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Assessing the Impact of Shoreline Changes on Framework Adaptive Tourism Development (Case Study: Mandiri Beach, Pesisir Barat, Lampung)

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ABSTRACT

This study investigates shoreline changes at Mandiri Beach, Pesisir Barat Regency, Lampung Province, during the period 2013–2024 using the Digital Shoreline Analysis System (DSAS). Landsat imagery was processed through Google Earth Engine (GEE) and ArcGIS, with the Modified Normalized Difference Water Index (MNDWI) applied to delineate land–water boundaries. Shoreline dynamics were quantified using DSAS metrics, including Net Shoreline Movement (NSM) and End Point Rate (EPR). The results reveal significant spatial variability: several segments experienced erosion, particularly in western and northeastern zones, while other areas showed accretion, mainly across gently sloping beaches and river mouths. In the primary research area, abrasion reached a maximum of 1.49 m with an average NSM of 1.41 m, and the End Point Rate indicated a gradual annual abrasion trend of 0.13 m/year. Meanwhile, Mandiri Sejati District exhibited more extreme changes, with maximum accretion of 11.84 m and maximum abrasion of 16.2 m, reflecting high sensitivity to environmental and anthropogenic pressures. These findings highlight the importance of adaptive coastal management framework to mitigate erosion risks and optimise accretion zones for sustainable tourism development. The study contributes to disaster mitigation planning, coastal resource management, and the integration of ecological conservation with tourism utilisation.

INTRODUCTION

Indonesia is an archipelagic nation with a coastline length of approximately 108. a coastline of approximately 108,000 km, making it one of the countries with the largest coastal extent ween two major oceans, the Indian Ocean to the west and south, and the Pacific Ocean to the east and north, Indonesia's coastal zones are strongly influenced by global oceanic dynamics, resulting in continuous shoreline adjustments driven by oceanographic processes, climate change, and human activities. With its extensive coastline spanning many islands, Indonesia is highly vulnerable to coastal change (Assifa et al., 2023; Hidayat et al., 2023; Purwanti & Koestoer, 2024; Saad et al., 2024; Tarigan, 2019).

Shoreline change may result from natural processes such as erosion and sedimentation; however, anthropogenic activities also play a significant role. Infrastructure development and the exploitation of coastal resources frequently accelerate the rate of change (Damar

Wicaksono et al., 2020; Maharani et al., 2023). One area experiencing significant changes to its coastline is Pesisir Barat Regency in Lampung Province. This area represents the potential for marine tourism along Indonesia's coast, particularly in regions bordering the Indian Ocean. Its high waves attract domestic and international visitors, particularly surfers. In recent years, changes to the coastline in this area have had significant environmental and socioeconomic impacts. For example, a storm surge during severe weather in 2018 damaged infrastructure and cut off the main bridge at Mandiri Beach. The tourism sector also suffered, with several accommodations and tourism companies reporting declines in visitor numbers and, in some cases, being forced to cease operations due to an inability to plan and mitigate the situation (Naik et al., 2026). The lack of an appropriate framework for responding to tourism development in coastal areas is a contribution and an output of this research.

This study highlights its novelty by demonstrating that Mandiri Beach exhibits shoreline dynamics distinct from those observed globally. Between 2013 and 2024, both erosion and accretion occurred, primarily driven by hydrodynamic forces in the Indian Ocean, including high-energy waves and strong currents. The beach's open position and lack of natural offshore barriers, along with limited coastal vegetation, make it more vulnerable than other tropical coasts with more natural protection (Bird, 2008; Fadly & Dewi, 2023). Similar phenomena have appeared in other tropical destinations: Phuket, Thailand, where shoreline retreat is linked to sea-level rise and intensive tourism (Nidhinarangkoon et al., 2023); Nha Trang Bay, Vietnam, where seasonal erosion and accretion are influenced by monsoon regimes (Cuong et al., 2024; Trung et al., 2025); and Mayo Bay, Philippines, where coastal erosion between 2013 and 2023 led to loss of protective vegetation and threatened tourism (Masancay & Jimenez, 2024). Compared to these cases, Mandiri Beach exhibits greater sensitivity due to the combined effects of high wave energy, an exposed geographic setting, and a minimal vegetative buffer. This combination makes Mandiri Beach a critical case for understanding tropical coastal dynamics and their impacts on sustainable tourism management.

To understand shoreline dynamics at Mandiri Beach, this study analyses shoreline displacement over the 2013–2024 period using the Digital Shoreline Analysis System (DSAS), a tool that detects and automatically computes shoreline distance and change rates. DSAS, a geographic information system extension, enables the quantitative measurement of shoreline change through statistical approaches, such as the End Point Rate and Linear Regression Rate (Himmelstoss et al., 2021). The application of satellite imagery in this analysis offers several advantages, including broad spatial coverage, relatively rapid processing times, and lower costs compared to field-based surveys (Baig et al., 2020; Oyedotun, 2014).

Previous studies have demonstrated that DSAS is effective at identifying patterns of erosion and accretion along coastlines. Examples of DSAS applications include analyses of shoreline change on Java's northern coast and studies in the waters of Teluk Awur, which combined Landsat data with hydrodynamic information such as tides and wind, revealing dominant erosional processes at several locations (Ibrahim et al., 2023). Nonetheless, focused investigations of shoreline change at Mandiri Beach remain limited. This study aims to address that gap by providing a DSAS-based, in-depth analysis to obtain more specific information on the area's coastal morphological dynamics.

The objective of this study is twofold. First, it aims to use the Digital Shoreline Analysis System (DSAS) to quantitatively assess shoreline dynamics at Mandiri Beach, focusing on erosion and accretion patterns that influence coastal tourism sustainability. Second, the study seeks to establish a benchmarking framework for comparing adaptive management strategies with those used in other coastal regions, both locally and globally, that face similar shoreline change phenomena. By addressing both objectives, this research not only generates site-specific insights but also contributes to broader coastal management discourse, offering transferable lessons for sustainable tourism development.

RESEARCH METHODS

Study Area

The study was conducted at Mandiri Beach Tourism Area, located in Mandiri Sejati village, South Krui Subdistrict, Pesisir Barat Regency (Error! Reference source not found.). Mandiri Beach is a designated priority tourism cluster in Pesisir Barat, Lampung, widely recognized as a surfing spot characterized by high-energy waves from the Indian Ocean (Lampung Province Regional Tourism Development Master Plan (RIPPDA), 2012). The beach's role in the local economy has intensified waterfront activities (access, amenities, and tourism enterprises) (Hampton et al., 2024). Furthermore, changes in coastal morphology have direct implications for facility safety, visitor experience, and destination image. Situated on the west coast of Sumatra and directly facing the Indian Ocean, Mandiri Beach is exposed to relatively high wave energy and longshore currents, which constitute the primary drivers of local erosion–accretion dynamics (Krishnan et al., 2022; Simarmata et al., 2025). A similar phenomenon—a mosaic of erosion and accretion along high-energy coasts—has been consistently documented in multi-decadal studies of central Vietnam, underscoring the importance of quantitatively measuring shoreline-change trends and hotspots (Quang et al., 2021).

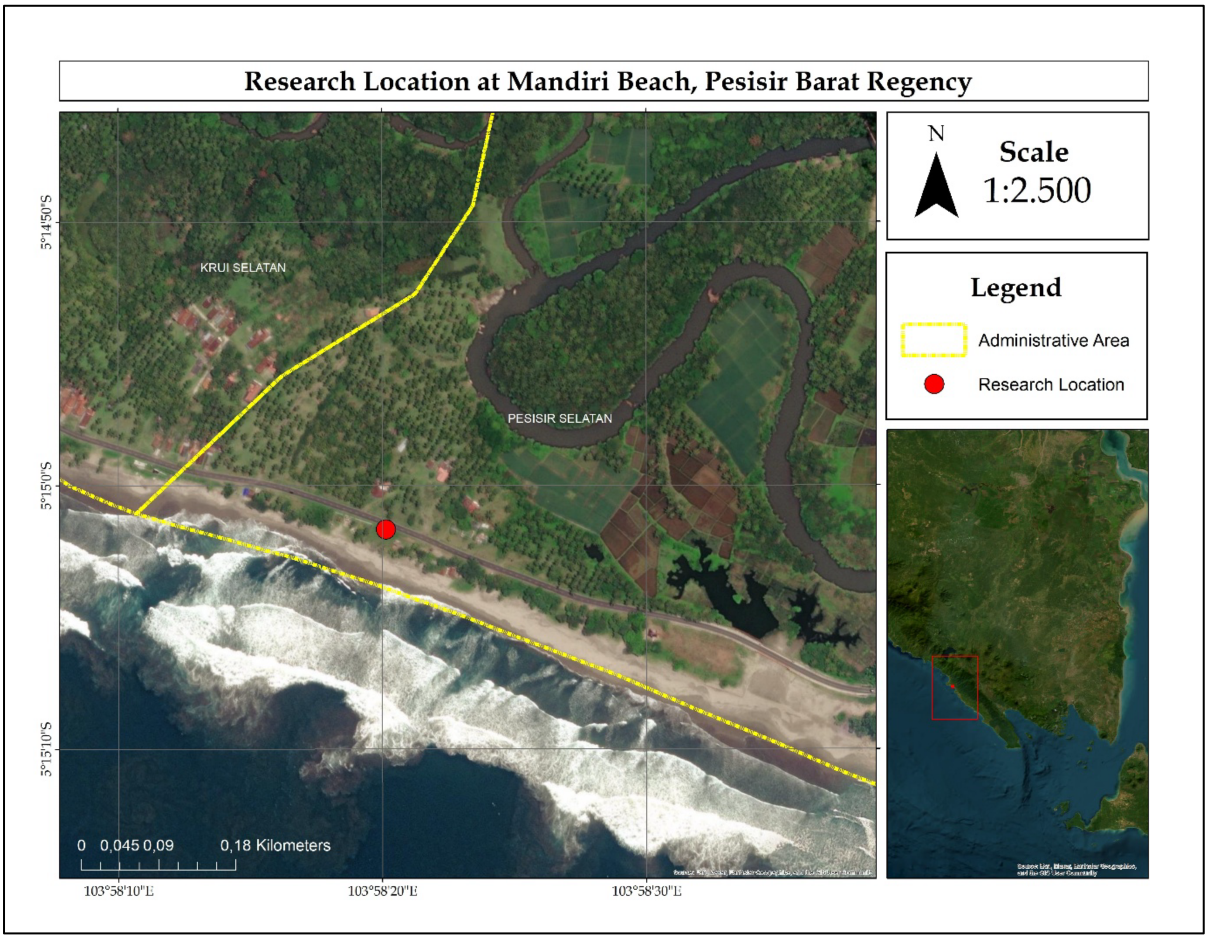

Figure 1. Research Study Map (Source: Research Results, 2025).

Data Acquisition Using Google Earth Engine (GEE)

Google Earth Engine (GEE) is a cloud-based platform designed for large-scale geospatial analysis that substantially simplifies the acquisition and processing of satellite imagery. The platform provides direct access to a multi-petabyte public data catalogue, including the complete archives of Landsat, Sentinel, and MODIS, as well as a wide range of other environmental datasets.

One of the key advantages of GEE lies in its ability to perform automated preprocessing tasks, such as tiling imagery, cloud masking, and spatial resolution adjustment. These features eliminate the need for users to manage complex file formats or configure sophisticated computational systems. The combination of accessibility, processing efficiency, and interactive visualisation makes GEE an invaluable tool for researchers, policymakers, and environmental practitioners. It is particularly effective in studies of landscape change, water resource monitoring, and spatially informed regional planning (Aziz et al., 2020; Gorelick et al., 2017) the temporal scope of the analysis covers 2013–2024.

Cloud Masking

The application of cloud masking in Google Earth Engine (GEE) is a critical step in ensuring reliable shoreline extraction from Landsat imagery. Cloud contamination can significantly distort spectral signatures, leading to misclassification of land–water boundaries. In this study, cloud masking was performed using the Fmask (Function of Mask) algorithm, which automatically detects clouds, cloud shadows, and snow based on spectral and thermal thresholds. This method has been widely recognized for its effectiveness in reducing atmospheric noise in multi-temporal Landsat datasets (Zhu & Woodcock, 2014).

However, while Fmask improves the clarity of shoreline delineation, it may also reduce spatial continuity by removing cloud-affected pixels, thereby introducing gaps in the dataset. (Gorelick et al., 2017) emphasize that GEE's integration of Fmask enables large-scale automated preprocessing, making it particularly suitable for long-term shoreline monitoring. Nevertheless, reliance on Landsat 8 imagery with a 30 m spatial resolution means that fine-scale shoreline dynamics remain unresolved, a limitation noted by (Pardo-Pascual et al., 2012).

Furthermore, residual uncertainties persist in cases of semi-transparent clouds or thin cirrus, which can escape detection and bias shoreline positioning (Frantz et al., 2018). Studies such as (Hagolle et al., 2015; Vermote et al., 2016) show that cloud-masking accuracy is strongly dependent on atmospheric conditions and sensor characteristics, underscoring the need for triangulation with higher-resolution imagery (e.g., Sentinel-2) or UAV-based surveys. Thus, while GEE cloud masking provides a robust foundation for shoreline change analysis, its limitations in spatial resolution and its exclusion of tidal phases must be acknowledged as sources of uncertainty in coastal geomorphological studies.

The Modified Normalized Difference Water Index (MNDWI)

MNDWI has been demonstrated as a practical approach for distinguishing water bodies from terrestrial surfaces in satellite imagery, particularly for land-cover change analysis and lake-surface monitoring. In a study by Aziz et al. (2020), MNDWI was applied to Landsat imagery to classify lake areas in the Lake Toba region. The method exploits the spectral contrast between the green and Short-Wave Infrared (SWIR) bands, thereby enhancing the distinct reflectance characteristics of water, low in SWIR and high in the green band. The delineation of land–sea boundaries in this study follows the formula proposed by (Xu (2006):

$$\mathrm{MNDWI} = \frac{(\mathrm{Green} - \mathrm{SWIR})}{(\mathrm{Green} + \mathrm{SWIR}} \quad \ldots\ldots (1)$$

Digital Shoreline Analysis System (DSAS)

This research employs the Digital Shoreline Analysis System (DSAS) to evaluate shoreline changes along Mandiri Beach, Pesisir Barat Regency. DSAS is a Geographic Information System (GIS)-based extension designed to measure shoreline change quantitatively using a range of statistical approaches. Its principal advantage lies in its ability to conduct automated, systematic change analysis across historical and contemporary datasets, thereby producing more consistent estimates (Baig et al., 2020; Saad et al., 2024).

In this study, shoreline change calculations were carried out using two primary DSAS methods: Net Shoreline Movement (NSM) and End Point Rate (EPR). The equations used in the analysis are as outlined by Himmelstoss et al. (2021).

$$\mathrm{NSM} = \mathrm{Earliest} - \mathrm{Recent\ Shoreline}$$

$$\mathrm{EPR} = \frac{\mathrm{NSM}}{\mathrm{time\ interval\ between\ the\ two\ shoreline}}$$

DSAS has demonstrated high effectiveness in analyzing shoreline changes both historically and spatially. Compared to field survey methods such as the Differential Global Positioning System (DGPS) or Total Station, DSAS offers several notable advantages. One of its primary strengths is the ability to utilize historical data from satellite imagery, topographic maps, and aerial photographs, thereby enabling shoreline change analysis over extended temporal scales (Oyedotun, 2014).

In addition, DSAS provides broader spatial coverage because it is based on globally accessible digital spatial data. Time efficiency is another advantage, as the analysis is performed automatically in a GIS environment, eliminating the need for extensive field mobilization. From a cost perspective, DSAS is considerably more economical because it does not require expensive survey equipment or complex field logistics (Baig et al., 2020).

Nevertheless, DSAS also has limitations. The accuracy of the analysis results depends heavily on the quality and resolution of the input data, as well as the precision of the digitization process. Scale inconsistencies, georeferencing errors, and positional uncertainties may affect the outcomes. In contrast, field survey methods such as DGPS and Total Station excel in positional precision and accuracy, particularly for short-term studies or intensive monitoring. Field-based approaches are also better at capturing real-time coastal morphological dynamics, including the driving factors of waves, tides, and human activities (Oyedotun, 2014).

To achieve the objectives of this research, a series of systematic steps was undertaken by utilizing satellite imagery and spatial analysis. The process began with data collection and preparation in Google Earth Engine (GEE), including selecting Landsat 8 imagery for the selected years, applying annual cloud masking, and cropping the study area to the Mandiri Beach boundaries. Subsequently, the Modified Normalized Difference Water Index (MNDWI) method was applied to separate water surfaces from land, thereby facilitating shoreline extraction (**Error! Reference source not found.**).

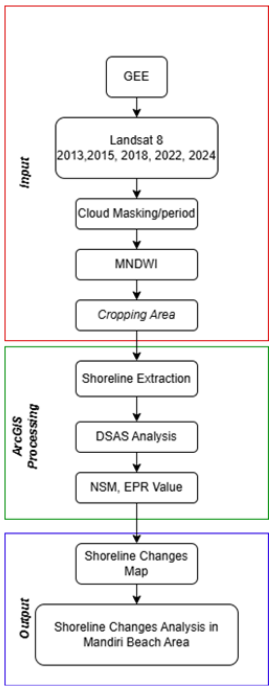

Figure 2. Research workflow (Source: Research Results, 2025).

From the MNDWI classification results, shorelines were extracted for each observation year. These successive shorelines were then analyzed using DSAS to calculate shoreline change metrics, including Net Shoreline Movement (NSM) and End Point Rate (EPR). The values obtained were validated with field data or high-resolution imagery when available. The final outputs consisted of spatial maps of shoreline change and quantitative reports describing erosion and accretion trends in the Mandiri Beach Tourism Area (**Error! Reference source not found.**).

Analysis of Literature: Adaptive Tourism Systems

The literature review stage is conducted through a systematic search of scientific publications, coastal zone policies, and technical reports to identify best practices from successful benchmark regions that manage coastal phenomena as strategic development assets. The gathered data is then analyzed using qualitative synthesis to examine the correlation between coastal geomorphological dynamics, specifically shoreline change rates quantified via the Digital Shoreline Analysis System (DSAS), and the enhancement of the '5A' tourism components (Attractions, Amenities, Accessibility, Ancillaries, and Accommodations) (Cooper, 2008). Grounded in the principles of Complex Adaptive Systems (CAS) and the Adaptive Cycle, a cohesive framework integrates various management models from these benchmark locations. This process yields an adaptive response framework for managing land accretion, aimed at securing ecological sustainability and economic resilience within the tourism sector.

Data Validation

Ensuring the accuracy of shoreline change analysis is essential for reliable coastal management and tourism planning. In this study, validation was conducted through direct field observations at Mandiri Beach, including interviews with local tourism business owners affected by erosion and aerial drone documentation. These qualitative approaches provided empirical evidence to validate the DSAS outputs, particularly in areas where infrastructure, such as villas, restaurants, and bridges, had been damaged. However, the absence of quantitative measurements using Differential GPS (DGPS) or Total Station limited the precision of validation, making this a primary methodological constraint (Azad et al., 2022; Oyedotun, 2014).

Uncertainty

Beyond validation, several sources of uncertainty were identified in the analysis. First, cloud cover in Landsat 8 imagery (2013, 2015, 2018, 2022, and 2024) was addressed using the Fmask algorithm in Google Earth Engine (GEE). While effective in removing cloud pixels, this process can reduce spatial quality and introduce gaps in data coverage (Gorelick et al., 2017; Zhu & Woodcock, 2014). Second, the spatial resolution of Landsat 8 (30 m) limits the detection of micro-scale shoreline changes, making DSAS more suitable for long-term macro-trend analysis than for fine-scale monitoring (Baig et al., 2020; Pardo-Pascual et al., 2012). Third, tidal variations were not incorporated into the analysis, which may lead to deviations in shoreline position, particularly in dynamic intertidal zones (Ibrahim et al., 2023; Luijendijk et al., 2018). Finally, georeferencing errors and manual digitization can introduce systematic biases in Net Shoreline Movement (NSM) and End Point Rate (EPR) calculations (Oyedotun, 2014; Himmelstoss et al., 2021).

Taken together, these limitations highlight that the DSAS results should be interpreted as long-term spatial estimates rather than precise daily shoreline positions. Transparency in both validation procedures and sources of uncertainty is therefore critical to ensure that the findings can be applied responsibly in adaptive coastal management and sustainable tourism development.

RESULTS AND DISCUSSION

Shoreline Extraction Quality and Validation

As an initial step in examining shoreline change, it is necessary to accurately extract the shoreline from satellite imagery to provide a reliable foundation for spatial analysis. In this study, imagery was processed in Google Earth Engine and further refined in ArcGIS to clarify the distinction between land and water and to enhance the quality of visual interpretation. The preprocessing and classification stages were designed to produce clear spatial separation between the two main classes while ensuring data consistency required for quantitative measurements of shoreline change rates. The results of shoreline delineation are graphically presented in Figure 3 to facilitate visual assessment.

The procedure for delineating the shoreline in the figure above was carried out using a layered analysis of the infrared band (band 6) in Landsat 8 imagery, which highlights reflectance differences between land and water. Subsequently, the Modified Normalized Difference Water Index (MNDWI) was applied to maximize the contrast between aquatic and terrestrial areas, thereby making the two-class classification more straightforward and reliable. From the classification map, the land–water boundary was delineated as a red line representing the shoreline. This step is crucial for detecting spatial changes and providing trustworthy input for coastal management planning. A similar approach was also employed in studies conducted by Aziz et al. (2020); Aziz (2023).

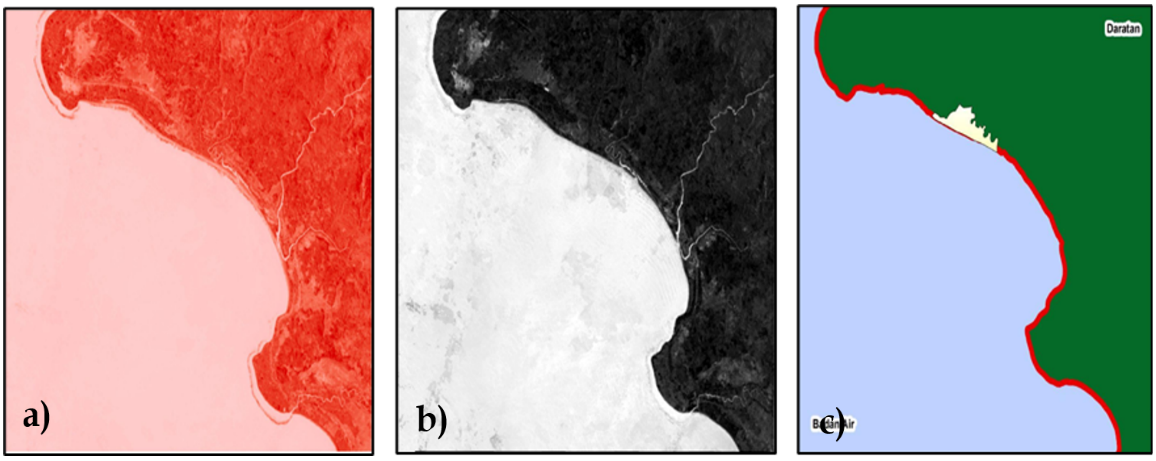

Figure 3. Satellite image (a) infrared band; (b) MNDWI; (c) Shoreline extraction (Source: Research Results, 2025).

Once the shoreline was derived from the annual imagery, these features served as the primary input for shoreline dynamics analysis with the Digital Shoreline Analysis System (DSAS). With DSAS, quantitative metrics such as End Point Rate (EPR) and Net Shoreline Movement (NSM) were calculated, each representing the annual rate of change and the total shoreline displacement over the observation period. The resulting maps illustrate patterns of erosion and accretion in the Mandiri Beach tourism area, Pesisir Barat Regency, for the period 2013–2024, thereby supporting the interpretation of change trends and the formulation of recommendations for sustainable management.

Spatial Patterns of Shoreline Change

The results of the shoreline dynamics analysis at Mandiri Beach in Pesisir Barat Regency, conducted using DSAS with the EPR and NSM metrics for the 2013–2024 period, reveal significant and varied coastal morphological changes. The EPR indicates the annual rate of shoreline position change, while the NSM reflects the cumulative displacement over the study period. Together, these indicators provide a temporal and quantitative overview of coastal trends (Figure 4).

The change maps reveal distinct patterns of shoreline evolution. Erosion dominates several segments, particularly in the western and northeastern sectors, causing a progressive landward retreat. This pattern suggests strong exposure to wave energy and limited natural buffering. The driving forces likely involve sea-level rise, high wave energy, and reduced coastal vegetation that would otherwise stabilize the shoreline (Figure 4). In contrast, accretion zones, mainly near river estuaries and sheltered embayments, indicate sediment deposition linked to fluvial supply and weaker hydrodynamic energy. Several segments remained relatively stable, reflecting a balance between erosion and sediment accumulation (Tarigan, 2019).

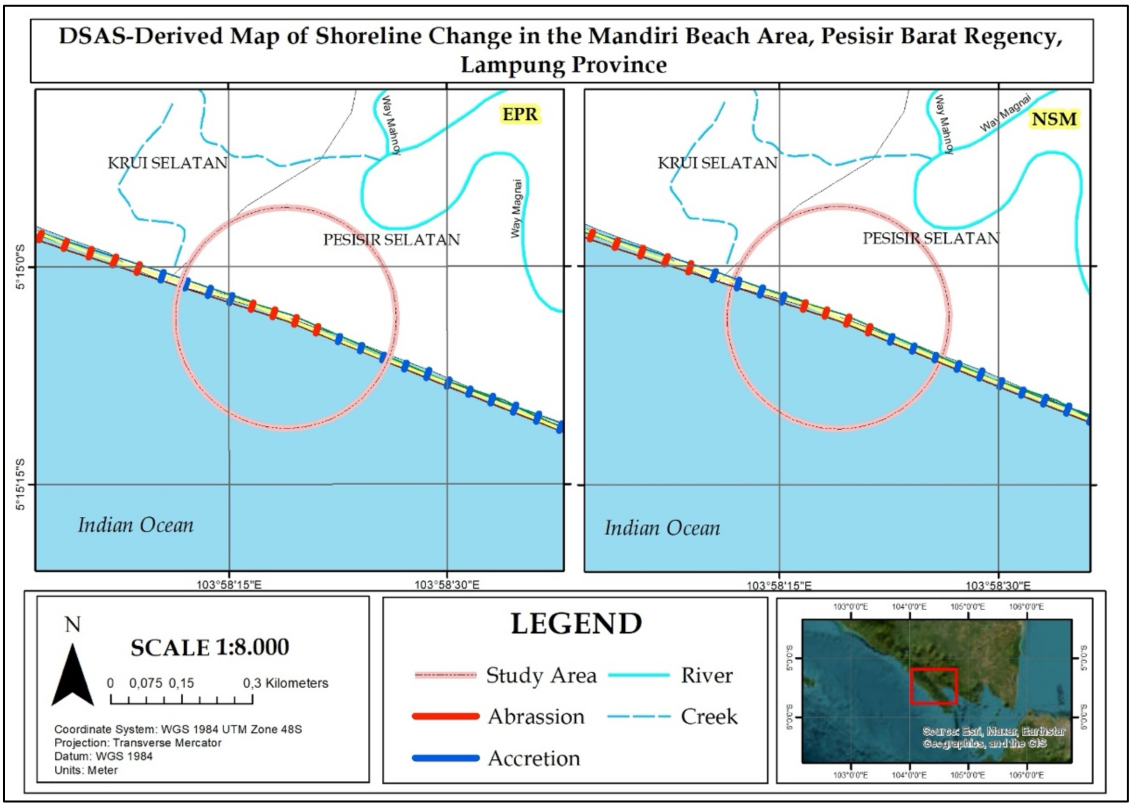

Figure 4. EPR and NSM results using DSAS (Source: Research Results, 2025).

To further interpret the processes underlying these observed shoreline changes, it is useful to consider four main driving factors: oceanographic forcing, geomorphological and sedimentary characteristics, anthropogenic pressures, and their interactions. From an oceanographic perspective, research by Castelle et al. (2022) on the sandy coast of Nouvelle-Aquitaine demonstrates that variability in wave climate, controlled by large-scale atmospheric patterns such as the WEPA index, significantly regulates longshore sediment transport gradients and long-term shoreline trends. In addition, a study by Q. Wang et al. (2023) on the Yalu River Estuary highlights the importance of hydrological variability and extreme events in shaping estuarine shoreline dynamics. Taken together, these findings reinforce that wave forcing and sediment supply variability are central to understanding the spatial differentiation of erosion and accretion at Mandiri Beach.

Building on this, anthropogenic pressures further modify the natural processes described above. For example, research by Hapke et al. (2013) shows that coastal infrastructure development can induce extreme progradation and alter long-term shoreline change rates, sometimes masking natural geomorphological signals.

Similarly, research by H. Wang et al. (2022) on Chongming Island indicates that reclamation and coastal engineering significantly reshape shoreline responses by altering sediment pathways and hydrodynamic conditions. Applying these insights to the context of Mandiri Sejati District, where more extreme NSM values were recorded, suggests that such interactions between natural processes and human activities may explain the amplified shoreline variability observed.

The shoreline dynamics analysis around the study area, based on NSM and EPR values, revealed significant changes in two main areas: (1) the primary study site and (2) Mandiri Sejati District. At the leading study site, a tendency toward mild erosion was observed; the maximum shoreline advance measured +0.39 meters, while the greatest retreat reached −1.49 meters, resulting in an average NSM of −1.41 meters. The EPR indicated a negative annual trend of −0.13 meters per year, suggesting a gradual shoreline retreat over the 2013–2024 period.

Table 1. Mandiri Beach DSAS Results

Location	NSM (Meter)				EPR (Meter/year)			
	Highest	Lowest	Average		Highest	Lowest	Average	
			(+)	(-)			(+)	(-)
Research Area	0,39	-1,49	0,39	-1,41	0,04	-0,14	0,04	-0,13
Mandiri Sejati District	11,84	-16,2	6,17	-5,9	1,07	-1,47	0,55	-0,54

(Source: Research Results, 2025)

Mandiri Sejati District exhibited a more pronounced pattern of change, with a maximum accretion of 11.84 meters and a maximum abrasion of 16.2 meters. The average NSM of −5.9 meters indicates that abrasion processes dominated despite the presence of accretion points (**Error! Reference source not found.**). The EPR in this area recorded the highest accretion rate of 1.07 meters per year and the highest abrasion rate of 1.47 meters per year, while the average annual abrasion rate was 0.54 meters per year. These results reflect the site's sensitivity to variations in environmental conditions and anthropogenic pressures, as observed in field documentation of erosion impacts at Mandiri Beach.

Within the Mandiri coastal sector (Pesisir Barat, Lampung), DSAS-based estimates indicate moderate shoreline mobility, with EPR ranging from −1.47 to +1.07 m/year and NSM from −16.2 to +11.84 m. Relative to other tropical coasts, these values lie below well-documented upper-end cases. On the central Vietnam coast, the strongest erosional cells reached EPR = −42.4 m/year, with high EPR–LRR agreement ($R^2 \approx 0.96$), evidencing intense, spatially heterogeneous retreat (Quang et al., 2021). A south-Java hotspot (Cilacap) showed an average retreat of about −14.6 m/year over two decades (B. Mutaqin et al., 2024), an order of magnitude greater than Mandiri. (Dey et al., 2021) report that in a macro-tidal tropical estuary, transect-level extremes approached ~−33 and +50 m/year (EPR/LRR/WLR envelope), again far exceeding Mandiri's range. Even when compared with an urbanized north-Java front (Pekalongan) that experienced sustained abrasion of ~3.95–4.02 m/year during 2016–2022, Mandiri remains in a low–moderate envelope (Endarsih et al., 2025). In terms of spatio-temporal behaviour, Mandiri's juxtaposition of erosion and accretion cells aligns with monsoon-modulated regime switching documented along the Pariaman coast of West Sumatra, even if magnitudes differ (Arif, 2020). Methodologically, these comparisons are consistent with DSAS best practices for EPR/LRR/WLR/NSM reporting and uncertainty, as outlined in the USGS DSAS user guide (Himmelstoss et al., 2021).

Abrasion Impact

Damage to one of the lodging facilities (villa) shown in **Error! Reference source not found.** was caused by coastal erosion triggered by high wave energy in the absence of natural or artificial buffers. The lack of coastal vegetation and protective structures accelerated the loss of supporting material, leaving the foundation without stable ground. Construction too close to the shoreline, without accounting for shoreline shifts, further increased vulnerability; as a result, parts of the building collapsed, and other structural elements became unstable due to the loss of supporting soil. This condition directly affected the lodging business's operations, and field observations indicate that the facility has been abandoned or is no longer in use.

Figure 5. Abrasion impacts (a) Villa; (b) restaurant; (c) bridges
(Source: Research Documentation, 2025)

The restaurant building in the Mandiri Beach tourism area (**Error! Reference source not found.**b) was constructed very close to the tidal boundary, almost parallel to the sand line, with no buffer zone. This position makes it highly vulnerable to wave attack, especially during high tide or extreme weather conditions, leading to scouring at the foundation base.

This phenomenon was also highlighted in the study by Mapaliey et al. (2021), which reported that intensive waves damaged and even swept away semi-permanent vendor stalls, destroyed parts of residential structures, and damaged supporting facilities such as fish auction sites and pedestrian access roads. Such damage reduced the operational capacity of the tourism site and disrupted the continuity of local businesses.

The condition of the bridge in Mandiri Sejati District (**Error! Reference source not found.**c) illustrates the combined effects of coastal abrasion and river erosion. Increased discharge and flow velocity during the rainy season or during high tide intensified shear forces, eroding soil around the foundation and weakening the structural support. The presence of an old, damaged bridge alongside a newly constructed replacement indicates that changes in flow patterns and erosion have significantly affected the resilience of transportation infrastructure.

Impacts on public infrastructure include reduced functionality of parking areas, damage to access networks connecting tourist attractions, and threats to coastal safety installations, thereby disrupting visitor management services (Mapaliey et al., 2021).

Tourism Adaptation System Framework in Coastal Accretion Areas

At the initial stage of developing a systemic framework for areas experiencing coastal accretion, it is essential to analyze the underlying resilience mechanisms and governance structures. To ensure that this adaptation remains sustainable, several core principles must be integrated into the management of newly formed land:

- Risk Assessment: conduct a rigorous assessment to determine whether the accreted land is permanent or merely a result of seasonal fluctuations prone to sudden erosion; this is crucial to prevent a "false sense of security" for tourism infrastructure investments (Naik et al., 2026).

- Nature-Based Solutions, implementing natural interventions, such as mangrove afforestation or sand dune restoration on accreted land, to serve as biological buffers for tourism infrastructure (Naik et al., 2026).
- Beach Carrying Capacity (BCC) is recalculated following the expansion of the terrestrial area to prevent overtourism, which could otherwise degrade the quality of the newly emerging ecosystem (Naik et al., 2026; Romero-Martín et al., 2025).
- Collaborative Governance, establishing strategic partnerships between government agencies, private operators, and local communities to collectively monitor the environmental quality and security of the additional land (C. Cristiano et al., 2020; Zhang et al., 2024).
- Digital Transformation, leveraging digital technologies for real-time shoreline monitoring and early warning systems to ensure the safety of tourists within dynamic coastal environments (Liu et al., 2024; Zientarski & Such-pyrgiel, 2019).

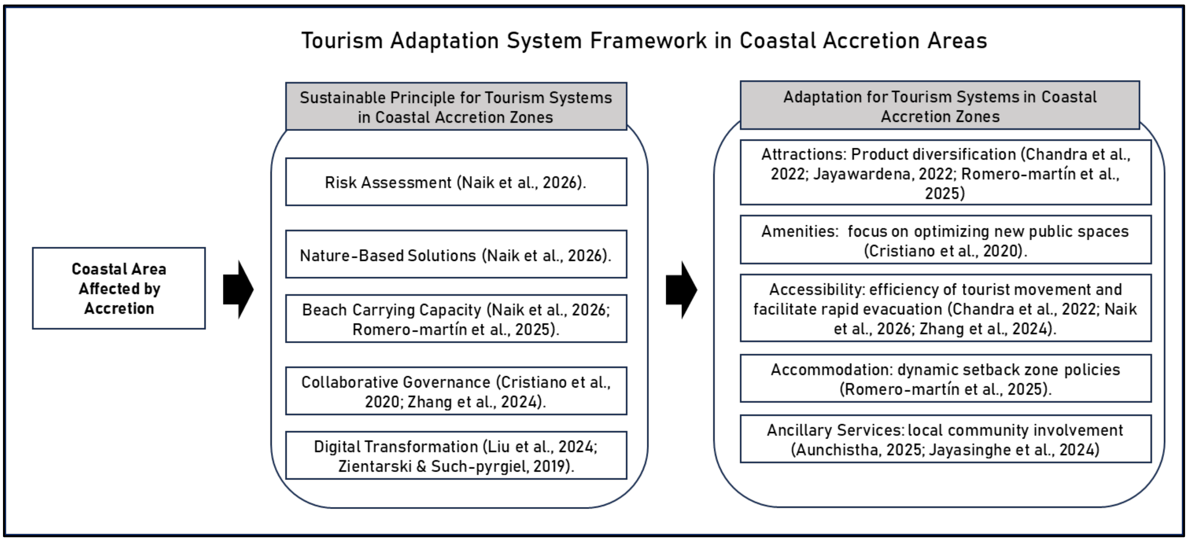

Figure 6. Tourism Adaptation Strategies within an Adaptive Coastal Management Framework (Source: Research Result, 2026)

Adaptation for Tourism Systems in Coastal Accretion Zones

The utilization of coastal accretion zones within the tourism system can be delineated through several adaptive strategies:

- lying land into active recreational areas, such as beach sports zones, ATV tracks, or ecological educational tours.
- **Amenities:** In accreted areas, amenities focus on optimizing new public spaces to enhance visitor satisfaction without compromising landscape aesthetics (Cristiano et al., 2020a). Further adaptation involves the strategic planning of supporting facilities such as gazebos, public toilets, and green open spaces, specifically within geomorphologically stable zones.
- **Attractions:** Product diversification is essential to reduce over-reliance on conventional "sun-and-sand" models (Jayawardena, 2022; Kanth et al., 2022; Romero-martín et al., 2025). Adaptive measures include transforming new, low-
- **Accessibility:** Accessibility adaptation aims to improve the efficiency of tourist movement and facilitate rapid evacuation during sudden environmental shocks (Kanth et al., 2022; Naik et al., 2026; Zhang et al., 2024). In accretion zones, this is implemented by designing flexible connectivity routes (e.g., wooden boardwalks or non-permanent pathways) that bridge the original landmass with the newly formed shoreline.
- **Accommodation:** This component requires the application of dynamic

setback zone policies. The development of lodging facilities, such as villas or homestays, must be restricted to safe zones to ensure structural robustness against long-term sea-level rise (Romero-martín et al., 2025).

- **Ancillary Services:** Strengthening local community involvement within the tourism value chain is vital for sustainability (Aunchistha, 2025; Jayasinghe et al., 2024). Adaptive actions include providing designated spaces for tourist information centers, lifeguard stations, and local SME (Small and Medium Enterprise) kiosks on the newly accreted land.

Accretion Potential

Shoreline position changes are often accompanied by relatively flat coastal slopes that tend to experience accretion or land expansion. This condition reduces the ability of waves to transport sediment, allowing particles to settle easily along the coast. The accumulated deposits subsequently form accretion zones and gradually extend the shoreline seaward (Bird, 2008). In addition, gently sloping beaches typically respond more calmly to tides and waves, resulting in lower erosive (abrasive) energy.

From the slope map of Pesisir Barat Regency (Figure 7), it is evident that most coastal areas have low gradients, ranging from 0–8%, indicated in green. These gentle slopes are widely distributed, particularly along the western and southwestern coastal zones of the regency, which also serve as centres of coastal activities and settlements. Such relatively flat topography significantly influences shoreline change patterns.

Areas experiencing accretion have the potential to develop as coastal sports tourism destinations, including surfing, horseback riding, ATV (All-Terrain Vehicle) tracks, and other recreational activities. Research indicates that wide and flat accreted land is suitable for developing adventure and recreational tourism. Furthermore, u using accreted areas for tourism can be done sustainably if planning accounts for environmental and conservation factors.

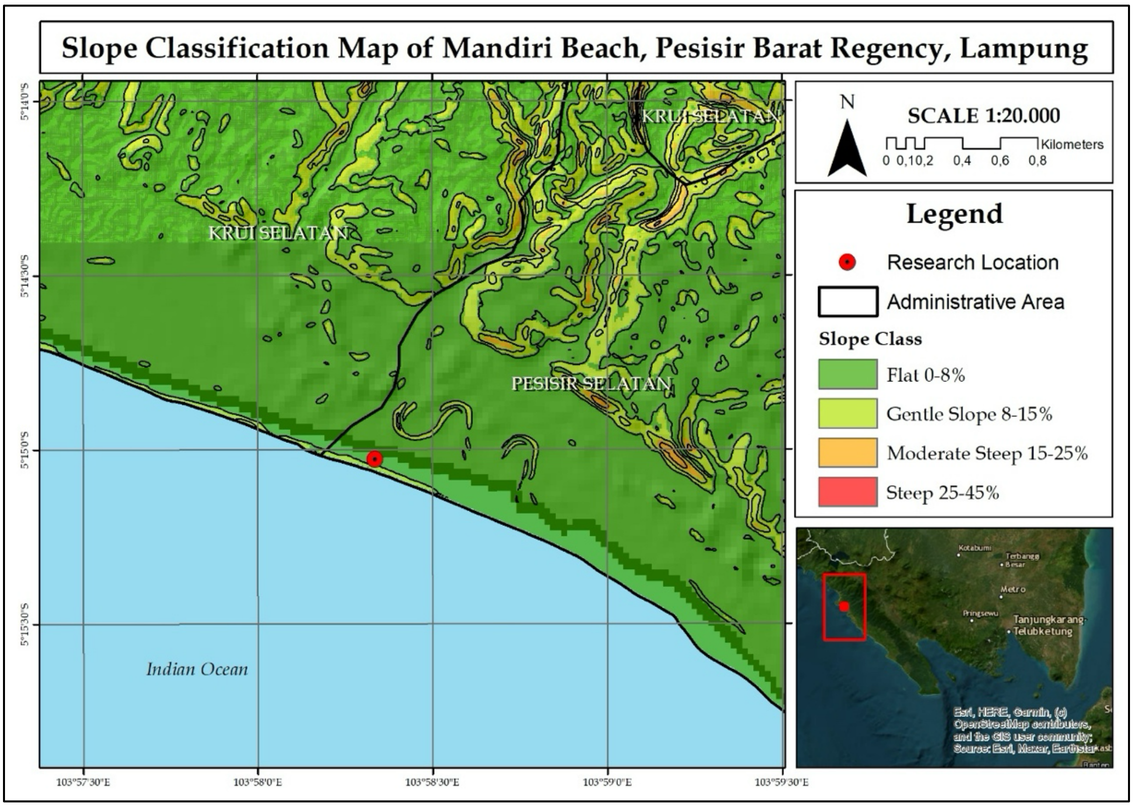

Figure 7. Slope Map Around the Research Area (Source: Research Results, 2025).

According to Febrianty (2017), in a study of coastal tourism development strategies at Batu Lima Beach, the dynamics of accretion and erosion have distinct implications for tourism utilization. In areas experiencing accretion, the expansion of land due to sediment deposition creates new opportunities to expand tourism infrastructure. Accreted land can be used for recreational facilities, green open spaces, or other tourism-supporting infrastructure. Conversely, in areas affected by erosion, land loss poses serious challenges, as it damages tourism infrastructure, including lodging, playgrounds, and food stalls, which can no longer function optimally (Febrianty, 2017). From the perspective of sustainable tourism, shoreline changes, whether erosion or accretion, directly affect the five main components of tourism (5A) developed by Cooper (2008):

- **Accommodation**: Shoreline change may threaten the sustainability of coastal lodging facilities due to land loss from erosion, or conversely, create new land for potential development in cases of accretion.
- **Ancillary Services**: Supporting facilities such as MSME centres, tourism service posts, and safety facilities may be severely affected if located in erosion-prone zones.
- **Amenities**: Small-scale infrastructure supporting visitor comfort, such as public toilets, seating areas, gazebos, and food stalls, is vulnerable to damage in erosion-prone areas, while accretion provides opportunities to plan new amenities more strategically.
- **Accessibility**: Access to beaches and connectivity between tourist attractions may be disrupted by erosion; conversely, accretion can improve access, for example by creating ATV tracks or horseback riding trails.
- **Attractions**: Accreted land has the potential to become new, high-value attractions, such as gently sloping sandy beaches suitable for recreational activities like surfing, seafood-based culinary tourism, or environmental education tourism (Febriyanty, 2017).

Considering these five aspects demonstrates that shoreline change studies are essential not only for designing erosion mitigation measures but also for the productive and sustainable utilization of accreted areas, balancing the ecological and economic values of tourism.

As one of the erosion mitigation measures, the construction of physical structures, such as seawalls and revetments, is often used in coastal areas. Coastal defences made of large rock boulders and wave-breaking structures are installed along the cliffs to protect them. These revetments are intended to reinforce the shoreline so that waves cannot easily erode it (Figure 8).

Figure 8. Coastal Protection Structure (Source: Research Documentation, 2025).

In another study (Mapaliey et al., 2021), a case study of coastal tourism in Bantul, Yogyakarta, focused on efforts to reduce erosion by implementing both structural and non-structural mitigation strategies integrated into coastal governance. Technically, one of the main plans is to construct coastal protective structures, such as seawalls and revetments, that dissipate wave energy before it reaches the shore. The presence of these protective structures is expected to slow shoreline erosion while maintaining the sustainability of tourism infrastructure and settlements in the buffer zone (Mapaliey et al., 2021)

Beyond physical approaches, erosion-reduction planning also emphasizes the importance of adaptive coastal spatial planning. This includes relocating tourism facilities away from erosion-prone shorelines and designating coastal buffer zones as protective areas (Mapaliey et al., 2021). From a socio-economic perspective, erosion-reduction strategies require the participation of community and tourism managers in maintaining cleanliness, monitoring development activities in coastal buffer zones, and supporting conservation programs. Thus, erosion mitigation planning relies not only on complex infrastructure but also on strengthening environmental governance and collective community awareness.

The study faces several limitations affecting how its findings are interpreted. The observation period is short (2013–2024), and reliance on medium-resolution satellite imagery may miss fine shoreline details. DSAS processing methods introduce uncertainty in shoreline determination due to positional inaccuracies, scale effects, and digitization errors. The study also makes limited use of field data, hydrodynamic modeling, and detailed analysis of local human activity. These constraints limit the full explanation of the complex factors driving shoreline changes at Mandiri Beach.

Extend the temporal range of shoreline observations and use high-resolution remote sensing data, such as Sentinel-2 imagery (10–20meter spatial resolution for environmental monitoring) and UAV (unmanned aerial vehicle) surveys. Acquire data consistently on the same day and season, as Mutaqin (2017) notes, to reduce tidal variation errors. Validate shorelines with GPS field surveys. Combine DSAS (Digital Shoreline Analysis System), GPS, sediment analysis, wave and tidal data, and hydrodynamic modeling to improve validation and better understand coastal erosion and accretion. Future studies must use an interdisciplinary approach and include socio-economic analyses of communities affected by shoreline changes, such as Mandiri Sejati. (Gopinath et al., 2023) show that shorelines are dynamic land-sea transition zones shaped by natural and human forces. (Hassan & Rahmat, 2016) Find that development, tourism, and recreation, together with sea-level rise, increase the vulnerability of low-lying areas to tidal flooding. Human interventions spatially alter erosion and accretion, so understanding local land use, tourism pressures, and community adaptation is essential. This knowledge enables adaptive coastal management plans that combine soft and hard engineering solutions for spatial planning and sustainable tourism. These plans should follow the Integrated Coastal Zone Management (ICZM) framework, which coordinates diverse stakeholder interests through centralized, cross-sectoral management. Future work must serve public interest and recognize the shared, open-access nature of coastal areas (Forst, 2009).

CONCLUSION

The findings of this study demonstrate that Mandiri Beach in Pesisir Barat, Lampung, has highly dynamic shoreline changes. These changes directly affect the sustainability of coastal tourism. Using the Digital Shoreline Analysis System (DSAS) from 2013 to 2024, the analysis revealed both erosion and accretion processes. These processes had varying intensities across different segments. The primary research area experienced mild but consistent erosion. There was an average annual retreat of −0.13 m/year. In Mandiri Sejati District, the shoreline showed more extreme fluctuations. It had a maximum accretion of 11.84 m and a maximum abrasion of 16.2 m. The results highlight the site's sensitivity to environmental drivers and human pressures. Damage to tourism infrastructure, such as villas, restaurants, and bridges, has occurred.

The study underscores the urgent need for an adaptive coastal management framework. This framework should integrate ecological conservation with tourism utilization. Practical policy implications include establishing safe coastal zoning regulations. Another step is adopting adaptive and eco-friendly infrastructure designs. Restoring coastal vegetation as natural buffers is also important. Disaster risk management strategies should be developed and supported by early warning systems. Furthermore, diversifying tourism products in accretion zones is recommended. Benchmarking Mandiri Beach against international coastal adaptation cases can also help strengthen economic resilience and global relevance.

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