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Prediction of Shoreline Changes using Digital Shoreline Analysis System (DSAS) in Mantanani Island, Sabah

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ABSTRACT

Small island coastlines are increasingly vulnerable to erosion due to the combined effects of hydrodynamic forcing, sea-level rise, and intensified human activities. Mantanani Island, a socio-ecologically important island system off the northwest coast of Sabah, Malaysia, has experienced pronounced shoreline instability in recent decades, yet quantitative erosion assessments remain limited. This study investigates historical shoreline changes from 2009 to 2023 using the Digital Shoreline Analysis System (DSAS) and integrated with satellite imagery. DSAS was employed to compute shoreline change statistics, including End Point Rate (EPR), and Linear Regression Rate (LRR), enabling robust spatial characterization of erosion and accretion patterns. The results show that the maximum and minimum EPR values are 5.39 and -2.91, respectively, whereas the maximum and minimum LRR values are 5.76 and -2.91, respectively. A negative value indicates erosion, and a positive value indicates accretion. Using historical data from 2009 to 2023, the predicted shoreline changes along Mantanani Island are 21.223 hectares for the next 10 years (2033) and 32.16 hectares for the next 20 years (2043). This study offers a valuable scientific basis for risk-informed coastal management, climate adaptation strategies, and sustainable planning for vulnerable island coastlines in Sabah and comparable tropical settings.

1. Introduction

Coastal zones are among the most dynamic and socio-economically critical environments globally, yet they are increasingly threatened by sea-level rise, intensifying storm regimes, sediment imbalance, and unregulated coastal development. Coastal regions globally are subject to dynamic geomorphological processes, and understanding these changes is crucial for effective coastal management and hazard mitigation. However, coastal regions are also highly vulnerable to environmental change, particularly shoreline movement caused by natural processes and human

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activities. One of the most critical indicators of coastal stability is the shoreline change rate, which measures how fast coastlines advance or retreat over time.

Shoreline change rate refers to the speed and direction of shoreline movement over a given period, typically expressed in meters per year (m/year). A negative rate indicates shoreline retreat (erosion), while a positive rate indicates shoreline advance (accretion). Shoreline change rate is a quantitative measure used to assess the stability and vulnerability of coastlines [1]. Advancements in remote sensing and Geographic Information Systems (GIS) have greatly improved the ability to monitor shoreline movement over time. Shoreline positions can be extracted from historical maps, aerial photographs, satellite imagery, and UAV (drone) data. One widely used tool for shoreline analysis is the Digital Shoreline Analysis System (DSAS), developed by the United States Geological Survey (USGS).

This facilitates the understanding of shoreline trends and supports the development of effective coastal management strategies [2]. Specifically, DSAS computes rates of change along each transect by measuring the distance of shoreline movement over time, thereby enabling the prediction of future shoreline positions through the extrapolation of constant rates of change [3]. A positive value indicates accretion, while a negative value signifies erosion, providing a clear quantitative measure of shoreline dynamics [4]. The versatility of DSAS extends to its ability to incorporate various statistical models for rate estimation, ensuring adaptability to diverse coastal environments and data characteristics [5].

The software also includes capabilities for establishing measurement locations, performing rate calculations, and providing statistical data essential for assessing the reliability of these rates, as well as a beta model for forecasting shoreline positions [6]. One of the key functionalities of DSAS is its ability to quantify shoreline movement in meters per year by generating transects perpendicular to a defined baseline, thereby calculating the endpoint rate of shoreline movement and providing detailed statistical analysis of coastal changes over time [7].

The system calculates the difference between the oldest and most recent shorelines, employing methods such as End Point Rate, Linear Regression Rate, and Net Shoreline Movement to provide a comprehensive understanding of shoreline dynamics [8-10]. These varied methodologies within DSAS enable researchers to select the most appropriate calculation technique based on data quality, temporal resolution, and specific research objectives, thereby enhancing the robustness of shoreline change assessments [11]. The software offers enhanced features for establishing measurement locations, performing rate calculations, and providing statistical data necessary to assess the reliability of the rates, as well as a beta model for forecasting shoreline positions [6].

The capacity of DSAS to calculate rate-of-change statistics from multiple historical coastline positions, often extracted from satellite imagery, has made it an indispensable tool for long-term shoreline evolution studies and the development of management and protection solutions for coastal areas [12]. The software's capability to generate comprehensive summary reports detailing all chosen settings, analysis data, and automatically generated statistics further solidifies its role as a robust platform for coastal research [6]. Moreover, DSAS is recognized for its free availability, user-friendly interface, and comprehensive documentation, which facilitate its widespread adoption in research to assess shoreline alterations and quantify coastal changes [13]. Accurate prediction of shoreline movement provides critical insights into both natural and anthropogenically induced coastal dynamics, thereby forming a foundational basis for strategic mitigation and adaptation measures [9].

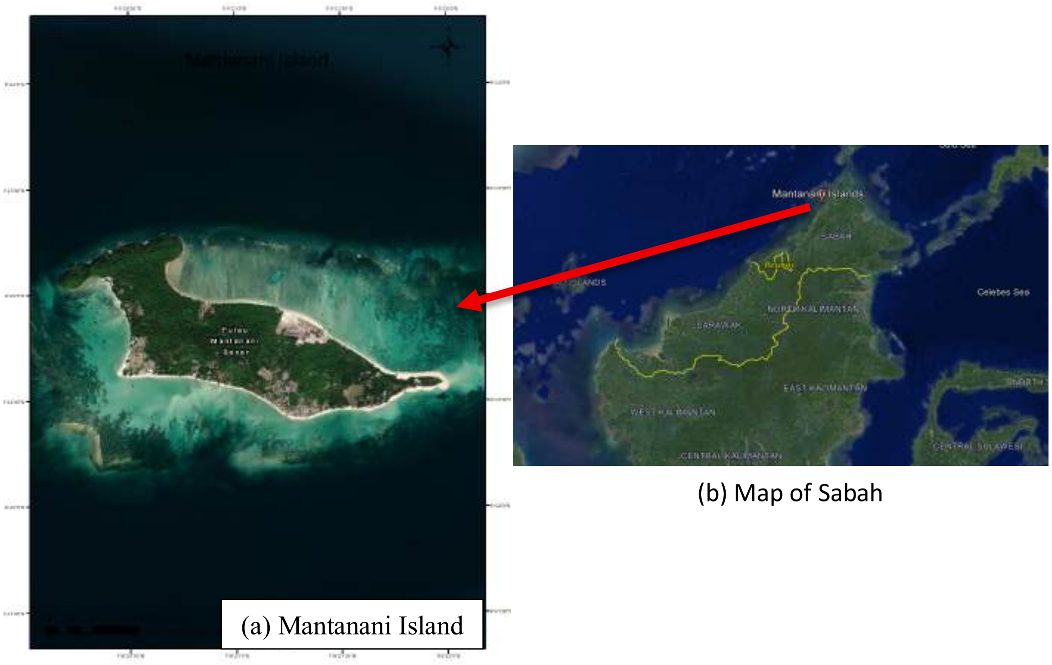
This study uses DSAS, an ArcGIS extension, to analyze shoreline changes on Mantanani Island, Sabah, by processing temporal datasets and satellite imagery to identify historical patterns and predict future shoreline positions [14,15]. This approach not only facilitates the precise delineation of erosion and accretion zones but also supports informed decision-making for coastal environmental planning and hazard zonation. The DSAS tool, integrated within ArcGIS, functions by generating a baseline parallel to the coastline, from which perpendicular transects are cast at specified intervals to measure shoreline displacement over time [16]. This methodology allows for the calculation of various statistical rates of change, thereby providing a robust framework for assessing shoreline evolution and forecasting future scenarios [17].

2. Methodology

2.1 Study Site

The Mantanani Islands consist of three islands located off the northwest coast of Sabah, Malaysia, opposite Kota Belud in northern Borneo. The largest island is Mantanani Besar, followed by Mantanani Kecil and Lungisan. This study site focuses on Mantanani Besar, a well-known tourist destination and recreation area. There are two villages on Mantanani Island: Kampung Siring Bukit and Kampung Padang, with a combined population of 1,000. Fishing has traditionally been the main source of income for villages. Mantanani Island was named after a warrior named "Nani" who always wore a blanket "manta" when fighting against Japanese occupation. In the Bajau Ubian language, the word for blanket is "manta" and "Mantanani" is the combination of these two words, representing the legendary story of "Nani" and "Manta".

Mantanani Island is a low-lying tropical island off the northwest coast of Sabah, Malaysia, making it particularly vulnerable to shoreline erosion, sea-level rise, storm surges, and monsoon-driven wave energy. Small islands have limited land area and low elevation, so even minor shoreline retreat can result in significant land loss, infrastructure damage, and community displacement. Studying shoreline change rates in Mantanani Island provides critical insights into how climate change impacts fragile island coastlines. Figure 1 shows the study site, Mantanani Island, and the map of Sabah.



(a) Mantanani Island

(b) Map of Sabah

Fig. 1. (a)Map of Mantanani Island, (b) Map of Sabah

Mantanani Island has experienced rapid growth in tourism, with the development of resorts, jetties, homestays, and shoreline recreational facilities. This development increases anthropogenic pressure on coastal systems, often altering natural sediment transport and exacerbating erosion (Figure 2).

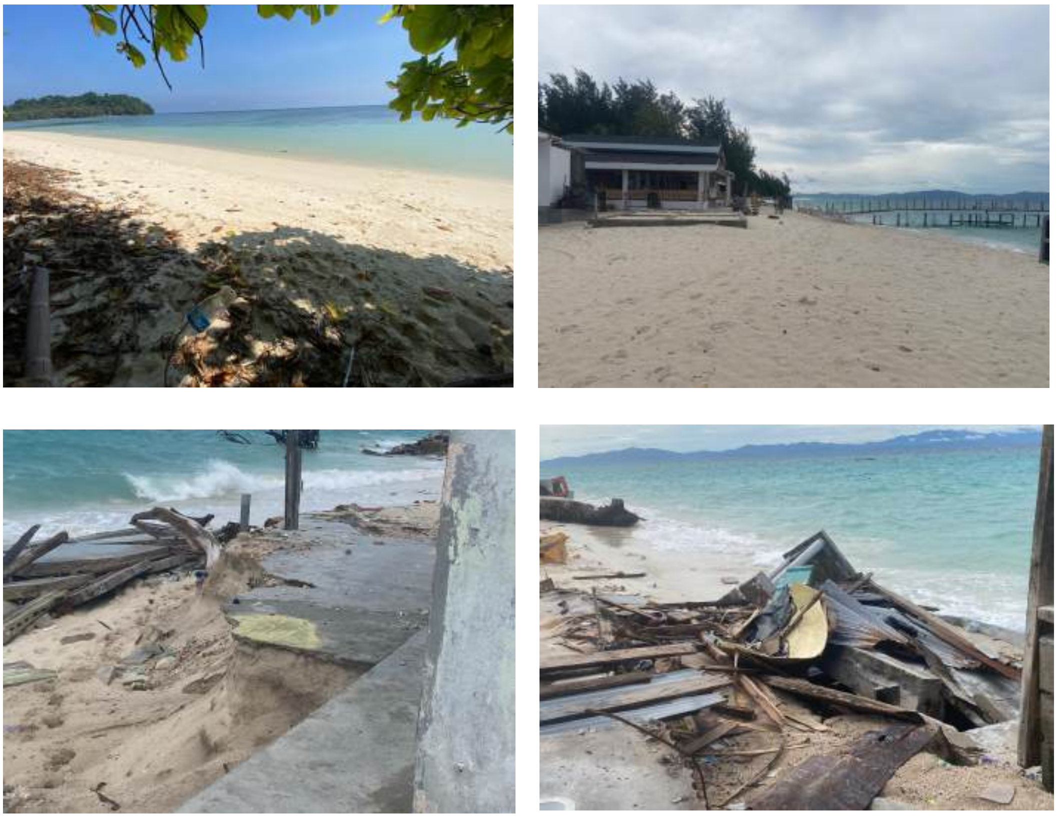


Fig. 2. (a) Mantanani coastal area (b) Resort in Mantanani (c) and (d) Erosion at Mantanani shoreline

2.2 Data Collection

The shoreline along Mantanani Island is about 8.96km long. The study focuses on data from 2009, 2011, 2016, and 2023. DSAS is an ArcGIS extension that calculates the rate of change of the shoreline vector. DSAS is an essential tool for monitoring and forecasting shoreline changes. Using DSAS in coastal change analysis enables the computation of rate-of-change statistics for a time series of shoreline positions. The statistics allow the nature of shoreline dynamics and trends in change to be evaluated and addressed. Figure 3 shows a data collection and processing flow chart using DSAS.

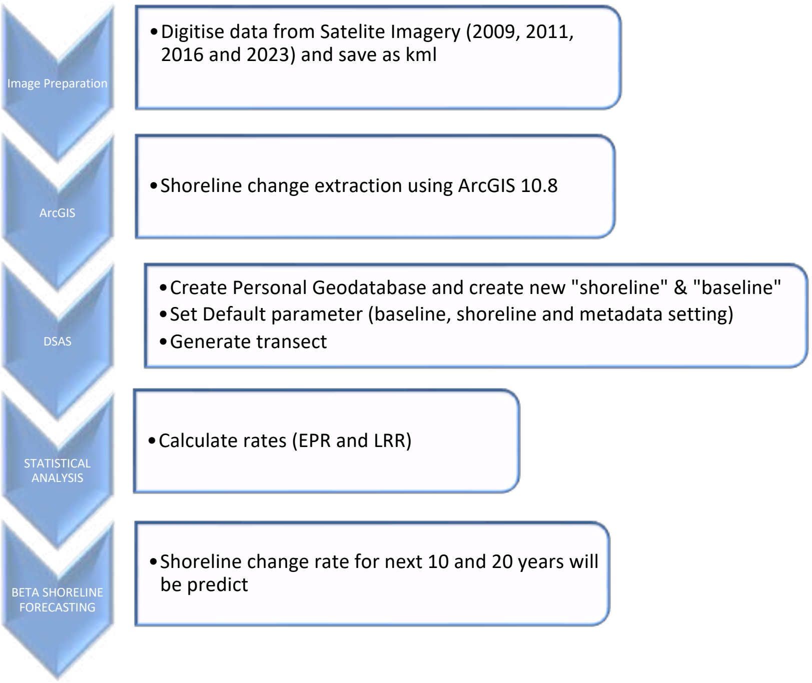


Fig. 3. Flow chart of data collection and processing using DSAS

The DSAS-based shoreline change assessment for Mantanani Island between 2009 and 2023 reveals pronounced spatial heterogeneity in erosion and accretion dynamics, underscoring the complex interplay between hydrodynamic forcing, sediment transport processes, geomorphological setting, and anthropogenic pressures.

DSAS calculates shoreline change rate by measuring how shorelines move over time along fixed transects. It uses multiple shoreline positions (from different years) and computes distances and rates statistically. In this study, 847 transects were generated along Mantanani Island with a transect spacing of 10 and a smoothing distance of 50. Figure 4 shows the transect analyzed using digitized satellite imagery (Google Earth). Yellow color denotes 2023, red denotes 2016, green denotes 2009, and blue denotes 2011.

Fig. 4. The transect was analyzed using digitized data from Google Earth. Yellow denotes 2023, red denotes 2016, green denotes 2009, and blue denotes 2011

2.3 Statistical Analysis

End Point Rate (EPR) was calculated to determine erosion and accretion rates within the 847 transect (Figure 4) along Mantanani Island. EPR, a crucial metric, is derived by dividing the distance of shoreline movement by the time elapsed between the oldest (2009) and the youngest (2023) shoreline positions based on Eq. 1.

$$\mathrm{EPR} = \frac{\mathrm{NSM}}{\text{time between oldest and most recent shoreline}} \tag{1}$$

Where Net Shoreline Movement (NSM) is the distance between the oldest and the youngest shorelines.

Linear Regression Rate (LRR) was applied to estimate the average rate of change using the four shoreline positions over time, with the statistics adjusted to fit a least-squares regression (Eq. 2) to all shorelines at each transect.

$$y = mx + c \tag{2}$$

Where
y = distance from baseline,
m = the slope (LRR method)
c = y intersect

The comparison between EPR and LRR indicates that EPR revealed short-term variability, whereas LRR provided more stable long-term trends. LRR was found to be more reliable for predictive modeling due to reduced sensitivity to temporal outliers.

2.3 Shoreline Prediction

DSAS is an option to calculate a forecasted shoreline position (10 and 20 years into the future) based on historical shoreline position data. The shoreline forecasting calculation uses the Kalman filter, as developed by Long and Plant [18], to predict future shoreline positions by combining observed and model-derived positions. The DSAS Kalman filter is initialized with the linear regression rate computed by DSAS. It then estimates the shoreline position and change rate at 10-day intervals and computes positional uncertainty at each step.

Accurate forecasting of coastal change is crucial for the sustainable management of coastal resources, particularly in areas with sensitive ecosystems such as mangrove forests. The historical trend on Mantanani Island was analysed using DSAS to forecast shoreline changes at 10- and 20-year horizons.

3. Results

3.1 Shoreline Changes from 2009 to 2023

Shoreline changes along the Mantanani coast, particularly in the South and East islands. Red indicates high erosion, green indicates moderate erosion, and yellow indicates accretion. The maximum value of EPR is 5.39, and the minimum value is -2.91. While for LRR, the maximum and minimum values are 5.76 and -2.91, respectively. Positive values indicate accretion, and negative values indicate erosion.

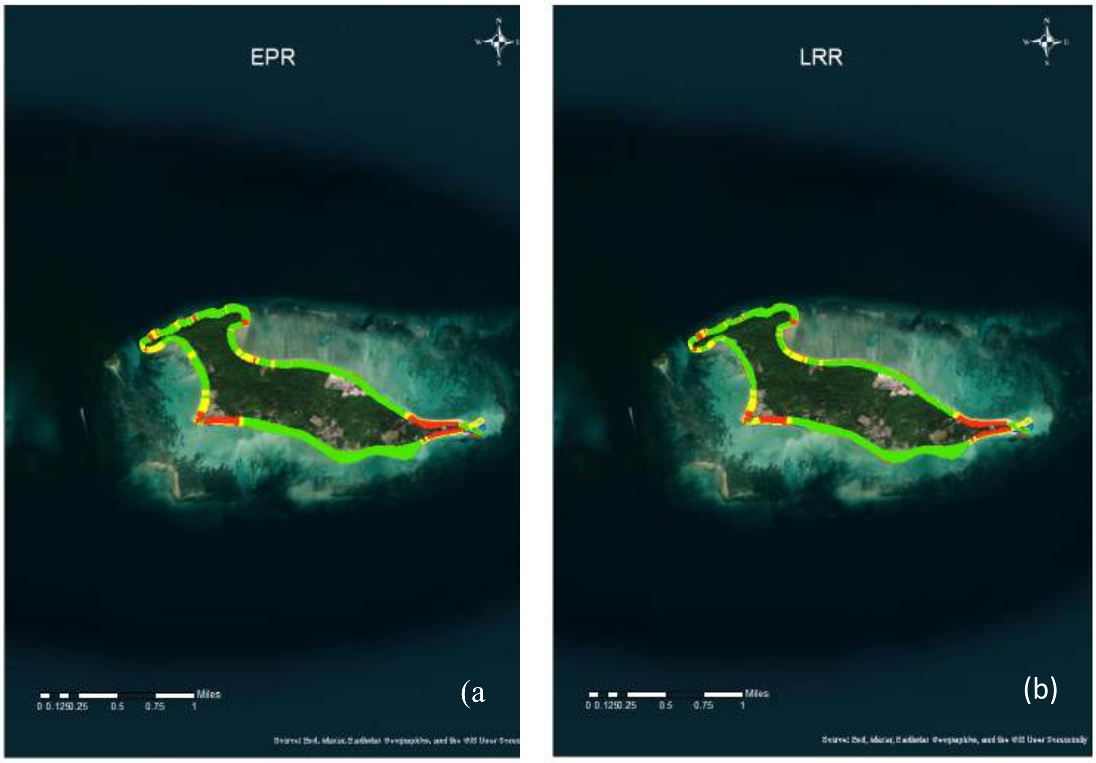


Fig. 5. (a) EPR and (b) LRR rate along Mantanani Coastal Area. Red=High erosion, yellow=moderate erosion and green=accreation

The worst erosion occurs at Sutera @Mantanani Resort, the homestay and village area. The derived End Point Rate (EPR) and Linear Regression Rate (LRR) metrics indicate that erosional processes predominate across multiple exposed coastal sectors, whereas localized accretion occurs in comparatively sheltered zones, highlighting the non-uniform response of island shorelines to environmental forcing.

The observed minimum EPR and LRR values of −2.91 m/year identify erosion hotspots concentrated around settlement and tourism-intensive areas, including Sutera @Mantanani Resort and adjacent village shorelines. These patterns are consistent with coastal settings where monsoon-driven wave energy, longshore sediment redistribution, reef degradation, and shoreline infrastructure development jointly amplify sediment loss and shoreline retreat. The intensification of erosion near developed shoreline segments suggests that human-induced modifications may be exacerbating natural coastal processes, reinforcing the need to integrate geomorphological sensitivity into tourism and infrastructure planning.

Conversely, maximum accretion rates exceeding +5 m/year indicate active sediment deposition in lower-energy environments, likely driven by sediment trapping mechanisms, beach morphodynamics, and localized wave refraction. This dual pattern of erosion and accretion underscores the importance of considering alongshore sediment connectivity when interpreting shoreline evolution, as sediment gains in one sector may correspond to sediment deficits in adjacent reaches.

The comparative performance of EPR and LRR further confirms that regression-based approaches provide more stable and statistically robust representations of long-term shoreline trends. While EPR effectively captures short-term variability and episodic fluctuations, LRR reduces sensitivity to temporal outliers, thereby improving reliability for long-term interpretation and predictive modeling. The deployment of 847 transects at 10 m spacing enhances spatial resolution and strengthens confidence in the detection of localized shoreline responses across Mantanani's approximately 8.96 km coastline.

3.2 Data Analysis

3.3 Forecasting for the Next 10 and 20 Years

The DSAS Kalman Filter forecasting framework enables probabilistic shoreline prediction by integrating historical shoreline trajectories with recursive statistical updating and uncertainty estimation. By initializing predictions with linear regression–derived shoreline change rates and iteratively refining estimates through observational correction, the model provides dynamically updated forecasts of shoreline position and associated confidence bounds. This approach enhances predictive robustness relative to static linear extrapolation, particularly in environments characterized by episodic erosion, measurement noise, and non-stationary coastal dynamics. Consequently, the Kalman Filter represents a powerful decision-support tool for forward-looking coastal risk assessment and climate adaptation planning.

Using historical data from 2009 to 2023, erosion along Mantanani Island was predicted. Figure 6 shows the area affected by erosion for the next 10 years (2033). The Kalman Filter model, integrated into the Digital Shoreline Analysis System (DSAS), provides a statistically robust and dynamic method for forecasting shoreline movement by combining historical shoreline trends with uncertainty estimates. The shoreline forecasting outcomes, generated using the DSAS Kalman filter framework, project substantial land loss of approximately 21.223 hectares over the next decade (Figure 6) and 32.16 hectares over the next two decades (Figure 7).

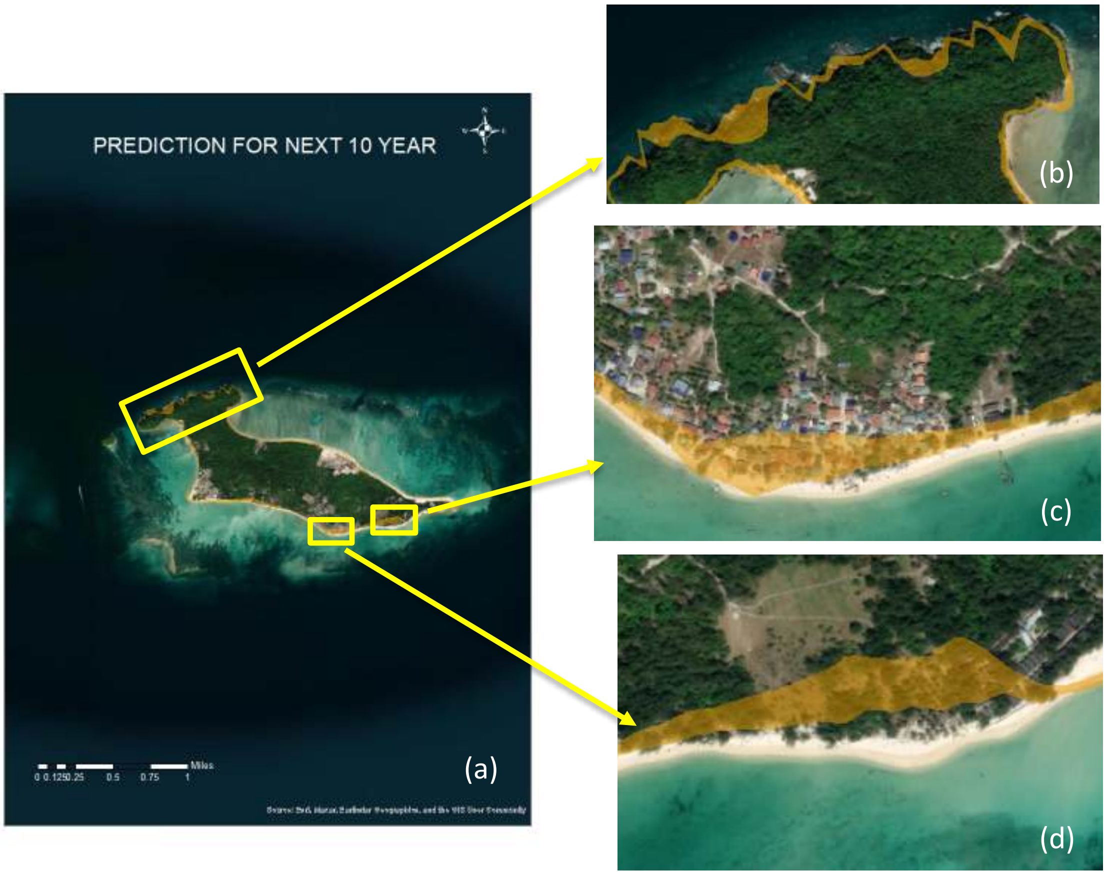


Fig. 6. Prediction of erosion along Mantanani Island for the next 10 years

These projections indicate that coastal retreat is likely to intensify under prevailing environmental and development trajectories, posing escalating risks to coastal settlements, tourism assets, freshwater resources, and ecosystem services. Given Mantanani Island's low elevation, limited land availability, and socio-economic reliance on coastal tourism, even moderate shoreline retreat may have disproportionately large socio-ecological consequences.

From a broader coastal science perspective, these findings reinforce the growing body of evidence that small tropical islands represent critical frontline systems in the context of climate-driven coastal change. The results highlight the necessity of transitioning from reactive shoreline protection toward proactive, risk-informed adaptation strategies, including coastal setback zoning, ecosystem-based shoreline stabilization (e.g., mangrove restoration and reef conservation), sediment management interventions, and continuous shoreline monitoring.

Over the next 20 years, the erosion footprint is expected to grow to 32.16 hectares, with continued inland retreat potentially threatening the resort, village area, and homestays. Half of the village is affected by erosion (Figure 7).

Fig. 7. Prediction of erosion along Mantanani Island for the next 10 years

4. Conclusions

This study provides a robust, spatially explicit quantification of historical shoreline change and future shoreline trajectories along Mantanani Island between 2009 and 2023, demonstrating the effectiveness of the Digital Shoreline Analysis System (DSAS) as a decision-support tool for island-scale coastal monitoring. The analysis reveals that shoreline erosion is the dominant geomorphological trend in several exposed coastal sectors, with retreat rates reaching approximately −2.91 m/year, whereas localized accretion exceeding +5 m/year occurs in sheltered segments influenced by sediment deposition.

Forecasting results indicate a projected loss of more than 30 hectares of coastal land over the next two decades, highlighting increasing vulnerability for coastal communities, tourism infrastructure, and ecologically sensitive habitats. These findings underscore the urgent need to integrate quantitative shoreline change metrics into coastal planning, hazard mitigation frameworks, and climate adaptation policies for small island environments in Sabah and comparable tropical regions.

Despite its contributions, this study is subject to limitations arising from shoreline-extraction uncertainty due to tidal variability and the spatial-resolution constraints of medium-scale satellite imagery. Addressing these uncertainties in future research will require integrating high-resolution UAV-derived shoreline mapping, hydrodynamic and sediment-transport modeling, field-based validation, and scenario-based climate projections to enhance process-based understanding and predictive accuracy.

Overall, this research establishes a scientifically rigorous foundation for evidence-based coastal management, offering a transferable analytical framework for shoreline monitoring, erosion risk assessment, and adaptive coastal governance across vulnerable tropical island systems. The DSAS methodology applied here can serve as a scalable model for regional shoreline change assessments, supporting long-term resilience planning amid accelerating climate and development pressures.

A limitation of this study is the uncertainty in shoreline extraction due to tidal variation. Besides that, the resolution constraints of medium-scale satellite imagery. Future studies should integrate UAV-derived high-spatial-resolution imagery, hydrodynamic modelling, and sediment analysis.

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