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ORIGINAL ARTICLE

Shoreline Change Detection and Future Prediction for Southwestern Coastline, Sri Lanka

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ABSTRACT

Coastal zones, important for human settlements and economies globally and particularly in Sri Lanka, are experiencing significant changes driven by natural and human-induced activities. This study investigated the shoreline changes over the southwestern coastal zone between for three periods as; 1988 to 2023, 1988 to 2001 and 2001 to 2023 by calculating the change rates, preparing erosion/accretion maps and predicting future positions for years 2034 and 2044.Landsat images and Normalized Difference Water Index (NDWI) were used for shoreline extraction and Digital Shoreline Analysis System (DSAS) tools was used to calculate change rates and predict future positions.. Findings reveal significant changes over the three study periods. During the 1988-2001 period, the mean Endpoint Rate (EPR) averaged 2.31 m/year, while the mean Linear Regression Rate (LRR) averaged 2.34 m/year. The majority of the study area faced land accretion, with only 200 out of 3,475 transects experiencing erosion. However, during the 2001-2023 period, erosion became predominant at an alarming rate of 62.72%, with 2,192 out of 3,495 transects facing erosion. During this period, the mean EPR and mean LRR shiftedto -0.46 m/year and -0.25 m/year, respectively. During the overall period of 1988-2023, only 404 transects out of 3,422 transects were eroded, with a decreased percentage of 11.81%. The mean EPR was 0.61 m/year, while the mean LRR was 0.52 m/year. Kalutara, Beruwala, Hikkaduwa, Kahawa, and Galle experienced significant erosion, aligning with previous vulnerability assessments. Predictions for 2034 and 2044 suggest a trend towards land accretion, potentially influenced by recent beach nourishment efforts. Even though the erosion rate decreased for the overall period 1988-2023, mitigation measures should be taken, especially for Kalutara, Beruwala, Hikkaduwa, Kahawa, and Galle areas.

1 Introduction

Coastal zones have become one of the most important environments for human settlements and economic activities over the years both in global and Sri Lankan contexts. According to a United Nations Environment Program report in 2022, approximately 45% of the global population is concentrated in the coastal zones. In Sri Lanka, one third of the total population of the country is settled in the coastal zone. It further reveals that the population density in this zone has been changed at an alarming rate, which has the potential to increase up to 134 people per km^2 in 2050 (Pussella and Gunarathna, 2022).

Coastal zones are exposed to a series of natural and anthropogenic processes like coastal erosion, accretion, sediment transport, environmental pollution, and coastal development that usually causes changes in long- and short-term spans (Aedla et al., 2015). One of the significant concerns associated with coastal regions is shoreline change, which refers to the alteration in the position and configuration of the coastline over time. The shoreline, which is defined as the position of the land-water interface at one instant in time, (Genz et al., 2007) plays an important role in the coastal area changes. Understanding shoreline change patterns and predicting future trends are essential for effective coastal zone management and planning.

Various shoreline mapping techniques have been used throughout history to understand the complex and dynamic nature of coastal zones. Ground surveying techniques and aerial photographs were widely used for shoreline mapping until the 1980s. Although these methods were accurate, they were labour intensive and time consuming, and limited by the lack of availability of high resolution imagery over long time periods (Boak and Turner, 2005). Since 1972, Landsat imagery with

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normalized indices such as Normalized Difference Water Index (NDWI) (McFeeters, 1996) has been widely utilized along with GIS and remote sensing techniques for shoreline mapping due to cost-effectiveness and data availability over long periods (Pardo-Pascual et al., 2012). In recent years, advanced techniques such as the Digital Shoreline Analysis System (DSAS) have enabled researchers to quantify shoreline changes with greater precision by using statistical models that calculate rates of erosion and accretion over time (Thieler et al., 2009). The use of machine learning algorithms and high-resolution satellite imagery, such as data from Sentinel-2 or commercial satellites, is also becoming more common, further improving the accuracy and detail of shoreline analyses (El-Asmar and Hereher, 2011).

The southwestern coastline of Sri Lanka contributes to the economic development of the country through fishing and tourism. Several tourist-attracted beaches, hotels, and places are located in southwestern coastal cities such as Galle, Ambalangoda, Hikkaduwa, Unawatuna, and Panadura. Additionally, the southwestern coastline of Sri Lanka harbours an exceptionally diverse ecosystem. Despite its significance, limited studies have focused on quantifying shoreline changes and predicting future shoreline positions in this region, particularly over an extended period. This gap highlights the need for detailed analysis and predictive modelling for sustainable coastal management and planning. Therefore, this study aims to quantify shoreline changes, visualise them using maps and graphs and predict the future positions for years 2034 and 2044 using satellite imagery and GIS tools.

2 Methodology

The study focuses on monitoring shoreline changes along the southwestern coast of Sri Lanka, which spans latitudes 5° 59’ 57” to 6° 43’ 28” N and longitudes 79° 53’ 51” to 80° 15’ 46” E. This region is economically significant, relying heavily on fishing and tourism as primary sources of income. Widely popular for its attractive beaches such as Galle, Unawatuna, Hikkaduwa, Ambalangoda, and Bentota, the area holds substantial appeal for tourists. Historically, the southwestern coastal zone of Sri Lanka has contributed the highest share to the country's Gross Domestic Product (GDP) over the past centuries (Amarasinghe, 2020), and this trend is expected to persist into the future. Therefore, understanding shoreline dynamics in this region is crucial for both environmental management and sustainable development initiatives. Fig. 1 shows the study area.

Eight images from Landsat 5 Thematic Mapper (TM), Landsat 7 Enhanced Thematic Mapper (ETM), Landsat 7 and 9 Operational Land Imager (OLI), and Thermal Infrared Sensor (TIRS) between 1988, 1992, 1995, 2001, 2005, 2015, 2021 and 2023 were acquired at unequal intervals between 1988 and 2023.

Fig. 1: Study area: south western coastline of Sri Lanka.

Note: Please note that the graphic scale is applicable only to the main maps and does not apply to the inset maps in Fig. 1 to 9.

Table 1 shows detailed information of the acquired Landsat data.

Table 1: Detailed information of utilized Landsat images.

Satellite and Sensors	Date of Acquisition (MM/DD/YY)	Path/Row
Landsat 5 TM	12/15/88	141/056
Landsat 5 TM	03/13/92	141/056
Landsat 5 TM	01/17/95	141/056
Landsat 7 ETM	02/10/01	141/056
Landsat 5 TM	02/13/05	141/056
Landsat 8 OLI_TIRS	01/08/15	141/056
Landsat 8 OLI_TIRS	02/09/21	141/056
Landsat 9 OLI_TIRS	04/12/23	141/056

All satellite images were in Landsat Level 2 Science product quality (USGS, 2021). Therefore, extensive image pre-processing was not necessary.

Fig. 2 shows the overview of the methodology used in this study, which is discussed in detail.

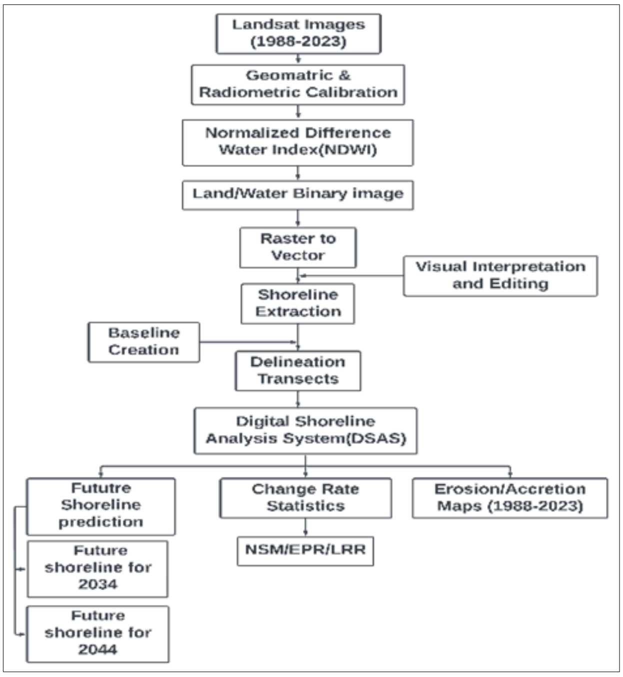

Fig. 2: Flow chart of the methodology.

After the extraction of the study area, NDWI algorithm (McFeeters, 1996) was applied to each image. The threshold value of 0 for NDWI was determined based on a combination of previous research (Xu, 2006) and a trial-and-error approach specific to this study area This threshold value was uniformly applied across all images to ensure consistency and mitigate the possibility of introducing errors from subjective interpretations. Green and Near Infrared (NIR) bands with equation 1 were used for the NDWI calculation.

$$NDWI = \frac{(Green - NIR)}{(Green + NIR)} \quad (1)$$

In the next phase, binary land/water images were created for all years using the reclassify tool in ArcMap. Subsequently, the reclassified land/water images were converted into vector data using the raster to polygon tool. Following this, the polygon features were transformed into lines using the polygon to line tool. These resulting polylines underwent manual editing to remove line segments that did not correspond to shorelines. Finally, the shorelines were smoothed using the Smooth Line tool with the PAEK (Polynomial Approximation with Exponential Kernel) algorithm (Arcgis.com, 2024). PAEK algorithm is a technique commonly used to reduce noise while preserving the essential shape of lines (Douglas and Peucker, 1973). This step ensured that the final shorelines were accurate representations of the coastline geometry.

All individual shorelines were combined into one shape file and imported into a personal geodatabase along with the baseline shape file

Transects were generated with a spacing set at 30 m intervals and the change rate metrics along transects were calculated with DSAS tools. These metrics included Shoreline Change Envelope (SCE), Net Shoreline Movement (NSM), End Point Rate (EPR) and Linear Regression Rate (LRR). The BETA Shoreline Forecasting tool within DSAS was used to generate projected shorelines for the years 2034 and 2044.

3 Results and Discussion

3.1 Shoreline Maps and Change Rates

Shorelines for years 1988, 1992, 1995, 2001, 2005, 2015, 2021 and 2023 were generated and mapped in an ArcMap environment. A significant change over the last three and half decades was observed around the study area. Fig. 3 shows extracted shorelines.

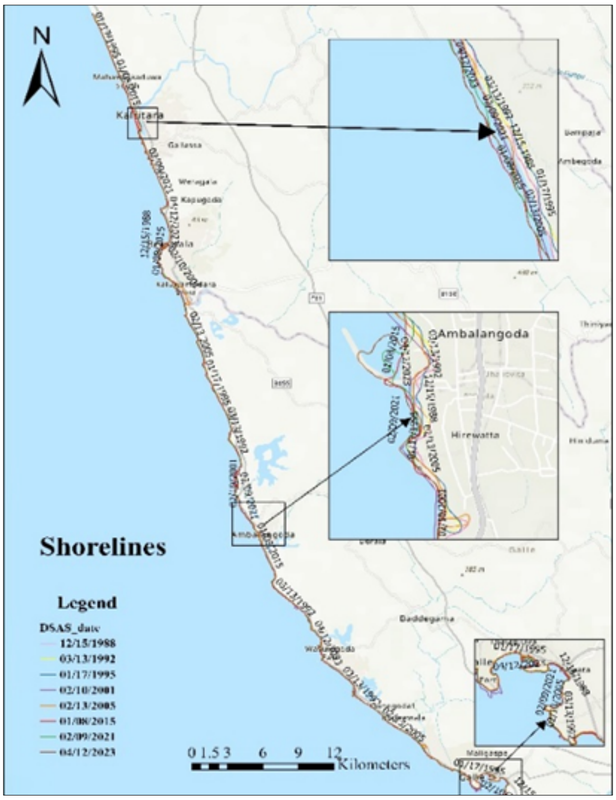

Fig. 3: Shorelines of selected areas from 1988-2023.

Shoreline change rates were calculated according to three-time frames; 1988-2001, 2001-2023 and 1988-2023. DSAS tools were used to calculate the change rate statistics SCE, NSM, EPR and LRR. Negative values in NSM, EPR and LRR indicate erosion while positive values indicate accretion. Table 2 shows an overview of the change rate statistics.

During the period from 1988-2001, the mean SCE was observed to be 33.83 m, with a standard deviation (S.D) of 15.77 m. The maximum change recorded during this timeframe was 153.98 m, while the minimum change was 0.08 m. The NSM had a mean value of 27.74 m, with a S.D of 18.11 m. The maximum observed NSM was 153.98 m, while the minimum was -61.37 m. The erosion/accretion rate (EPR) had a mean value of 2.31 m/year, with a S.D of

1.55 m/year. The maximum EPR recorded was 13.25 m/year, while the minimum was -6.89 m/year. The LRR averaged at 2.33 m/year, with a S.D of 1.46 m/year. The maximum LRR observed was 13.30 m/year, while the minimum was -5.52 m/year.

Table 2: Overview of Change Rate Statistics.

	Year	1988-2001	2001-2023	1988-2023
SCE	Mean (m)	33.83	50.36	60.38
	S.D (m)	15.77	70.17	62.68
	Max (m)	153.98	452.55	410.17
	Min (m)	0.08	0.23	0.23
	Year	**1988-2001**	**2001-2023**	**1988-2023**
NSM	Mean (m)	27.74	-9.34	21.1
	S.D (m)	18.11	44.29	44.64
	Max (m)	153.98	212.56	239.47
	Min (m)	-61.37	-286.82	-314.94
	Year	**1988-2001**	**2001-2023**	**1988-2023**
EPR	Mean (m/yr)	2.31	-0.46	0.61
	S.D (m/yr)	1.55	2.64	1.3
	Max (m/yr)	13.25	9.59	6.98
	Min (m/yr)	-6.89	-12.97	-9.18
	Year	**1988-2001**	**2001-2023**	**1988-2023**
LRR	Mean (m/yr)	2.33	-0.25	0.51
	S.D (m/yr)	1.46	2.23	1.26
	Max (m/yr)	13.3	10.07	7.21
	Min (m/yr)	-5.52	-15.04	-8.52

Between 2001 and 2023 (see Table 2), the mean SCE increased to 50.36 m, with a notably higher S.D of 70.17 m compared to the previous period. The maximum SCE recorded during this time was 452.55 m, while the minimum remained consistent at 0.23 m. The NSM mean dropped to -9.34 m, with a S.D of 44.29 m. The maximum erosion observed was -286.82 m, while the maximum accretion was 212.56 m. The mean EPR decreased to 0.46 m/year, with a S.D of 2.64 m/year. The maximum accretion rate was 9.59 m/year, and the maximum erosion rate was -12.97 m/year. The LRR mean reduced to 0.25 m/year, with a S.D of 2.23 m/year. The maximum LRR recorded during this period was 10.07 m/year, and the minimum was -15.04 m/year.

Over the entire period of 1988 to 2023, the mean SCE increased to 60.38 m, with a S.D of 62.68 m. The maximum SCE observed was 410.17 me, and the minimum remained at 0.23 m. The mean NSM rose to 21.10 m, with a S.D of 44.64 m. The maximum NSM recorded was 239.47 m, and the minimum was -314.94 m. The mean EPR slightly decreased to 0.61 m/year, with a S.D of 1.30 m/year. The maximum accretion rate was 6.98 m/year, and the maximum erosion rate was -9.18 m/year. The mean LRR also decreased to 0.51 m/year, with a S.D of 1.26 m/year. The maximum LRR observed was 7.21 m/year, and the minimum was -8.52 m/year.

3.2 Erosion/Accretion Maps

Erosion/Accretion maps for 1988-2001, 2001-2023 and 1988-2023 were prepared using the NSM statistics. Table 2 shows the transect-wise study conducted for three time periods.

The overall trend of the southwestern shoreline was accretion from 1988 to 2001. Among the total number of 3,475 transects, only 200 transects generated negative values. Therefore, only 5.76% of the total transects has shown erosion. Fig. 4 shows the erosion/accretion map between the period 1988-2001. Kalutara north and south, Hikkaduwa, Galle, Maggona, Devinigoda and Beruwala were among the eroded areas during this time period. Comparatively lower anthropogenic activities such as sand mining, shrimp farming, and lower number of residents around the area may have contributed for the overall accretion trend.

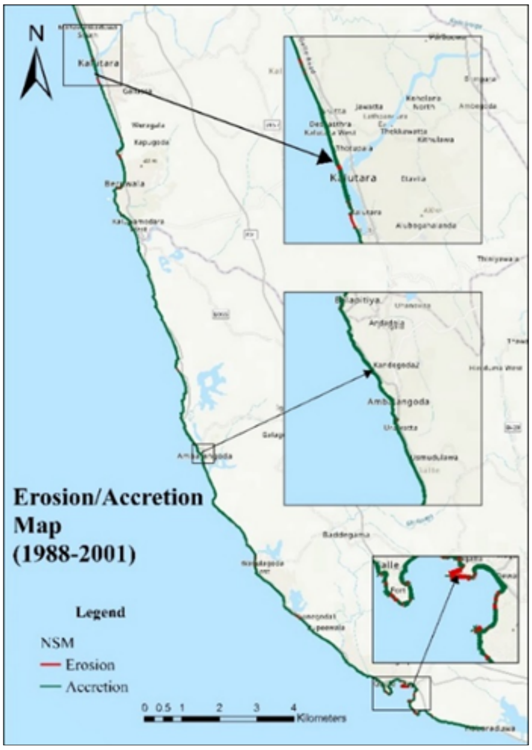

Fig. 4: Erosion/Accretion from 1988-2001.

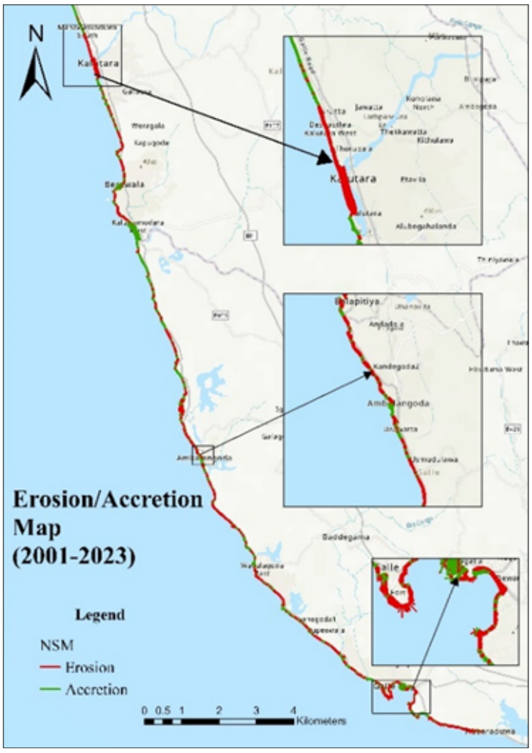

Fig. 5: Erosion/Accretion from 2001-2023.

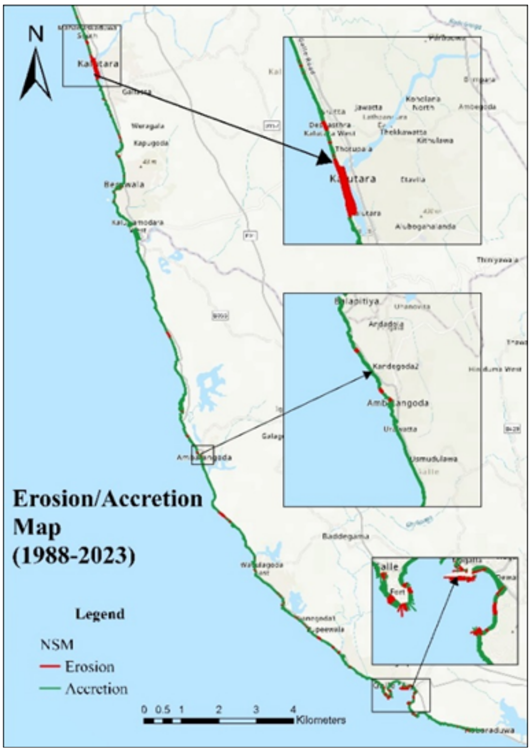

Fig. 6: Erosion/Accretion from 1988-2023.

However, with the increase in the human activities and population around the southwestern coastal zone, along with the rise in population density along the shoreline, erosion became predominant across most areas from 2001 to 2023. As seen from Fig. 5, 2,192 out of the total 3,495 transects have shown erosion which is 62.75% of the total transects. The tsunami disaster in 2004 likely emerged as a prominent factor contributing to the overall erosion trend observed between 2001 and 2023 (Morton et al., 2007). However, in later years, shoreline positions show signs of accretion compared to conditions observed in 2005.

Overall, the analysis spanning from 1988 to 2023 indicates a reduced amount of accretion compared to the period from 1988 to 2001. Between 1988 and 2023 (see Fig. 6), only 404 transects out of 3,422 experienced erosion, which is around 11.81%. Specifically, between 1988 and 2023, areas such as Kalutara, Beruwala, Doowee Modara, Patabendi Mulla, Kahawa, Hikkaduwa, Boossa, Gintota, Unawatuna, and Galle experienced heavy erosion, with more than 15 m of land loss. This confirms the inclusion of Galle, Hikkaduwa and Kahawa as highly vulnerable areas by (Lin and Pussella (2017) and Hikkaduwa, Galle, Kalutara North by Amarasinghe (2020). This also confirms the findings by Kirishanthan (2022), where Kalutara was identified to be an area prone to erosion. Kalutara suffered the most significant erosion due to the flood events in 2017, which caused erosion of sand bars close to the estuary, resulting in the erosion of a vast area of beach in Kalutara North.

3.3 Predicted shorelines for 2034 and 2044

Compared to the shoreline observed in 2023, the majority of the predicted shoreline positions indicate an accretion trend. However, certain areas like Kalutara, Galle, Hikkaduwa, Beruwala, Doowemodara, Maha Payagala, Maggona west, and some areas around Waskaduwa continue to suffer from erosion. Among the predicted 2034 and 2044 shorelines, Kalutara, Doowemodara, and Beruwala still show signs of erosion, while Hikkaduwa, Galle, and Payagala exhibit less erosion. Fig. 7 shows the predicted shorelines for year 2034 and year 2044 where areas around Galle Hikkaduwa and Kalutara indicate eroding trends.

Kalman filter approach (Himmelstoss et al., 2021) was used along with the linear regression rate calculated by DSAS to estimate shoreline position and change rate at each 10th of a year, using an estimate of positional uncertainty at each time step. However, the methodology does not account for all factors driving shoreline change, leading to potential limitations in its accuracy. While it assumes that linear regression of past shoreline positions sufficiently predicts future positions, this assumption may not always be true due to the complexity of shoreline processes and the absence of certain model inputs. Therefore, in the DSAS user guide, they strongly advised to include uncertainty bands associated with the predicted shorelines (Himmelstoss et al., 2021).

Fig. 8 and 9 illustrate the uncertainty bands associated with the predicted shorelines for 2034 and 2044, providing insight into the potential range of shoreline positions. These bands highlight the possible variation due to factors such as human activities and other environmental influences that may alter the shoreline beyond the predicted linear trends (Himmelstoss et al., 2021).

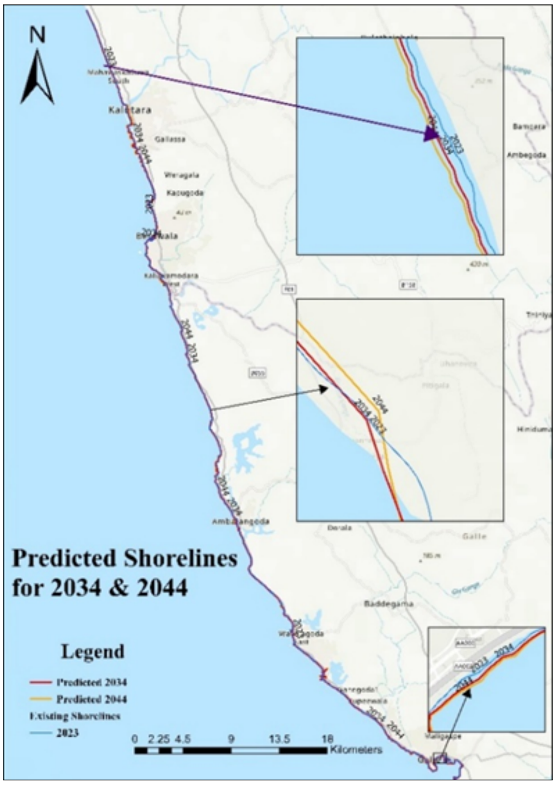

Fig. 7: Predicted Shorelines for 2034 and 2044.

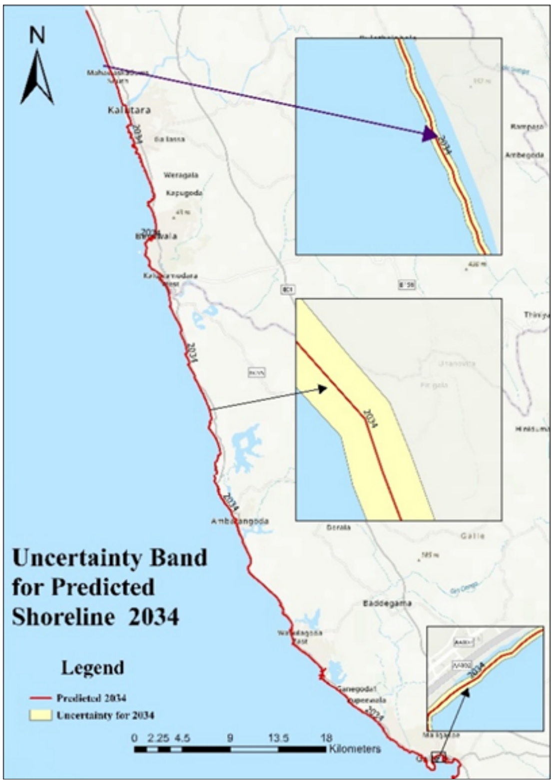

Fig. 8: Uncertainty Band for predicted 2034 shoreline.

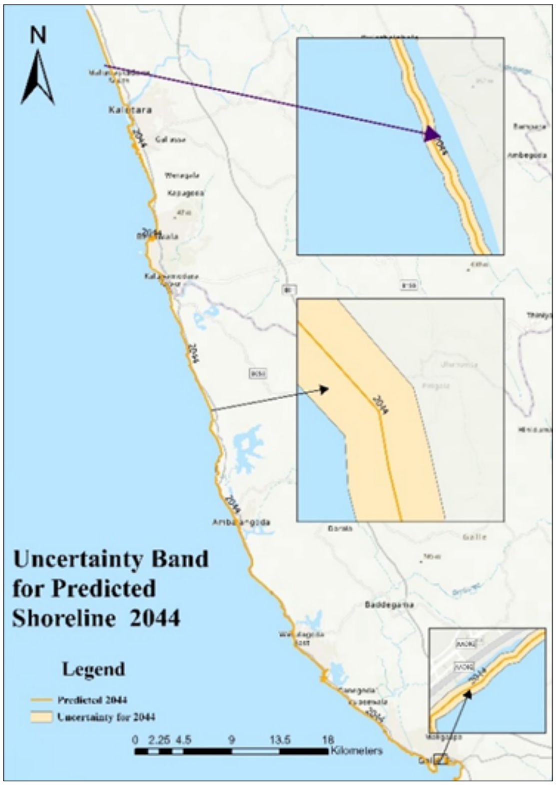

Fig. 9: Uncertainty Band for predicted 2034 shoreline.

4 Conclusion

The primary objective of the study was to determine the rates of shoreline change along the southwestern coastline of Sri Lanka by analysing historical data from 1988 to 2023. Using methods such as NDWI and DSAS tools, both erosion and accretion rates were successfully quantified. In addition, the study aimed to predict future shoreline positions for 2034 and 2044 based on the quantified shoreline change rates. The results suggested accretion trends in most areas, but also identified regions, such as Kalutara and Beruwala, as facing significant erosion. The inclusion of uncertainty bands in the predictions enhances the reliability of the results. Moreover, the study achieved its final objective of visualizing erosion and accretion along the southwestern coastline through detailed maps and graphs.

Although the study provided key findings, further research should be conducted in the area using more accurate data and advanced technology to improve the accuracy of predictions and support sustainable development and effective management of the southwestern coastline of Sri Lanka

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Author Contributions

Conceptualization O.N.W., methodology and analysis O.N.W. and I.A.K.S.I, writing - original draft preparation, O.N.W., review I.A.K.S.I., and editing, O.N.W. All authors have read and agreed to the published version of the manuscript.

Conflict of Interest

The authors declare no conflict of interest.

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