GIS-based Analysis of Coastal Vulnerability in Southern Province of Sri Lanka: Insights from Matara District Coastal Area

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Abstract
Coastal erosion is a substantial natural hazard that is affecting both the environment and human communities globally. Sri Lanka's coastline is about 1600 kilometres, with rich biodiversity and resources, and faces growing coastal erosion, notably in the southern coastal region especially in the Matara District. Therefore, understanding the causes and effects of coastal erosion is essential. This study aims to evaluate shoreline changes from 2000 to 2020 (Weligama to Dikwella) and involves three stages such as mapping shoreline changes using satellite data (Landsat) a digital shoreline analysis system (DSAS), statistical analysis for shoreline changes rates over 20 years, identifying interplay between factors. DSAS measures shoreline changes using baseline approaches and results are presented for both northeast monsoon (NEM) and southwest monsoon (SWM) seasons. NEM shows coastal accretion in Matara due to sediment transportation, while SWM reveals erosion in Devinuwara through strong waves and sediment movement. Sea level rise, rainfall, and river flow correlations influence erosion patterns. Overall, this study emphasizes the use of advanced technology to understand and monitor coastal erosion, help decision-making and develop effective strategies for protecting coastlines.

Keywords: Coastal erosion, Digital shoreline analysis systems, Northeast monsoon, Shoreline changes, Southwest monsoon

1 Introduction

Coastal regions play a crucial role in sustainable development as 60% of the global population resides within approximately 100 kilometres of coastlines, depending on their environment and natural resources for their various needs. However, the ever-changing nature of shorelines, characterized by fluctuations in erosion and accretion, raises significant concerns [1]. The coastline of Sri Lanka spans approximately 1600 kilometres rich with natural resources and diverse species. However, coastal erosion has emerged as a growing concern. The expansion of the population exerts pressure on coastal zones, leading to ecosystem strain and an increased risk of erosion, particularly in the southwest coastline zone of Sri Lanka, specifically around the Matara District [2]. The study area comprising Mirissa, Polhena, Weligama, and Dikwella in Matara was chosen due to its significance as a popular tourist destination and the pronounced challenge posed by coastal erosion, particularly relevant to the tourism sector. The region's vulnerability, diverse geographical features, and potential socio-economic impacts make it an informative context for studying coastal erosion dynamics and their implications [3].

The objective of the study is to examine changes in the southern coastline of Sri Lanka, focusing on the Matara District (Weligama to Dikwella). This investigation includes factors such as monsoons, sea level rise, rainfall, and river flow, as these elements collectively contribute to the dynamics of coastal erosion and accretion in this region. The selection of these specific factors is based on their well-established roles in influencing erosion patterns and their relevance to understanding the comprehensive forces driving shoreline changes in the study area. For assessing shoreline shifts, the study employed the digital shoreline analysis system (DSAS) alongside multi-temporal satellite data. The investigation focused on the period between 2000 and 2020.

2 Methodology

To analyse the shoreline changes in response to various factors along the Matara District coast, three stages of work have been followed:

1. Satellite data (Landsat) analysis and interpretation for shoreline mapping.
2. Use of statistical techniques for estimating shoreline change rates over 20 years.
3. To determine the interplay between factors such as the southwest monsoons (SWM) and northeast monsoons (NEM), sea level rise, rainfall, and river flow, for shoreline alteration.

The analysis of shoreline changes in Matara District (Latitude: 5.9949 N, Longitude: 80.5488 E) involved the utilisation of 40 images from Landsat 7 and Landsat 8, sourced from the USGS Earth Explorer platform. These images, captured during both SWM and NEM, covered 20 years.

The University of Hawaii Sea Level Centre (UHSL) website was used to collect ten years of daily sea level rise data (tide gauge data) for the Colombo station (lat 6.950222, long 79.850139). The collected data encompassed the timeframe between 2006 to 2020. Data regarding monthly river discharge for the Nilwala Ganga at Pitabeddara station was collected from the Irrigation Department, Sri Lanka for twenty years. Daily rainfall data for Sri Lanka were downloaded from the Climate Hazard Centre, USA [4].

Mapping the shoreline movement was carried out for SWM and NEM for 20 years and estimation of the rates of shoreline changes was carried out using USGS's 2010 DSAS 4.2 [5]. DSAS calculates the rate of shoreline changes using the measurement baseline approach. For this investigation, a manually created baseline was established by scanning an area 500 m inland from the nearest shoreline, considering the overall orientation of the shoreline. This baseline served as the reference point for transect measurements conducted by the DSAS application [6]. Then the end point rate (EPR), weighted linear regression (WLR) and net shoreline movement (NSM) were used at each transect to establish historical rates of shoreline changes [6].

The EPR quantifies the speed of erosion or accretion in a particular coastal area over time. NSM evaluates the overall change in coastline position, encompassing both erosion and accretion effects. On the other hand, WLR is used to model the relationship between shoreline positions and time [7].

After data collection, statistical analyses were undertaken to assess the correlations between coastal erosion and the various influencing factors. The collected dataset, encompassing sea level rise data, river outflow, and rainfall, was subjected to examination utilising MS Excel. Distinct analyses were performed for the SWM and NEM seasons regarding river outflow and rainfall data. Correlation coefficients were calculated for these distinct periods using the respective rainfall and river flow values. Microsoft Excel was employed for conducting these analyses.

3 Results

3.1 Shoreline change – NEM

In four zones, Weligama, Matara, Dewinuwara, and Dikwella, the shoreline noticed varied rates of erosion and accretion during the NEM as shown in Fig. 1.

Based on the data presented in Table 1, the analysis using the EPR method reveals a notable coastal accretion rate of 3.74 cm per year in the Matara District during the NEM season from 2000 to 2020. Additionally, the highest NSM value recorded within this period is 78.53 cm.

3.2 Shoreline changes – SWM

Between 2000 and 2020, the SWM season revealed significant erosion across the four highlighted zones depicted in Fig. 2. According to the data presented in Table 2, within the SWM period, the Devinuwara coastal area exhibited the ERP value of -3.74 cm/per year and maximum average NSM of -64.55 cm Conversely, the lowest NSM value was statistically recorded in Dikwella at -14.88 cm.

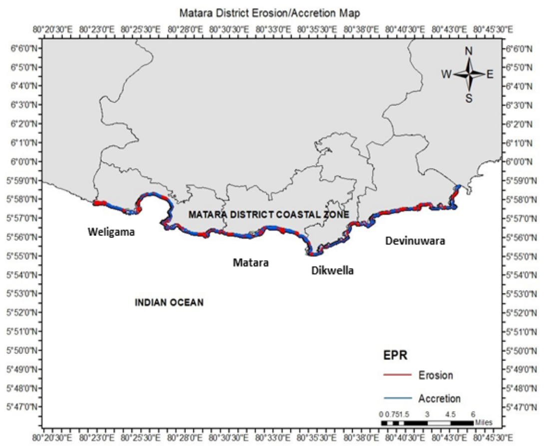


Figure 1: Erosion/accretion rates map in northeast monsoon for 2000-2020 during northeast monsoon

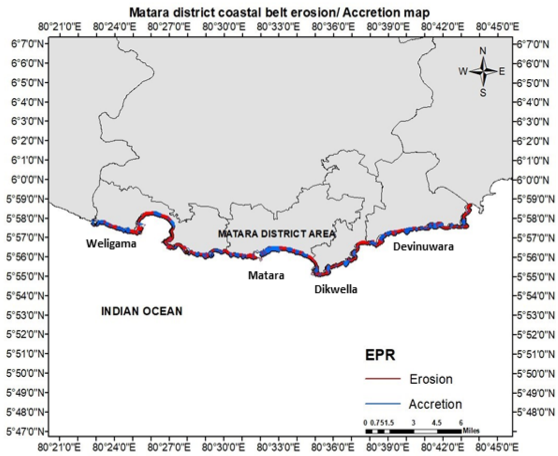


Figure 2: Erosion/accretion rates map in southwest monsoon for 2000-2020

Table 1: The EPR, NSM and WLR values for the cities of Weligama, Matara, Dewinuwara, and Dikwella from 2000 to 2020 in the northeast monsoon and southwest monsoon

Time	Area	Net shoreline movement- NSM	End point rate-EPR	Weight linear regression-WLR
NE	Weligama	55.03	1.3	0.85
	Matara	78.53	3.74	3.91
	Dikwella	24.98	2.81	1.89
	Devinuwara	26.7	1.34	1.38
SW	Weligama	-45.41	-2.8	-4.93
	Matara	-56.02	-2.27	-2.66
	Dikwella	-14.88	-3.01	-1.87
	Devinuwara	-64.55	-3.74	-1.56

3.3 Mean Sea level rise and net shoreline movement variation 2006-2016

As shown in Fig. 3, it illustrates the average annual mean sea level variation in Colombo, Sri Lanka, over 10 years from 2006 to 2016. The graph depicts an increasing trend in mean sea level height between 2006 and 2016. The data used for this analysis were seasonally corrected. As shown in Fig. 3, by combining the annual average mean sea level (MSL) data from 2006 to 2016, shoreline changes resulting from sea level rise were examined.

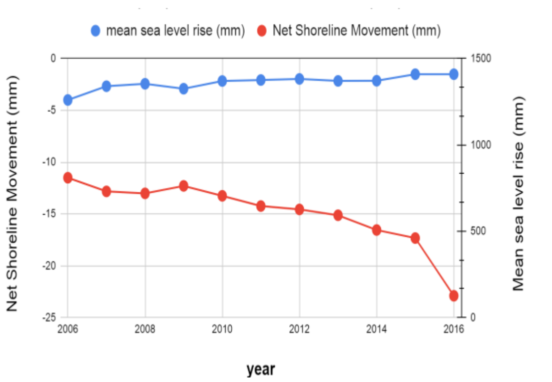
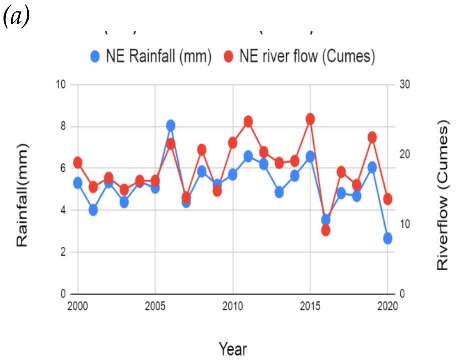


Figure 3: Average mean sea level (mm) variation and net shoreline movement(mm) from 2006 to 2016

3.4 River flow and rainfall

(a)



(b)

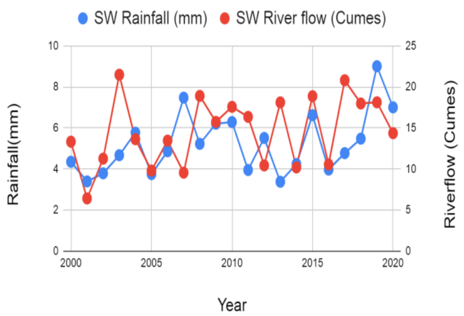


Figure 4: Variation of annual rainfall and river flow at Matara. a) Northeast monsoon period. b) Southwest monsoon period

According to Fig. 4(a), the findings indicate minimal changes during the NEM season from 2000 to 2020. However, in the SWM season, both rainfall and river flow experienced substantial increases as shown in Fig. 4(b).

Table 4(a): Correlation between rainfall and river flow in northeast monsoon

NE	Rainfall	River flow
Rainfall	1	0.82
River flow	0.82	1

R-squared value (R^2) = 0.82

Table 4(b): Correlation between rainfall and river flow in southwest monsoon

NE	Rainfall	River flow
Rainfall	1	0.87
River flow	0.87	1

R-squared value (R^2) = 0.87

Based on the data presented in Tables 4(a) and 4(b), it is evident that correlation coefficients between river flow and rainfall exhibit positive values during both the NEM and SWM seasons.

4 Discussion

4.1 Shoreline change during NEM and SWM seasons

The results revealed significant accretion in four coastal zones of Matara during NEM. The calm weather during the NEM, coupled with sediment transportation from the northern region, influenced the accretion in the southern part of Sri Lanka [8]. Matara coastal region recorded the highest positive EPR and NSM during the NEM, indicating the highest total and yearly accretion from 2000 to 2020. The east India coastal currents (EICC) and monsoon currents, travelling south during the NEM, carry wave-generated energy and sediment (e.g., clay size grains) parallel to the coastlines of India and Sri Lanka, leading to deposition in the coastal zone [9]. Also, sands at the Matara beaches come from inland rivers and are transported along the coastline by longshore currents. The straight shape of the beach, between headlands in the Matara coastal region, plays a significant role in accumulating more sediment during the NEM [10]. This is because straight beaches have a unique advantage, efficiently dispersing the energy of incoming waves. When waves reach a straight beach, their energy spreads out along the entire length of the beach. As a result, sediment carried by these waves settles more uniformly. This effective energy distribution prevents erosion from being concentrated in specific areas and the gradual build-up of sediment over time. In essence, the straight beach configuration, coupled with its positioning between protective headlands, acts as a natural mechanism for sediment accumulation during the NEM, contributing to the observed increase in shoreline deposits [11].

During the SWM in Sri Lanka, powerful winds generate intense waves along the south-to-northwest coastline. These waves lead to beach narrowing and flattening of the intertidal beach face. Concurrently, longshore currents predominantly move sediments northward. This is evidenced by sand spits along the western and northwestern coasts, with Matara's Polwatta and Nilwala Ganga mouths corroborating the northward sediment transport. Consequently, sediment accumulation is lower on the southern coast during the SWM.

Also, the high erosion rate during the SWM is attributed to stormy conditions that generate strong onshore currents (swash) following wave breaks, countered by powerful offshore currents (backwash). This interplay erodes the beach, depositing sediments in the wave breaker zone and causing beach narrowing. Conversely, during the NEM, sediment deposited in the wave breaker zone is returned to the beach by calmer short waves, leading to broader beaches.

4.2 Mean sea level rise

Concurrently, the shoreline trend lines indicate negative shifts, indicating coastal erosion within the same period. Thus, the investigation suggests that the NSM trend line from 2006 to 2016 corresponds to erosion. Additionally, the relationship between shoreline movement and sea level rise implies the influence of factors other than sea level rise on coastal erosion [5].

4.3 River flow and rainfall

The southwest coast of Sri Lanka is primarily drained by monsoon rains, including rivers, streams, and lagoons [12, 13]. The analysis indicates limited changes during the NEM season between 2000 and 2020 (Fig. 4a). However, there was a significant increase in rainfall and outflow during the SWM season (Fig. 4b). Sediment sources for the coastal region include rivers, with the Nilwala river being a significant contributor to the Matara District. The Polwatu River also deposits sediment into Weligama Bay. Both river flow and rainfall exhibit a positive correlation, with the SWM having the strongest impact. The fluctuation of river flow during the SWM is substantial due to its stronger and stormier nature compared to the NEM, leading to higher rainfall in the region. Consequently, the beaches in the southwest coastal areas experience deterioration. However, the presence of headlands that protrude into the water results in sandy bays, as observed in the Mawella and Gandara areas. In contrast, the absence of beach nourishment sources contributes to the erosion seen in stony coastlines, which has worsened over time.

5 Conclusion

In conclusion, the study's findings shed light on the intricate dynamics of shoreline changes along the coastal regions of Matara, Sri Lanka, during the SWM and NEM seasons. Notably, the research indicates that both accretion and erosion processes are at play, resulting from a combination of natural factors that influence sediment transport and sea level dynamics.

In the NEM season, Matara's southern coast undergoes significant accretion due to favourable weather conditions, aided by sediment from the East India coastal currents and monsoon currents. The straight beach design and geographical location further promote sediment build-up, leading to positive shifts in shorelines.

Conversely, during the SWM season, wave generation along the south-northwest coastline leads to beach narrowing and flattening. Longshore currents predominantly move sediments northward, evidenced by sand spits formation along the western and northwestern coasts. This dynamic contributes to lower sediment accumulation on the southern coast during the SWM. Furthermore, the interplay of stormy conditions during the SWM generates strong onshore and offshore currents, exacerbating beach erosion and narrowing.

The study emphasizes the interrelation of river flow, rainfall, and erosion. Monsoon rains bring sediment via rivers like Nilwala, while the intense SWM, characterized by more intense rainfall and stormier conditions accelerates erosion due to increased rainfall and river flow. The correlation between shoreline movement and sea level rise indicates that factors beyond sea level changes also contribute to coastal erosion.

The complex interplay of natural forces such as monsoon currents, river flow, rainfall, and sea level changes in shaping the Matara coastal landscape. The findings emphasize the need for informed coastal management strategies that take into account these dynamics to mitigate erosion, protect vulnerable areas, and ensure the long-term sustainability of the region's coastal environment.

Acknowledgement

The authors gratefully acknowledge the Irrigation Department, Sri Lanka, for sharing the river flow and rainfall data in the period of 2000-2020. The project was funded through a university research grant.

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