Among these, the one-line model is a widely adopted numerical method that simplifies shoreline movement into a dominant one-dimensional form, focusing on longshore sediment transport as the primary driver of change. This model enables simulation of shoreline evolution over time using inputs such as wave direction, bathymetry, and sediment characteristics. It remains popular due to its conceptual simplicity, adaptability, and computational efficiency (Francone & Simmonds, 2023; Seenath, 2022; Soomere et al., 2025).

Previous empirical studies have demonstrated the effectiveness of the one-line model in mapping shoreline changes in various coastal contexts. Fuad et al. (2021) applied the one-line model along the Situbondo coast in East Java and found erosion–accretion patterns consistent with local dynamics, including the use of the CERC sediment transport formula to estimate change rates. Seenath (2022) introduced a hybrid 2D/one-line formulation to incorporate sea-level rise effects through a time-varying closure depth, which successfully reproduced multi-decadal shoreline evolution on sandy coasts. Tao et al. (2024) developed a polar-coordinate-based one-line model to improve accuracy on embayed beaches. Recent models such as COAST-PROSIM integrate wave–structure interactions into the one-line framework, enhancing adaptability to various coastal settings while maintaining computational efficiency (Scala et al., 2025).

However, despite these advances, many studies focus on generalized or large-scale regions, while site-specific modeling for smaller yet economically and ecologically important locations like Batu Karas Beach remains limited. Batu Karas, located in Pangandaran Regency, West Java, is a popular coastal tourism destination known for its sandy beaches and surfing activities. Understanding its shoreline dynamics is essential for balancing tourism development with environmental protection. Based on this context, the present study aims to analyze shoreline changes in the Batu

Karas Beach area using a one-line model implemented with the finite difference method. The results are expected to provide scientific insights that support sustainable and site-specific coastal management and planning

2. Methodology

2.1. Research Location and Data

This study was conducted at Batu Karas Beach, located in Pangandaran, West Java, Indonesia. The data used in this research include:

- Initial shoreline position (baseline) data derived from satellite imagery,
- Significant wave height (Hs), wave period (T), and wave direction (θ) obtained from ECMWF sources,
- Bathymetric data used to determine the depth of closure (D) and the active sediment transport depth.

2.2. One-Line Theory Model

The one-line theory is used to model changes in shoreline position based on longshore sediment transport (LST). The fundamental equation (Stripling et al., 2017) is:

$$\frac{dy}{dt} = -\frac{1}{D} \cdot \frac{\partial Q}{\partial x} \tag{1}$$

where:
$y(x,t)$: shoreline position as a function of time,
$Q(x)$: sediment flux along the shoreline (longshore sediment transport),
D : active transport depth (also known as depth of closure),
x : spatial coordinate along the shoreline.

2.3. Longshore Sediment Transport (LST) Formulation Using the CERC Equation

To calculate the value of $Q(x)$, the CERC (Coastal Engineering Research Center) formula is applied (Tao et al., 2024):

$$Q = K \cdot H_b^2 \cdot sin(2\theta_b(x)) \tag{2}$$

where:
K : empirical coefficient,
H_b^2 : wave height at breaking,
$\theta_b(x)$: wave angle at breaking relative to the shoreline orientation.

2.4. Numerical Simulation

- The coastal domain was discretized into a one-dimensional grid along the shoreline with an interval of 100 meters, covering a total length of 2200 meters.
- The simulation was carried out using the finite difference method, employing an explicit scheme to compute shoreline changes over time.
- The initial shoreline position was input as $y_0(x)$ and updated iteratively using the numerical scheme throughout the simulation period (1 year).

2.5. Visualization and Result Analysis

- Shoreline changes were analyzed to identify areas of erosion (negative values) and accretion (positive values).
- The results were visualized in the form of graphs or maps comparing the initial and final shoreline positions.

3. Results and Discussion

3.1. Spatial Patterns of Change: Zone Segmentation

This data is the result of a one-dimensional shoreline change model simulation (one-line shoreline model) that compares the initial shoreline position in 2023 with the simulated final position in 2024, as shown in Figure 1. The data are organized based on points along the shoreline transect at 100-meter intervals, ranging from 0 meters to 2200 meters alongshore position.

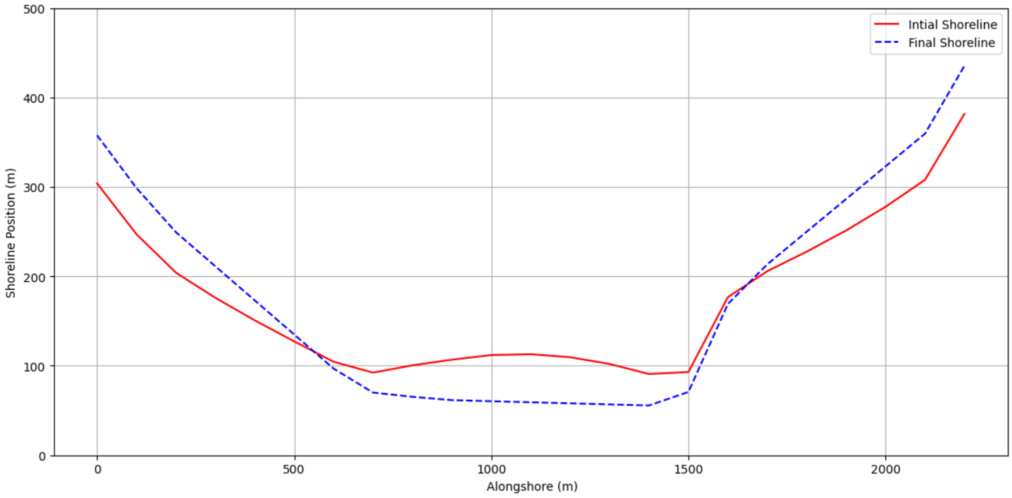

Figure 1: Initial shoreline position in 2023 and final shoreline position in 2024 based on simulation results.

Each point records the shoreline position in meters, representing the distance from a fixed land reference point toward the sea. Thus, a smaller shoreline position in 2024 compared to 2023 indicates erosion, while a larger position indicates accretion. This simulation data reveals complex and asymmetric coastal dynamics. At several points, the shoreline experiences significant retreat (erosion), while at others, it advances (accretion). The shoreline position change is calculated as the difference between the 2024 and 2023 shoreline positions. This value helps identify the magnitude of shoreline displacement over one year, indirectly reflecting the intensity of sedimentation or erosion processes. For example, at the 0-meter point, a shift of −53.73 meters indicates severe erosion, while at the 1100 meter alongshore position, a shift of +53.73 meters indicates maximum accretion.

The simulated shoreline change from 2023 to 2024 shows a clear spatial pattern, in which the coastline can be segmented into three main zones based on the nature of the changes observed: the dominant erosion zone, the dominant accretion zone, and the transitional zone. The dominant erosion zone is identified in the initial segment up to approximately 500 meters and the final segment beyond 1700 meters alongshore position, as illustrated in Figures 2 and 3.

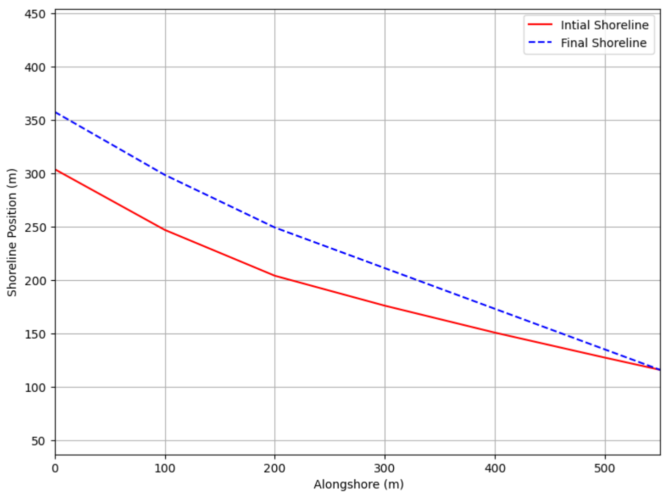

Figure 2: Abrasion on the initial segment.

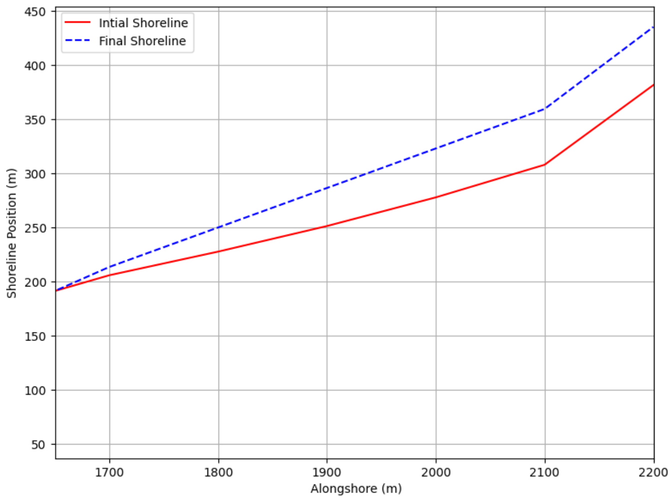

Figure 3: Abrasion on the final segment.

In these zones, the shoreline consistently shows negative values, indicating shoreline retreat due to erosional processes. The most severe erosion occurs at the 0 meter and 2200 meter alongshore point, each showing a displacement of approximately −53.73 meters. This phenomenon may result from the concentration of high wave energy at the unprotected ends of the shoreline, along with the possible lack of sediment supply from surrounding areas (Xie et al., 2024).

Meanwhile, the dominant accretion zone is found between 600 meters and 1500 meters alongshore position, as shown in Figure 4. In this zone, the shoreline advances significantly, with positive changes exceeding 50 meters at certain points for example, at the 1100-meter point (+53.73 meters). This indicates an accumulation of sediment due to longshore currents that actively transport and deposit material in this area (Lim & Lee, 2023; Putra et al., 2020). It is highly likely that this zone serves as a sediment deposition area, receiving material eroded from the preceding erosion zones.

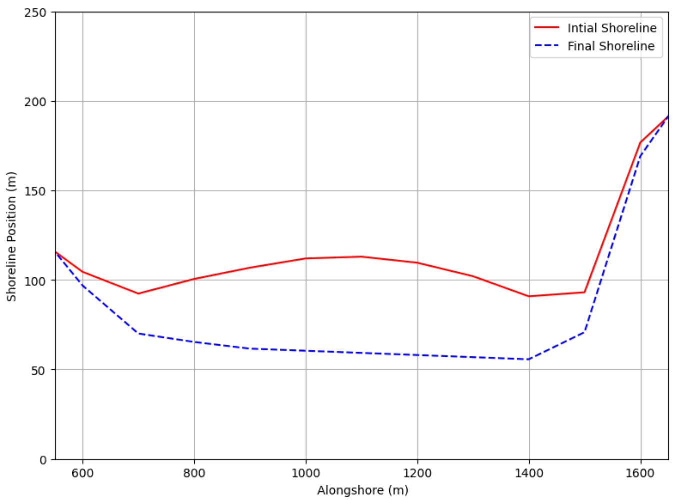

Figure 4: Accretion in the middle segment.

The transition zones are located around the 500–600 meter and 1500–1700 meter segments, where shoreline changes are not extreme and tend to approach zero or fluctuate slightly between mild erosion and mild accretion. These zones are important to monitor, as they have the potential to become unstable areas where shoreline positions shift rapidly due to seasonal or oceanographic dynamic changes (Zhang et al., 2024).

Such spatial patterns are crucial to analyze in the context of coastal area planning and management (Hastuti et al., 2024). This segmentation not only illustrates the physical impact of wave and current processes on the shoreline but also provides a scientific basis for zoning policies such as erosion mitigation, accretion zone conservation, and transition zone monitoring. By understanding the spatial distribution of shoreline change in more detail, targeted interventions such as constructing protective structures or restoring coastal vegetation can be more effectively implemented in the most vulnerable zones.

This simulation is particularly valuable as it provides a detailed and predictive spatial representation of shoreline changes. Such models typically use physical parameters like wave height, wave direction, and beach slope to estimate shoreline movement caused by longshore sediment transport. Therefore, the resulting data serve not only as a representation of empirical conditions but also as a tool to project future scenarios in coastal area management (Tao et al., 2024).

It is important to note that shoreline changes obtained from this simulation can be influenced by various external factors such as the construction of hard structures (e.g., jetties, groins), reclamation activities, climate change (e.g., sea-level rise), and seasonal wave regime shifts. In the context of sustainable coastal management, this data can be used to identify erosion-prone zones, plan coastal protection through vegetation or infrastructure, and adapt coastal spatial planning policies to align with natural dynamics and numerical model projections.

3.2. Coastal Management Implications

The simulation results of shoreline change from 2023 to 2024 provide crucial insights for sustainable coastal planning and management. The clear identification of erosion and accretion zones highlights the need for spatially-based and adaptive management strategies. In erosion-prone areas that experienced significant shoreline retreat such as segments 0–500 meters and 1700–2200 meters—immediate intervention is required to mitigate land degradation, loss of coastal ecosystems, and potential threats to infrastructure and human settlements. Such interventions may include the construction of hard structures such as breakwaters, groins, or revetments, as well as soft approaches like coastal vegetation rehabilitation (e.g., mangroves or coastal pines) and beach nourishment (Rashidi et al., 2021).

Meanwhile, accretion zones that show natural shoreline advancement should also be managed wisely. Although accretion can be considered a positive process due to land gain, excessive sediment accumulation may lead to the siltation of river mouths or disruptions to navigation and fisheries. Therefore, regular monitoring is necessary to ensure that the accretion process does not produce harmful secondary effects. Additionally, accreted areas can be strategically utilized for coastal habitat conservation and as natural buffer zones against storms and extreme wave events.

Transition zones exhibiting unstable dynamics must become a focus of long-term monitoring. These areas tend to be highly responsive to seasonal and climatic changes, and may shift between erosion and accretion zones over time. A risk-based management approach and early warning systems are crucial to be implemented in these segments.

Overall, the simulation results underscore the importance of integrating scientific data into coastal spatial planning processes, especially in the formulation of Coastal Zone and Small Island Zoning Plans (RZWP3K). Information on shoreline dynamics should be embedded in the planning of coastal infrastructure, protected areas, settlement zones, and coastal economic regions. Moreover, collaborative approaches involving government agencies, coastal communities, researchers, and the private sector need to be strengthened within a pentahelix model framework to ensure effective, adaptive, and sustainable coastal management amidst increasing climate change pressures and human activities.

4. Conclussion

This study effectively applied the one-line model to analyze shoreline dynamics at Batu Karas Beach, Pangandaran Regency, revealing significant spatial variations in erosion and accretion patterns throughout the study period. The simulation results identified erosion-prone areas on the western and eastern sections of the coastline, while accretion was concentrated in the central zone, likely driven by the influence of longshore currents that promote sediment deposition. Shoreline changes were found to be influenced by the interplay of wave height, wave direction, and coastal topographic characteristics. The performance of the model demonstrates its usefulness in capturing shoreline change trends, although its predictive accuracy could be further improved through consistent calibration with field measurements and satellite-derived shoreline data. These findings underscore the need for integrated and site-specific coastal management strategies that consider spatial shoreline dynamics. Recommended actions include the construction of coastal protection measures in erosion-prone zones and the conservation of coastal vegetation in accreting areas to support ecological resilience and reduce the adverse effects of environmental degradation and expanding tourism activities in Batu Karas.

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