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Prediction of Coastline Changes in Sulaman Lake Mangrove Forest Reserve, Sabah using Kalman Filter Model

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ABSTRACT

Sulaman Lake Mangrove Forest Reserve is an integral part of the region's natural heritage, which is vital for ecological balance, supporting biodiversity, and protecting coastlines from erosion. This study aims to analyze the shoreline changes from 2013 to 2023 using the Digital Shoreline Analysis System (DSAS) and predict the coastline changes in the Sulaman Lake Mangrove Forest Reserve, Tuaran using the Kalman Filter model. End Point Rate (EPR) and Linear Regression Rate (LRR) statistical analysis were used to estimate the trends of the shoreline changes. The result show that the maximum and minimum EPR is 0.71m/year and -11.86m/year while for the maximum and minimum LRR is 0.49m/year and -11.84m/year respectively. The Kalman Filter is a recursive mathematical algorithm applied to historical coastline data to predict future changes. After forecasting shoreline changes using the Kalman Filter model, the inundation area is about 74.3 acres @ 30 ha for the next 10 years (2033) and 136 acres @ 55.2 ha for the next 20 years (2043). The finding highlights critical erosion at area facing to open sea reducing towards inland. Therefore, integrated coastal management strategies is needed to mitigate erosion impact, and the sustainable conservation of the Sulaman Lake Mangrove Forest Reserve. The mitigation measures for shoreline erosion prevention to ensure environmental stability and resilience of the mangrove forest.

1. Introduction

Mangrove forests are intertidal ecosystems found in tropical and subtropical regions. Located at the interface of marine and coastal ecosystems, they provide many essential ecological functions. Mangrove ecosystems also act as effective pollution filters, removing most pollutants from water passing through the root zone and providing valuable recreational and tourism opportunities and marine recreational sports. They also play a vital role in the biological, physical, and chemical functions of marine ecosystems, but they are also one of the most seriously deteriorating ecosystems in the world [25].

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Malaysia's mangrove constitutes approximately 537,686 ha, and Sabah covers more than half of the total area, 364,100 ha. Meanwhile, the mangroves in Sarawak and Peninsular Malaysia account for 132,000 ha (23%) and 104,181 ha (18%), respectively [17,20]. Management efforts to conserve and preserve the mangrove forest can be significantly assisted with accurate monitoring data of the mangrove ecosystem over a long period. A robust and cost-effective remote sensing and GIS-based technique is necessary to monitor the condition of the mangrove forest over the vast coastal area.

Coastline changes have the role and functions of the mangrove forest, which protects the coast against abrasion from waves, tidal inundation, and storm surges. Several studies have analysed coastline changes in mangrove forests using field surveys or amending old carrier maps [19]. The wave action and tidal forces have caused significant shoreline erosion, which can be observed through the increase in the shoreline retreat rate within the study area. This erosion has led to a gradual land loss and a coastline transformation over time [8,10,15,27].

Coastal environments are characterized by their inherent dynamic, as they are constantly influenced by a variety of natural processes, such as erosion, sedimentation, and tidal changes, alongside [12,13,21]. Understanding these dynamic characteristics is vital for effectively assessing and predicting future alterations in coastal areas, particularly in sensitive ecosystems like the Sulaman Lake Mangrove Forest Reserve. By studying the interplay between natural and human-induced changes, we can gain insights into how the coastline will evolve and implement strategies to protect these valuable environments for future generations.

This erosion will reduce the function of mangrove forest. These changes can be determine using Digital Shoreline Analysis System (DSAS), to thoroughly assess and model the shoreline changes along the Selangor coast in Malaysia. According to Maulud *et al.,* [13], these studies have offered essential insights into the patterns of coastline transformations, helping to identify the key drivers behind these changes. Understanding these factors is critical for developing effective management strategies to preserve these coastal ecosystems in the face of ongoing environmental challenges.

The DSAS was utilized to systematically identify and quantify shifts in the coastline. By extracting the position of the coast at various points perpendicular to the shoreline, the study was able to provide a detailed analysis of shoreline change over time, highlighting both natural and anthropogenic influences on coastal erosion and accretion patterns [2].

The Kalman Filter model was used to predict the future coast position for the Sulaman Lake Mangrove Forest Reserve. To analyse these changes in detail, they employed the DSAS, a tool that enables the assessment of shoreline movement over time. Their research utilized EPR as a statistical method to accurately calculate the rates of both erosion and accretion along the mangrove coastlines. The current study builds on previous investigations by utilizing the Kalman Filter model, a proven effective technique in predicting coastal dynamics in other regions [5,16]. Using the Kalman Filter model, Ciritci and Türk [6] used satellite images from 1984 to 2018 to calculate the shoreline change rate and predict the future 10 and 20 years.

Basiouny *et al.,* [3] analyzed the coastal change between 1973 and 2015 along Ras El-Hekma in the northwest of Egypt using satellite imagery by the EPR method, and they predicted the future shoreline. Afterward, they compared the shoreline extracted from the high-resolution satellite image of 2015 with the predicted shoreline for 2015. They obtained the RMSE value of the predicted shoreline for 2015 to be 15.75 m. Mukhopadhyay *et al.,* [14] aimed to analyze the 142-km-long shoreline in the Puri region of India by the EPR method using Landsat images of 1972, 2001, and 2010 and to predict the shoreline between 2015 and 2025. The prediction of the future position of the shoreline in mangrove forests is of great importance in planning studies in coastal areas, making effective decisions in coastal management, and determining changes occurring on the coast. This study analyzes erosion along the coastline in the Sulaman Lake mangrove area from 2013 to 2023.

Also, it proposes and demonstrates how to use the efficient tool named the Kalman Filter model to predict future shoreline changes in the forest vegetation [26].

A previous study conducted by Besar *et al.,* [4] focused on the Sulaman Lake Mangrove Forest Reserve and provided valuable estimates regarding the carbon stock within this vital ecosystem. The findings of this research underscore the necessity for more in-depth investigations into the dynamic changes occurring in this significant coastal habitat, as the ecological balance of mangrove forests plays a crucial role in carbon sequestration and coastal protection. There is no study related coastline erosion conducted in this area. Mangrove forests are important carbon sinks. Shoreline changes leading to the destruction of these forests reduce their ability to sequester carbon, contributing to climate change.

By applying this model, the study can offer accurate predictions of coastline shifts, which are important for understanding how natural processes like tides, storms, and human activities influence the stability and health of the coastline. This study needed for management planning with taking into account with dynamic shoreline. The findings of this study will guide informed decisions regarding land use, conservation priorities, and development policies in the coastal areas of Sabah. The predictive model could guide policymakers in allocating resources and planning for coastal infrastructure or conservation projects in light of potential coastline shifts. Therefore, the objectives of the study are to determine the shoreline changes in Sulaman Lake Forest Reserve, to identify maximum and minimum value of erosion and accretion and to predict future shoreline change rate based on historical data.

2. Methodology

Shoreline along the Sulaman Lake Mangrove Reserve were digitized from the Google Earth for years 2013, 2016, 2020 and 2023. The four years of shoreline data were analysed using DSAS and statistical analysis to estimate the shoreline change rate.

2.1 Study Area

This research study took place at the Sulaman Lake Forest Reserved, located in Tuaran, Sabah, Malaysia (Figure 1). This unique area is classified as a mangrove forest situated on the west coast of Sabah, nested within the jurisdiction of the Kota Kinabalu forestry district. Encompassing a substantial land area of approximately 2,635 hectares, Sulaman Lake Forest Reserved was officially designated as a Class V Forest reserve under the Forest Enactment of 1968 [20].

The mangrove ecosystem at this site is characterized by several common species, prominently including *Rhizophora apiculata*, *Rhizophora mucronata*, *Avicennia alba*, and *Ceriops decandra* [4]. This area, designated as the Wetland Sanctuary (SWS), is specifically managed to foster conservation efforts, provide educational opportunities, and promote eco-tourism activities.

Four years (2013, 2016, 2020, and 2023) between 2013 and 2023, shoreline changes were analyze. Along Sulaman Lake Forest Reserve, the 5.5km long of the shoreline including mangrove forests, aquaculture, and villages. This study focusing Papat estuary to Kampung Serusup. In between this location there a number of human activities such as aquaculture, tourist, homestay, restaurant (Figure 2).

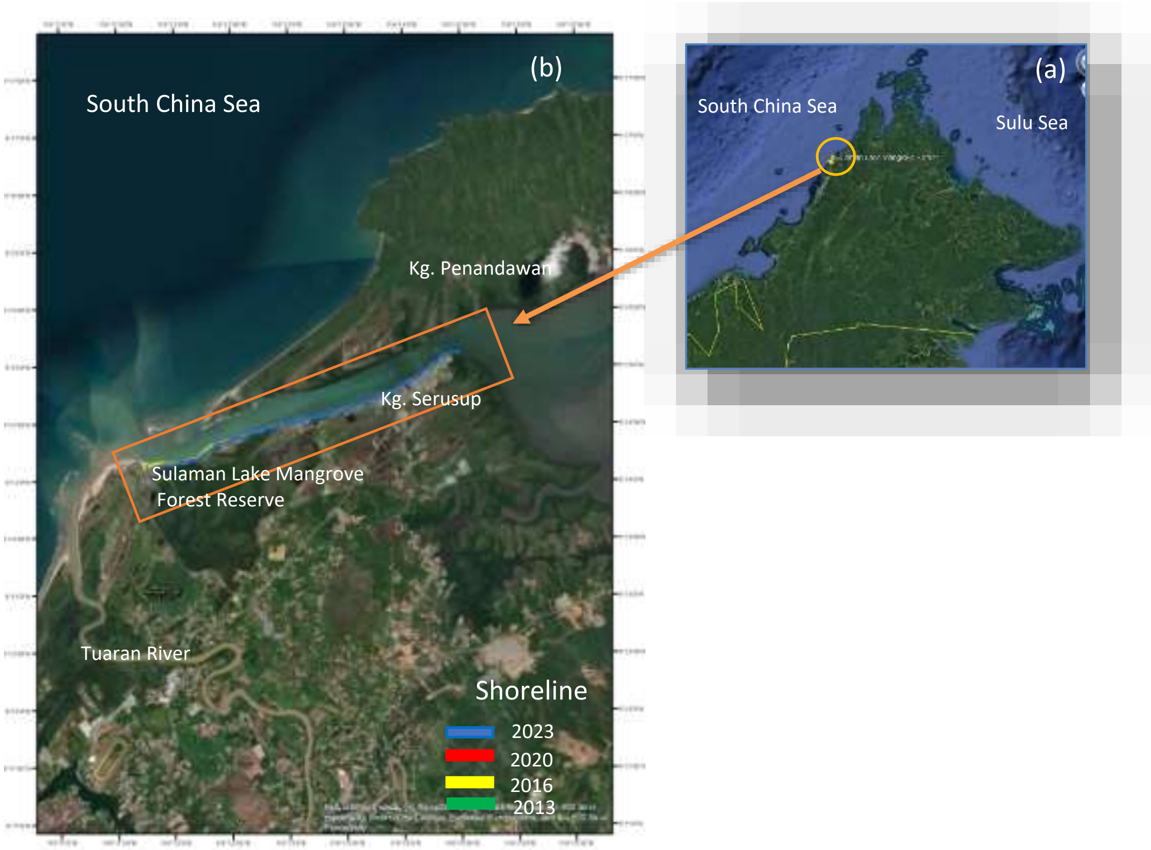

Fig. 1. (a) Map of Sabah and (b) Sulaman Lake Mangrove Forest Reserve and adjacent area

Fig. 2. The picture of Sulaman Lake Mangrove Reserve Forest and adjacent area. a) homestay, b) resort, c) restaurant and d) aquaculture

2.2 Data Collection

Shoreline of 5.5km distance along the Sulaman Lake Mangrove Forest Reserve were digitized from the Google Earth for four years 2013, 2016, 2020 and 2023. DSAS is an ArcGIS extension tool that calculates the rate of change of the shoreline vector. DSAS allows three methods to create a baseline: a) Buffer, b) Pre-existing baseline, and c) New feature class, but in this study, “the new feature class method was used. DSAS is an essential tool that can be used to monitor and forecast shoreline changes. Using DSAS in coastal change analysis is its ability to compute the 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.

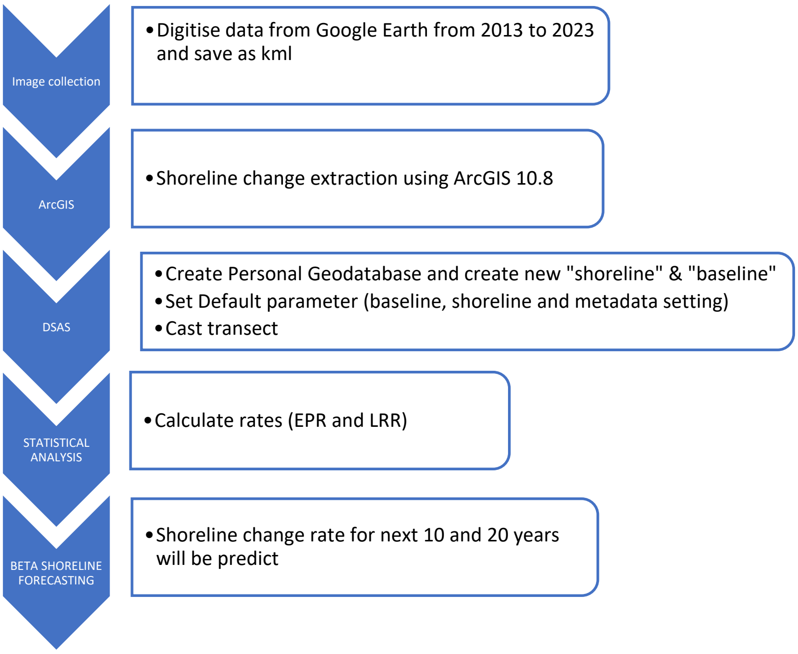

Fig. 3. Flow chart of data collection and processing using DSAS

EPR was calculated to determine erosion and accretion rates within the 537 transect (Figure 1 and 4) between Kuala Papat to Kampung Serusop. EPR, a crucial metric, is derived by dividing the distance of shoreline movement by the time elapsed between the oldest (2013) and the youngest (2023) shoreline positions (Figure 4) 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 a distance between the oldest and the youngest shorelines.

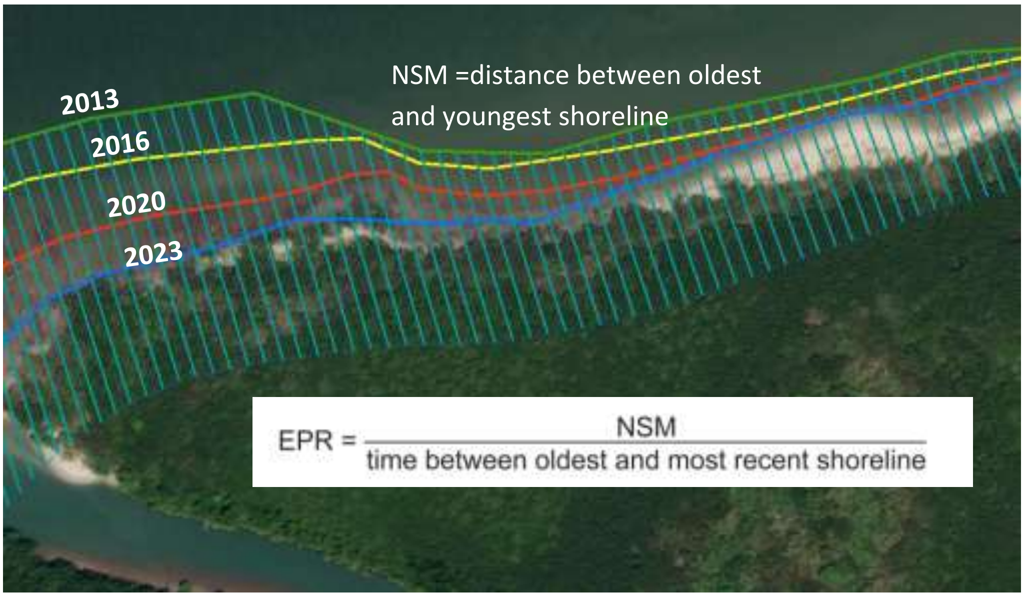

Fig. 4. Transect and shoreline changes for 2013, 2026, 2020 and 2023

LRR was applied to estimate the average rate of change using the four shoreline positions over time with the changed statistics of fitting a least square regression (Eq. (2)) to all shorelines at each transects (Figure 4).

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

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

2.3 Prediction of Shoreline using Kalman Filter Model

DSAS is an option to calculate a forecasted shoreline position (10 and 20 years into the future) based on historical shoreline position data [24]. The shoreline forecasting calculation uses the Kalman filter as Long and Plant [11] developed to forecast future shoreline positions by combining observed shoreline positions with model-derived positions. DSAS Kalman filter approach is initialized with the linear regression rate calculated by DSAS. It then estimates the shoreline position and change rate for every 10th of a year and estimates positional uncertainty at each step.

Mapping and forecasting shoreline change involve analyzing multiple historical shoreline positions to predict future shoreline features. DSAS can be used for long-term shoreline mapping and forecasting over periods of 10 to 20 years. Erosion in coastal areas occurs due to a combination of natural factors, including wave action, tidal patterns, and sediment transport, as well as human-induced changes such as land use modifications and urban development [23]. Accurate forecasting of coastline changes is crucial for the sustainable management of coastal resources, particularly in areas with sensitive ecosystems like mangrove forests.

The historical trend of the Sulaman Lake Mangrove Forest was analysed using DSAS to forecast shoreline changes in the coastline after 10 and 20 years. The step for BETA shoreline forecasting to calculate the prediction of shoreline change rate is summarised in Figure 5.

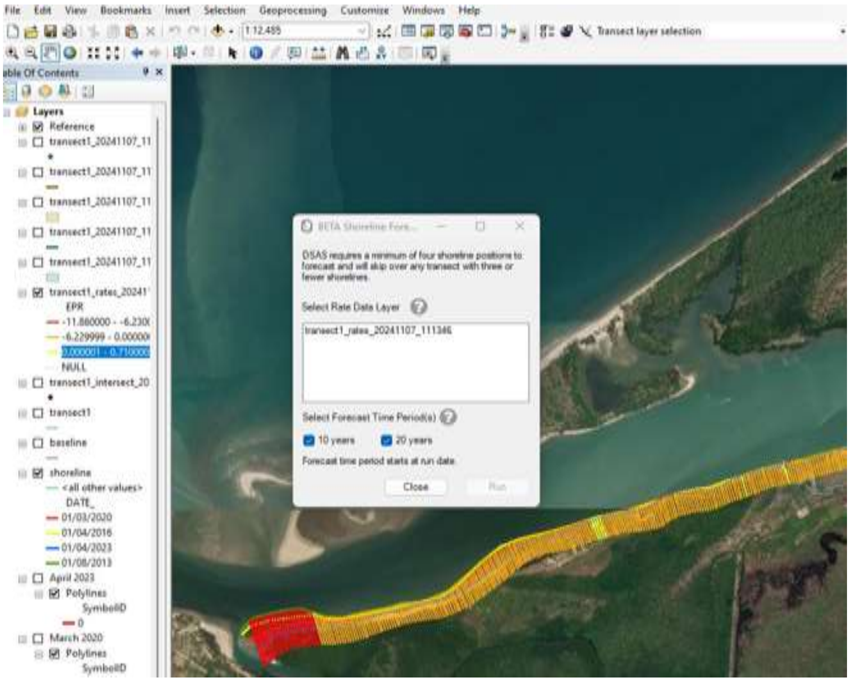

Fig. 5. BETA shoreline forecasting to predict erosion

3. Results and Discussion

3.1 Analysis Shoreline Change Rate from 2013 to 2023

High value of shoreline changes in Sulaman Lake Forest Reserve which < -6.23 m/y was identified at estuary of Papat and decreasing towards Kg. Serusup (about 0.71) (Figure 6). The worst case (high erosion) is in the mangrove area (red color), which is the value between -11.86 and -6.23. This condition could tentatively hazard for communities, especially in coastal areas, as it is highly susceptible to increasing coastal disasters. The EPR value coastline in yellow color indicates accretion area while the orange color means low erosion. Based on the ground truthing, the erosion has damage coastal structures at Papat estuary (Figure 6).

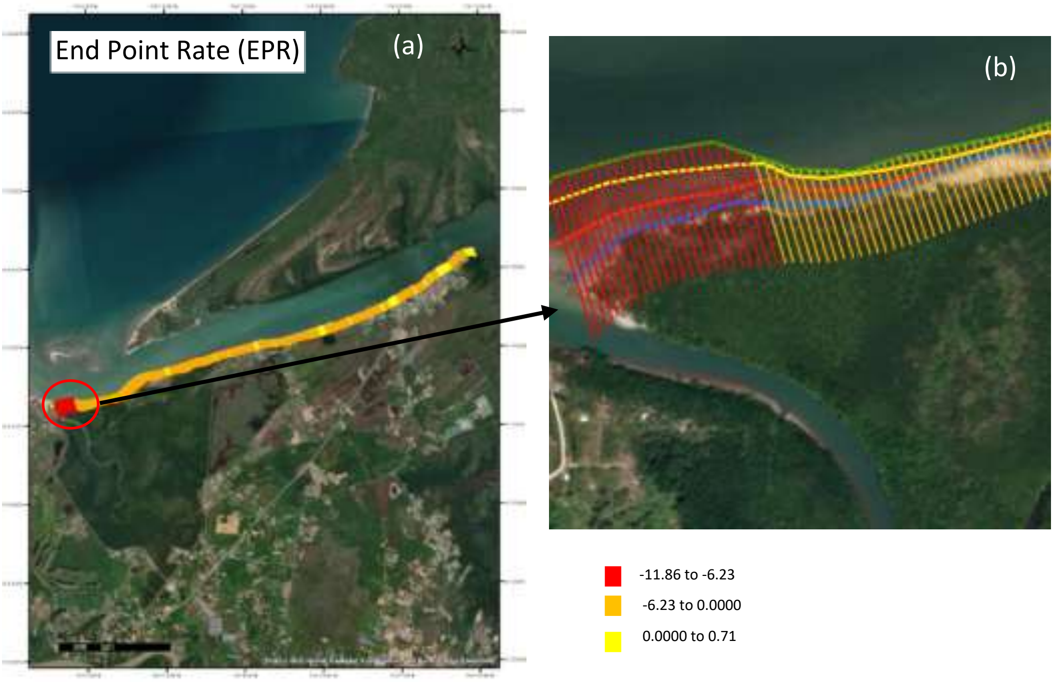

Fig. 6. End Point Rate analysis. a) EPR result along the study site, b) EPR for high erosion area

LRR represents the slope of the regression line and is used to analyze shoreline changes. It is determined by fitting a least squares regression line to all shoreline points along a transect. A strong wind impacted the estuary, generating significant wave forces. Two areas have been identified as high-risk for erosion: the first is the mangrove forest, and the second is the jetty and village area. Figure 7 shows the Linear Regression Analysis. About 1km from Papat estuary was high erosion towards

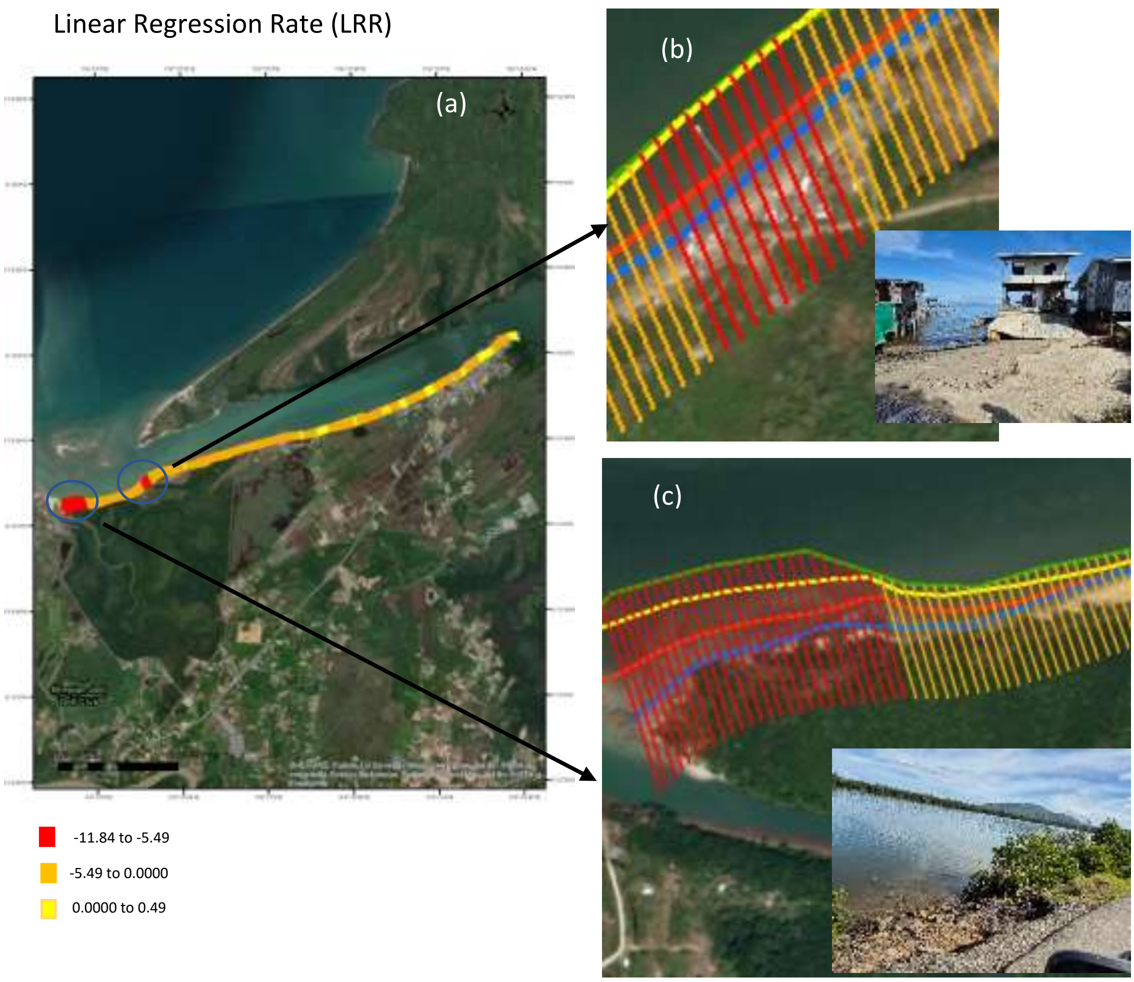

Fig. 7. Linear Regression analysis a) LRR result along the study site, b) and c) LRR for high erosion area

3.2 Statistical Analysis

Shoreline erosion has a negative value, mainly near the estuary. However, the positive value is increasing towards Kg Serusup (Figure 8). This area is used for aquaculture, resorts, and housing. The estuary experienced erosion when the shoreline was reduced by about 0.1km from 2013 to 2023. The drastic changes were caused by the wave and current, but further inside, there was not much change because the wave was smaller.

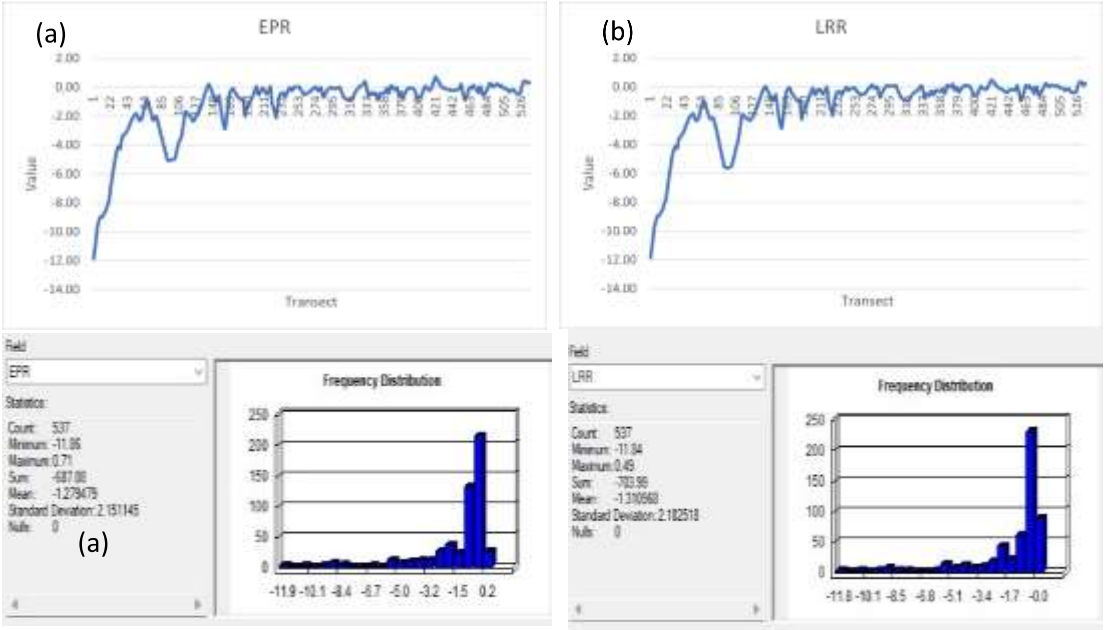

Fig. 8. Statistical analysis using DSAS. a) EPR, b) LRR

3.3 Prediction of Shoreline Changes using Kalman Filter Model

The Kalman Filter is a filter that makes future predictions based on historical data from a modeled system. Instead of being referred to as a filter, this approach might be thought of as a prediction tool. The forecasting of the Sulaman Lake shoreline after 10 and 20 years is shown in Figure 9. The results showed that the affected area for the next 10 years covers 74.3 acres or 30 ha. The affected area for the next 20 years is 136 acres or 55.2 ha.

Fig. 9. Prediction shoreline change rate a) next 10 year, b) next 20 year

Shoreline changes in the Sulaman Lake Mangrove Forest Reserve can significantly affect the local ecosystem, biodiversity, and community livelihoods. Mangrove forests are crucial in coastal protection, environmental balance, and supporting local economies. The removal or degradation of mangrove forests leads to a decline in species that rely on these ecosystems for food, breeding, and shelter, impacting terrestrial and aquatic biodiversity.

Many local communities depend on the mangrove forests for fishing, timber, and non-timber forest products. If shoreline changes destroy these habitats, it could result in reduced resources for the community, leading to economic challenges. Mangroves provide breeding grounds for many marine species. The loss of mangrove habitat due to shoreline changes can lead to declining fish populations, directly affecting local fishermen and food security.

The Sulaman Lake Mangrove Forest Reserve shoreline changes can have wide-ranging ecological, social, and economic consequences. Understanding these implications and taking action to protect and restore mangrove habitats is crucial to ensuring the sustainability of both the environment and the livelihoods that depend on it. Practical conservation efforts, such as coastal restoration, sustainable management, and community engagement, are key to mitigating the negative impacts of shoreline changes.

The mitigation measures for shoreline erosion prevention focus on mangrove forests' environmental stability and resilience. A nature-based solution such as mangrove restoration, promoting natural regeneration, and constructing permeable groins or damage-affected methods to mitigate shoreline protection. Planting mangroves in degraded areas is a highly effective method to restore the coastal ecosystem and enhance resilience against climate change impacts [1,9]. Mangroves serve as a bioshield by attenuating wave energy and reducing erosion along coastal regions [1,9].

The protection provided by mangrove forests in terms of wave energy reduction and shoreline stabilization has been well-documented. Mangroves can reduce wave heights by up to 66% and dissipate wave energy by 70-90% over a 100 m wide mangrove belt [9]. These findings highlight the importance of mangrove conservation and restoration efforts to enhance coastal resilience, especially in climate change-induced sea level rise and increased storm frequency and intensity.

Geotextile tubes or containers can be used for temporary erosion control or to create a foundation for mangrove planting. However, they should be considered a short-term solution and carefully planned to minimize environmental impact. Hybrid engineering approaches that combine natural and engineered features, such as permeable groynes or dams, can effectively reduce longshore currents and facilitate mangrove restoration [7,9].

Long-term monitoring and adaptive management strategies are essential to track the effectiveness of shoreline protection measures and inform future interventions. Monitoring programs should assess the physical and ecological changes, such as shoreline position, sediment dynamics, and mangrove growth and survival, to ensure the long-term sustainability of the coastal ecosystem [7,9,18,22].

In conclusion, a comprehensive and multifaceted approach is necessary to mitigate shoreline erosion and enhance the resilience of mangrove forests. It includes nature-based solutions, community engagement, hybrid engineering, and long-term monitoring, all within the framework of Integrated Coastal Zone Management.

4. Conclusions

Coastal environments are highly vulnerable to transformation, with natural processes and human activities inducing significant alterations to shoreline characteristics over time. In the Sulaman Lake Mangrove Forest Reserve, understanding and predicting coastal changes is crucial for effective environmental management and conservation efforts. Mangrove forests, such as those in the Sulaman Lake area, play a vital role in coastal ecosystems, providing essential ecosystem services and carbon sequestration capabilities. However, these valuable resources face threats from various factors, including sea level rise, erosion, and anthropogenic disturbances. Monitoring and predicting coastline changes in this region can inform strategies to preserve the integrity of the mangrove forest and mitigate potential impacts.

In addition, the importance of Sulaman Lake Mangrove Forest Reserve is the sanctuary is home to *Bruguiera hainesii*, a rare and threatened species of mangrove that plays an essential role in maintaining the health of the ecosystem. The presence of *Pteroptyx gelasina*, a unique and rare firefly species, further highlights the biodiversity of this area. These combined features make the Wetland Sanctuary a critical site for both conservation and environmental education, providing a refuge for endangered species while promoting sustainable interaction with the natural world.

This study identifies is Maximum and Minimum EPR is 0.71 and -11.86 while Maximum and Minimum 0.49 and -11.84. The worse erosion area along mangrove forest is at Papat River estuary area. The prediction of the future position of the shoreline in mangrove forest is of great importance in planning studies in coastal areas, making effective decisions in coastal management, and determining changes occurring on the coast. Mitigation measures based on the beach vulnerability level around the mangrove area (using soft and hard approaches) will be provided. Decision-makers could use the results of this research to implement strategies for integrated coastal zone management that incorporates an increased awareness and urban growth management to protect the affected areas.

The importance of study shoreline change rate along mangrove areas is vital for future management and conservation efforts. By employing the Kalman Filter model, this study was able to forecast future coastline changes within the Sulaman Lake Mangrove Forest Reserve, providing valuable insights for policymakers and stakeholders. Overall, the findings of this study underscore the need for continuous monitoring and proactive management strategies to ensure the long-term sustainability of the Sulaman Lake Mangrove Forest Reserve and other similar coastal ecosystems in the region. The mitigation such as complex structure and soft structure will be recommended.

5. Future Research

Future research should explore the involvement of local communities in data collection and monitoring efforts. It could include training local stakeholders to use technologies like mobile apps for reporting environmental changes or collaborating with local institutions to track ecosystem shifts. Community-based monitoring programs can boost local involvement in conservation efforts, improve project sustainability, and ensure that traditional knowledge is integrated with scientific methods for a more comprehensive approach to management. Investigate the impacts of human activities such as coastal development, tourism, fishing practices, and agriculture on the mangrove ecosystem and surrounding coastline. Understanding these impacts could help mitigate adverse effects and guide conservation efforts.

A long-term monitoring program should be established that tracks the ecological health of the mangrove forest and the socioeconomic status of the surrounding communities. This data would be crucial for understanding the broader impacts of environmental changes on livelihoods and the effectiveness of conservation initiatives. Long-term monitoring can help track the resilience of mangrove ecosystems to climate change and provide early warning signs of ecosystem degradation or shifts.

Research could focus on developing adaptive management strategies that are flexible and responsive to changes in environmental conditions. This approach would allow for the adjustment of conservation plans based on updated predictions of coastline changes and other environmental factors. Adaptive management could be tested through pilot projects in the Sulaman Lake region to ensure that conservation efforts remain relevant and effective over time.

Collaboration with national environmental organizations, international conservation bodies, and academic institutions can facilitate knowledge sharing, improve research methods, and foster cross-border conservation initiatives. Engaging in international research networks and partnerships can also help integrate the findings from Sulaman Lake into global discussions on mangrove conservation and coastal protection.

Future research should focus on assessing the effectiveness of local and national coastal management, conservation, and climate adaptation policies. Understanding the governance frameworks and their impact on mangrove ecosystems will be crucial for creating supportive policy environments. Investigating policy gaps and suggesting improvements for better-integrating climate change adaptation and coastal zone management into local governance structures can have significant positive impacts.

Research into the effectiveness of public awareness campaigns on the importance of mangrove conservation, climate change adaptation, and sustainable coastal management should be pursued. It can also include assessing how education can help change behavior to reduce environmental degradation. Community education campaigns could raise awareness about the role of mangroves in protecting coastal areas from the effects of climate change and promote participation in conservation activities.

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