Scientific African 28 (2025) e02685

Contents lists available at ScienceDirect

Scientific African

journal homepage: www.elsevier.com/locate/sciaf

Geospatial analysis of shoreline change of ethekwini coastline from 1990 – 2023

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A R T I C L E I N F O

Editor DR B Gyampoh

Keywords:
Shoreline
Coastline
Climate change
Sea level rise
Digital shoreline analysis systems (dsas)

A B S T R A C T

Coastal areas are dynamic environments impacted by both natural and anthropogenic processes. Hence, it is important to continually and accurately monitor these areas for change and develop coastal management strategies. The present study uses the Digital Shoreline Analysis System (DSAS) and satellite imagery to assess the changing dynamics of the Durban coastal stretch of the eThekwini Municipality from 1990 to 2023. Net Shoreline Movement (NSM), End Point Rate (EPR), and Linear Regression Rate (LRR) were calculated in DSAS to analyse the shoreline changes. The analysis revealed significant variations in erosion and accretion across the coastline. The average shoreline movement was 2.49 m in the north and -7.42 m in the south, indicating predominant erosion in the southern regions. Specifically, 53.85 % of transects in the north and 71.9 % in the south were negative distances, highlighting erosion areas. The EPR analysis indicated an average annual change rate of 0.09 m/year for the north and -0.22 m/year for the south, with erosion rates averaging -2.05 m/year in the north and -1.21 m/year in the south between 1990 and 2023. The LRR method corroborated these findings with annual changes of -0.01 and -0.37 m/year, respectively. High erosion rates were concentrated in areas such as Umhlanga Rocks and Beachwood, while engineered structures contributed to accretion in parts of Durban North. Conversely, the southern coastline, particularly around Amanzimtoti and Isipingo, experienced more erosion than accretion due to fewer protective structures. This study highlights the dynamic nature of shoreline changes along the Durban coast. Understanding these trends is essential for effective coastal planning and management and building resilience against the multiple hazards ravaging coastal communities.

Introduction

The shoreline defines the dynamic physical interfaces between land and the sea. Over the years, these coastal zones have experienced tremendous modification in shape and size in response to various physical and anthropogenic processes shaping the shoreline over time [1]. Shoreline change studies have become a concern for coastal managers and engineers worldwide due to their significant threat to the ever-rising coastal populations, biodiversity, and infrastructures. Specifically, shoreline change dynamics are often defined by various erosion and accretion processes that configure the coastline [2]. Scientific research trends in coastline analysis

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https://doi.org/10.1016/j.sciaf.2025.e02685
Received 26 November 2024; Received in revised form 20 March 2025; Accepted 3 April 2025

indicate that the shoreline constantly changes due to opposing sediment supply and removal mechanisms. Equilibrium is achieved when these processes are balanced [3–5]. However, research shows that such an equilibrium is never reached due to numerous irregularities in natural and anthropogenic activities operating the coastline [6,7]. Consequently, the shoreline is constantly changing its morphology and position over different spatial and temporal scales in response to determining processes such as sea level rise, tides, winds, currents, waves, and land subsidence due to excessive groundwater extraction, among other factors [6,8,9]. In addition, changes in hydraulic processes such as the river cycle and geomorphic change (e.g., development of spit and dunes), seismic events, and anthropogenic activities, including land use changes, amplify the rate of shoreline changes over time [10–12]. Thus, accurately delineating the shoreline is crucial for monitoring and detecting periodic changes for effective coastal zone management, planning, risk reduction, and sustainable development.

The conventional approach for delineating the position of shoreline changes relies on field surveys of current shoreline levels, aerial photographs, and topographic maps. These data are then compared to historical data sets using techniques such as the linear regression rate (LRR), jackknife (JK), and end point rate (EPR) [7,13,14]. However, these methods are very sensitive to human errors, labor intensive, and have limited spatiotemporal coverage. Recent advancements in remote sensing (RS) and geographic information systems (GIS) technologies have led to a significantly improved understanding of the effects of coastal geomorphological processes on shoreline change [3]. RS data are often used in shoreline change studies due to their broad, accessible, and multispectral qualities for distinguishing infrared imagery portions of land and water and their cost effectiveness [2,15]. Satellite data may be analyzed using advanced image processing techniques to delineate shoreline changes accurately. Some widely used approaches include image classification, threshold slicing, and machine learning techniques [16]. Several researchers have quantitatively assessed the spatiotemporal changes in shorelines on a global scale [4,17]. Highlighting the application of DSAS, which is an ArcGIS extension designed for measuring, quantifying, computing, and estimating rates of shoreline change from multiple historical shoreline change rates [4,18,19]. This method frequently utilizes five statistical metrics, namely the shoreline changes envelope (SCE), net shoreline movements (NSM), End Point Rate (EPR), Weighted Linear Regression rate (WLR), and Linear Regression Rate (LRR), to evaluate both long-term and short-term shoreline changes [20]. Specifically, the LRR and WLR methods use historical shoreline data to determine how quickly the coastline changes. This is by analyzing specific sections of the coastline; these methods fit a regression line to the shoreline points over time to calculate the rate of erosion or accretion for specific transects.

Many studies have focused on analysing shoreline dynamics in various coastal regions. For instance, Hakkou et al. [21] utilized this approach to examine the Moroccan Atlantic coast near Kenitra between 1936 and 2014, employing data from diverse sources, such as topographic maps, aerial photographs, and field measurements. Similarly, Daud et al. [22] investigated shoreline change trends in Selangor using Landsat satellite imagery from 1990 to 2015. In this regard, Masria et al. [23] applied the DSAS methodology with Landsat images to study shoreline changes between 1984 and 2004 on the promontory coast in the northwest Nile Delta. Zambrano-Medina et al. [24] also employed DSAS to analyze shoreline fluctuations over the Gulf of California using Landsat imagery from 1981–2020, assessing erosion and accretion patterns while forecasting the shoreline change rate for the years 2030 and 2050, respectively. Despite the extensive use of DSAS and satellite imagery in such studies, research remains scarce addressing extensive coastal stretches while predicting future shoreline positions over South Africa.

Studies focused on monitoring and modelling the coastline plays a significant role in developing effective coastal zone management [24]. This is particularly true in the contemporary context of climate change impacts/variability in sea-level rise, increased coastal erosion, and floods along the eThekwini coastline [25]. Specifically, these changes affect various community livelihood activities and tourism, all of which are critical economic activities along the coastline [26]. In this regard, one of the prerequisites for effective coastal planning, hazard zoning, and management is to provide an accurate and precise position of the shorelines to detect past and future changes in the eThekwini shoreline. While shoreline change analysis is critical, few studies have examined changes along the eThekwini shoreline.

For example, Allison et al. [8] analysed recent sea-level variations around South Africa using tide gauge records and satellite altimetry. Cooper & Green [27] studied the effects of sea-level rise on shoreline change across Southern Africa using various geomorphological approaches. Specifically, Cawthra et al. [25] assessed the influence of ocean currents on sediment dynamics on the narrow 8 km wide beach of the Durban, demonstrating that the Durban Eddy, located inshore of the Agulhas Current, along with bottom surges induced by high swells and marine storm events, has played a significant role in influencing large-scale shoreface dynamics, while Leuci et al. [26] investigated trends in sandy beach variability along a 9.6 km stretch using a topographic survey data approach, reporting a net loss of 177,885 m^3 in volume and 29,375 m^2 in area. Although these studies contribute to understanding the broader coastal dynamics in South Africa and eThekwini, they are limited to specific sections of the coastline that are $<$10 km long and do not leverage advanced DSAS to capture these changes over time. In addition, an exhaustive and consistent regional investigation of shoreline change is required annually to determine the vulnerability of populations and infrastructures to shoreline changes. To address these gaps, we assessed the shoreline change of the eThekwini Coastline from 1990 – 2023 using Landsat images, Google Earth, and an innovative geospatial analysis approach for effective coastline management. The outcomes of this research will inform decision-making processes on sustainable coastal management approaches, contributing to enhanced resilience against shoreline risks along the eThekwini coastal area. Furthermore, it provides a framework for integrating geospatial analysis into regional disaster risk reduction strategies, benefiting neighbouring coastal areas that face similar challenges.

Given the critical role of coastal areas in economic development, understanding their evolving dynamics over time is essential, particularly in climate change, which is expected to influence the effects on coastal communities [28]. Evidence suggests that shoreline changes may increase, and so too their impact on vulnerable coastal populations [8,29]. While DSAS has long been recognized and studied [4], this research aims to conduct a comprehensive geospatial analysis of shoreline changes along the eThekwini coastline from 1990 to 2023 by leveraging advanced DSAS tools. The study aims to assess historical and projected shoreline changes for effective coastline management and community resilience in eThekwini

Study area

eThekwini is located on the east coast of Kwa-Zulu Natal Province of South Africa. The Durban Bay on eThekwini is one of the largest and busiest harbors in the country. Geographically, eThekwini is bounded between latitude −29° 52′N and 30° 0′ 12′N and longitude 31° 10′E and 32° 6′E, respectively. Its coastline covers a length of approximately 98 km and stretches from the Sapref oil refinery in the South to the Northern coastal area of Durban North and the Indian Ocean to the East. eThekwini has a surface area of approximately 2, 292km^2 and is just over 2 to 4 m above sea level. This makes the coastal area vulnerable to active geomorphic processes such as waves, high tide, currents, longshore drift, storms, and sea level rise [26]. Consequently, erosion and accretion transportation and deposition processes constantly shape the coastline. The major geomorphic feature includes the formation of sandy beaches, dunes, cliff retreats, and saltwater intrusion due to sea level rise and global warming impacts. Generally, the area is a low-lying coastal region characterized by wave-dominated sandy beaches, mudflats, and dunes [26]. The minimum and maximum tidal heights of the area range between 0.8 to 2.4 m, respectively [30].

In addition, eThekwini has a complex topographic gradient extending from an inland plateau to the Great Drakensberg Mountains range. The elevation ranges between 1 to 3442 m above sea level [31], which has significantly affected the shoreline position due to various sediment transport and deposition shaping its position, especially along the south Durban shoreline [25]. eThekwini climate is diverse, influenced by its varied terrain. Near the coast, it exhibits a subtropical climate, while inland, the climate is temperate and gets colder towards Drakensberg's escarpments in the higher altitudes [31]. The average temperature range is between 19.7 °C and 24.8 °C minimum and maximum, with an annual rainfall of approximately 900–1009 mm, respectively [32]. The coastal tracks experience over 1 to 3 tropical cyclones annually with varying intensity during the summer months, which last from December to April. The climate has favoured various cyclonic and storm activities along the coast, significantly contributing to erosion and accretion, especially during high-impact precipitation and flooding [27]. Coastal erosion constantly threatens the population and infrastructures along the coast [26,33,34] (Fig. 1).

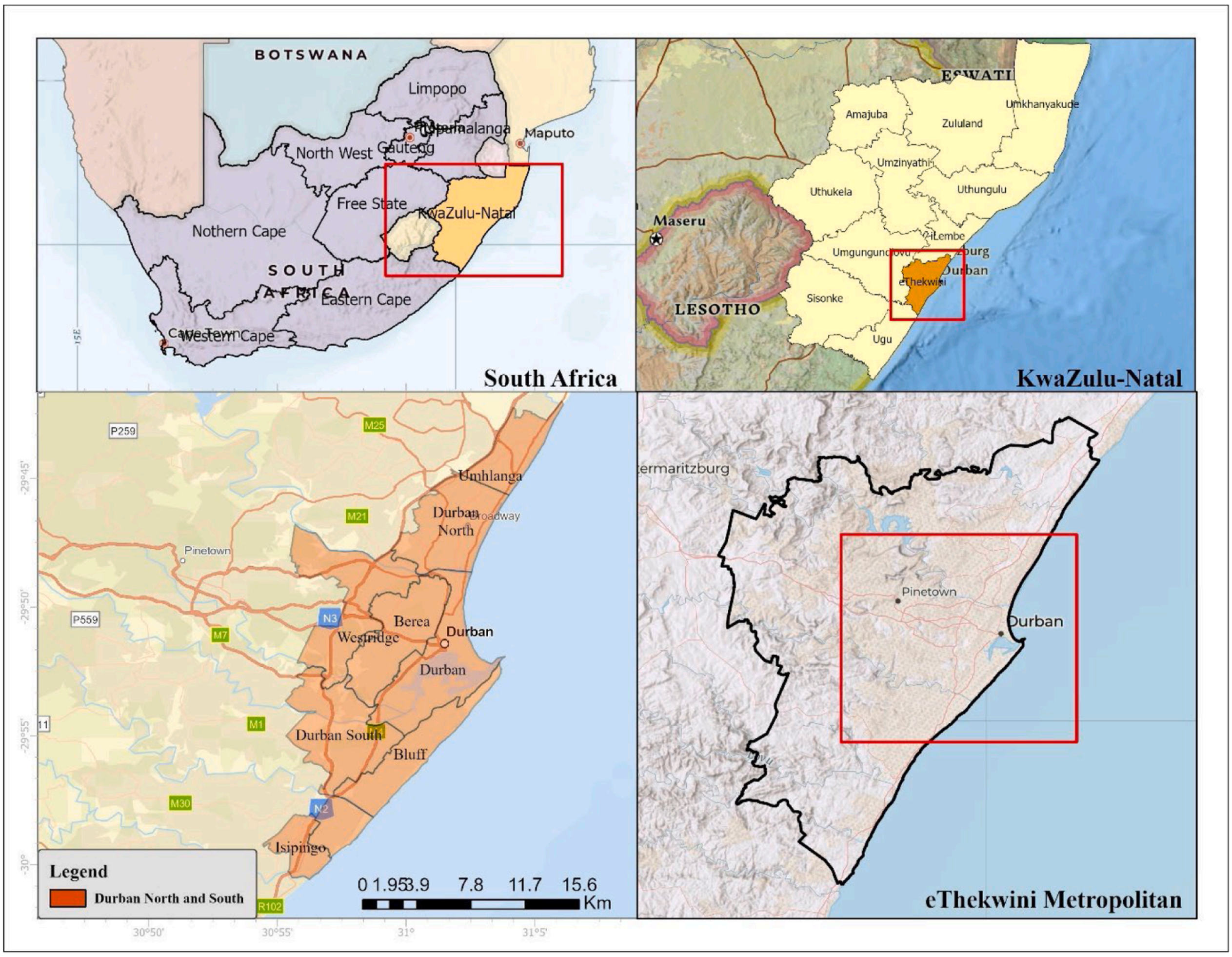

Fig. 1. The Coastline of Durban, eThekwini, KwaZulu-Natal, South Africa.

Material and methods

Coastal environments are highly dynamic systems that undergo continuous changes due to various natural and anthropogenic factors [35–37]. Monitoring and analyzing these changes is crucial for understanding coastal processes, managing resources, and mitigating potential hazards. One widely used tool for this purpose is the Digital Shoreline Analysis System, which enables quantifying and visualizing shoreline changes over time [19,35]. The Landsat series of satellites provides a valuable source of long-term, high--quality imagery with global coverage, making it a suitable choice for large-scale shoreline monitoring [35,38]. The most practical and affordable medium-resolution imagery dataset for shoreline study is Landsat imagery, which is extensively utilized for changes in shorelines in coastal locations worldwide [39,40]. The Landsat multispectral resolution with broad and recurrent data coverage dates to the 1970s. This enables the observation and measurement of surface geophysical characteristics of land and water, and its capacity to differentiate between these characteristics has demonstrated its value for coastal studies [40–42]. Landsat Thematic Mapper (TM) of 1990 and 2000, Enhanced Thematic Mapper (ETM+) 2010, and Operational Land Imager (OLI) 2023 were used to extract the shoreline used for the analysis. The Landsat images were downloaded from the United States Geological Survey (USGS) official website (Table 1).

Shoreline extraction

According to Dolan et al. [43] and Moore [44], the physical boundary between land and water is the optimal definition of the shoreline. The shorelines were extracted Using semiautomated and manual onscreen digitization techniques [45–48]. False colour composite and Normalized Difference Water Index (NDWI) were used to extract the data for the shoreline analysis. High-resolution images from Google Earth Pro were used for validation and adjustments.

A false colour composite utilizes specific spectral bands from satellite imagery to represent features in colours that differ from their natural appearance. This technique highlights water bodies, vegetation, and land cover types that might be indistinguishable in true color images. The most common band combinations include:

NIR, Red, Green: This combination enhances vegetation, making it appear bright red due to its high reflectance in the near-infrared spectrum, while clear water appears darker compared to turbid waters, which appear lighter.

SWIR, NIR, Red: This scheme emphasizes various land features such as vegetation (green), bare soil (purple), and active fires (bright red).

The NIR, Red, and Green bands 432 in Landsat 4–5 and 7 and 543 in Landsat 9 were used for this study to perform the on-screen digitalization of the images from 1990 to 2023 to extract the shoreline. We used the composite images for unsupervised classification using the Iso cluster in ArcGIS 10.8 to differential land and water pixels. The classified images were reclassed and converted to vectors to delineate the shoreline. The composite images were also used for the Normalized Difference Water Index (NDWI) to delineate the boundary between land and water. NDWI is particularly effective in differentiating water bodies from other land types by exploiting the reflective properties of water in specific spectral bands. NDWI is calculated using the Eq. (3):

$$\boldsymbol{NDWI} = \frac{Green - NIR}{Green + NIR} \tag{3}$$

This formula emphasizes water features by maximizing the contrast between water and non-water surfaces, making it easier to delineate coastlines.

Where:

Green (e.g., Landsat 8 Band 3) enhances water reflectance.

NIR (e.g., Landsat 8 Band 5) absorbs water, making water appear darker.

After performing the NDWI, thresholding was applied to separate water from land by identifying a threshold NDWI > 0 as water and NDWI of ≤ 0 as land. The binary was converted into a vector for all the images using raster to vector function in ArcGIS 10.8. The extracted shorelines were converted to kml/kmz format and exported to Google Earth Pro for validation and adjustments.

Error and uncertainty estimation

The shoreline position's accuracy and rate of change can be influenced by several sources of error, such as the tide level position, digitizing error, resolution, and image georeferencing [49–51]. The uncertainty and its propagation in shoreline mapping and extraction based on remote sensing are equally important for ascertaining the accuracy and significance of the results [52,53]. Consequently, the positional and measurement uncertainty were assessed in this investigation. Positional uncertainty refers to characteristics and events, such as seasonal error (E_s), tidal fluctuation (E_{td}) and shoreline proxy offset (E_o), that reduce the precision

Table 1
Summary of Acquired Landsat Images.

Sensor	Date	Resolution
Landsat TM	05/24/1990	30m
Landsat TM	03/24/2000	30m
Landsat ETM+	04/13/2010	30m
Land OLI	03/08/2023	30m

and accuracy of establishing a shoreline position from a given dataset [53,54]. Measurement uncertainties are related to the skill and approach, such as digitization error (E_d), rectification error (E_r), and pixel error (E_p) [54,55]. In the present study, the satellite images were already orthorectified and processed. The rectification errors were obtained from the metadata of all the Landsat images used for the study, as all Lansat contain a geometric RMSE value in their metadata. Many shoreline proxies, including land-water boundaries and low and high-water lines, can be used for shoreline delineation because satellite images taken during low tide have the best visibility of physical features on the landward side of the shoreline [56,57]. Therefore, the satellite images used for this study were acquired between March and May to avoid atmospheric and tidal errors. All the images have a uniform resolution of 30 m; therefore, E_p, E_s errors were ignored. Finally, using Eq. (1), the total uncertainty value for the shoreline position error of the specified time period (U_t) was computed by taking into consideration both the positional and measurement uncertainties:

$$U_t = \pm\sqrt{E_s^2 + E_{td}^2 + E_d^2 + E_p^2 + +E_r^2} \tag{1}$$

The total uncertainty (U) in each transect was derived using Eq. (2):

$$U_a = \frac{\sqrt{U_1^2 + U_2^2 + \ldots + U_n^2}}{Year_n - Year_1} \tag{2}$$

Where U_1, U_2, …and U_n signifies the uncertainty values of the shoreline from 1990 to 2023, and $Year_1$ and $Year_n$ represent the first and the final year under study, which in this case are 1990 and 2023, respectively. Table 2 shows that the highest yearly uncertainty calculated for individual transects is about ±0.32 m/year.

Shoreline change calculation

The coastline change analysis was conducted using the DSAS version 5.1, a USGS-developed tool for shoreline change statistics and forecasting. It utilizes time-series shoreline data from aerial photos, satellite images, or field measurements. The analysis involved four steps: shoreline preparation, baseline creation, transect generation, and shoreline change computation. A geodatabase was created for digitized shorelines from different years, with attributes including date formats (MM/DD/YYYY). Baselines were buffered and reprojected, and transects were generated at 100-meter intervals, extending 1000 m perpendicular to the shore.

Three statistical methods—End Point Rate (EPR), Net Shoreline Movement (NSM), and Linear Regression Rate (LRR)—were used to analyze shoreline changes along the transects. NSM measured overall shoreline movement between the oldest and most recent shorelines, while EPR quantified annual change rates by dividing NSM by the time elapsed. A total of 208 transects in Durban North and 207 in Durban South were analyzed, revealing patterns of accretion (positive values) and erosion (negative values). The study demonstrated the efficiency of DSAS in shoreline change analysis compared to conventional techniques. The EPR values were computed by dividing the NSM values by the total number of years (DSAS 5.1 user guide 2021) using Eq. (4).

$$EPR = \frac{Net\ Shoreline\ Movement}{No.\ of\ years\ between\ earliest\ and\ latest\ years} \tag{4}$$

Prediction of future shoreline

Predicting future shoreline changes is challenging, but it can be useful in long-term planning and decision-making related to coastline management [58,59]. Longitudinal predictions are challenging since shorelines are among the most dynamic geomorphological structures on Earth's surface [60].

To forecast the dynamic changes at the coastlines, the Kalman filter developed by Long and Plant in 2012 was used to determine the future shoreline position. The DSAS Kalman filter technique estimates shoreline position, rate of change, and positional uncertainty at each time step, which is first initialized using the linear regression rate calculated by DSAS (DSAS 5.1 user guide 2021). Shoreline forecasting is only possible for data containing at most four shorelines, although LRR and WRL can be computed with three or more shorelines. Therefore, if the input data contains fewer than four shoreline dates, a shoreline forecast will not be generated (DSAS 5.1 User Guide 2021) after Projecting the shoreline to 2033 and 2043. The projected shorelines were used to calculate the NSM and LRR to ascertain the changes rather than just the change in the positions of the projected shorelines. Fig. 2 shows the methodological flow chart of the study.

Table 2

Shoreline Uncertainty Calculation for all the Extracted Shorelines.

	1990	2000	2010	2023
Seasonal error (E_s)	0	0	0	0
Tidal fluctuation (E_{td})	6.9	7	7	7.1
Rectification error (RMSE) (E_r)	4.5	4.6	5.1	6.8
Digitizing error (E_d)	15	15	15	15
Pixel Error (E_p)	0.5	0.5	0.5	0.5
Total Shoreline position error (U_t) m	22.40	22.50	22.50	22.60
Annual error (U_a)	0.32 m/year			

Result

Mapping of shoreline change was carried out for Durban coastal stretches of the eThekwini coastline for the period 1990 to 2023. To estimate coastline change, the NSM, EPR, and LRR techniques were used, and the details of the spatial (maps) and statistical changes of the coastline over these periods are presented in Figs. 3a-g , 4, 5, 6, 7, 8a-d and Tables 2, 3, 4, 5, 6 for Durban north and south.

Net shoreline movement (NSM)

The net shoreline movement (NSM) statistics for Durban North and Durban South indicate notable spatial differences in shoreline dynamics, which reflect variations in natural processes and human activities. Figs. 3a and 3d revealed the Net shoreline Movement of Durban's north and south coastline.

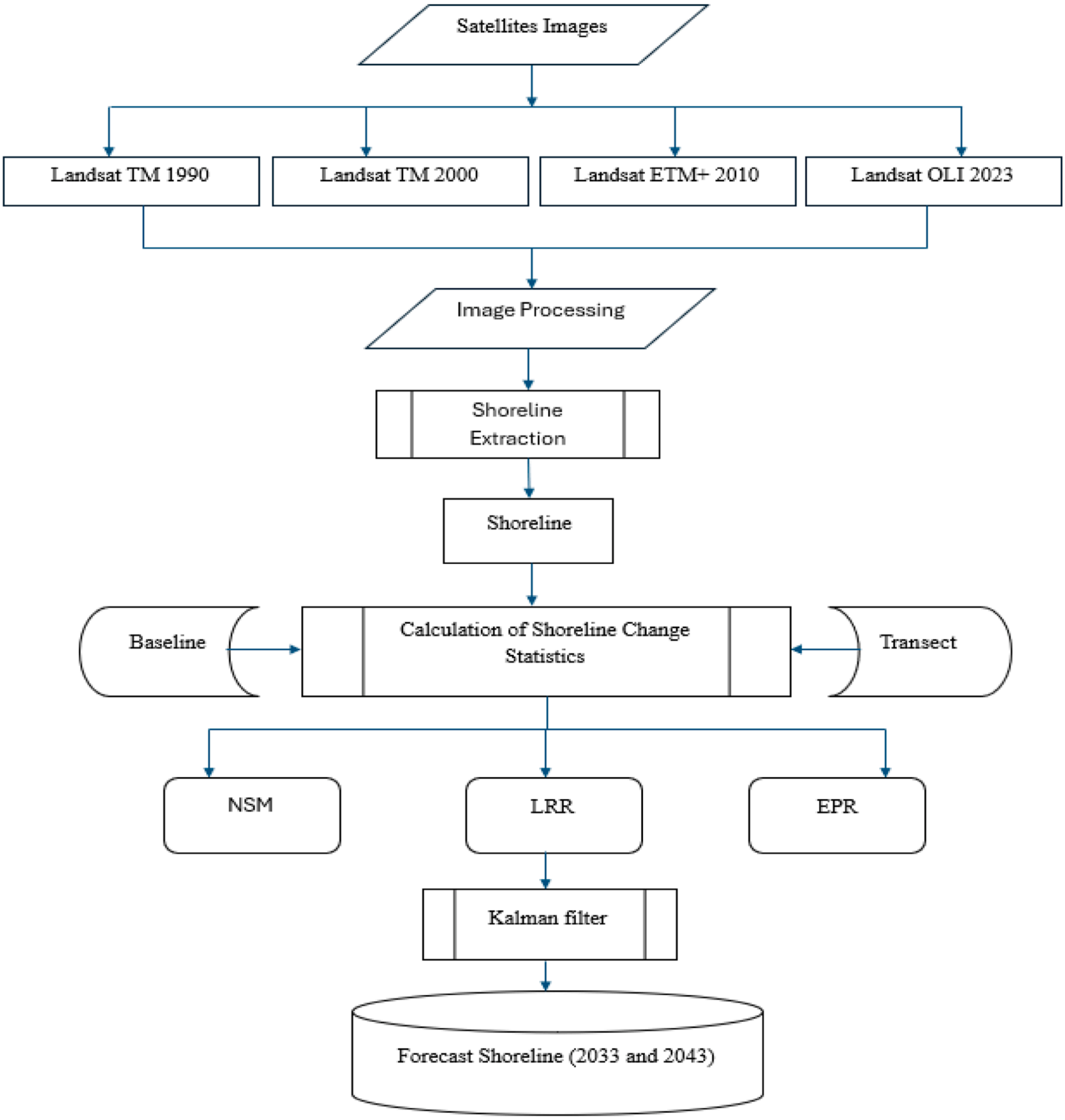

Fig. 2. Methodological flow chart.

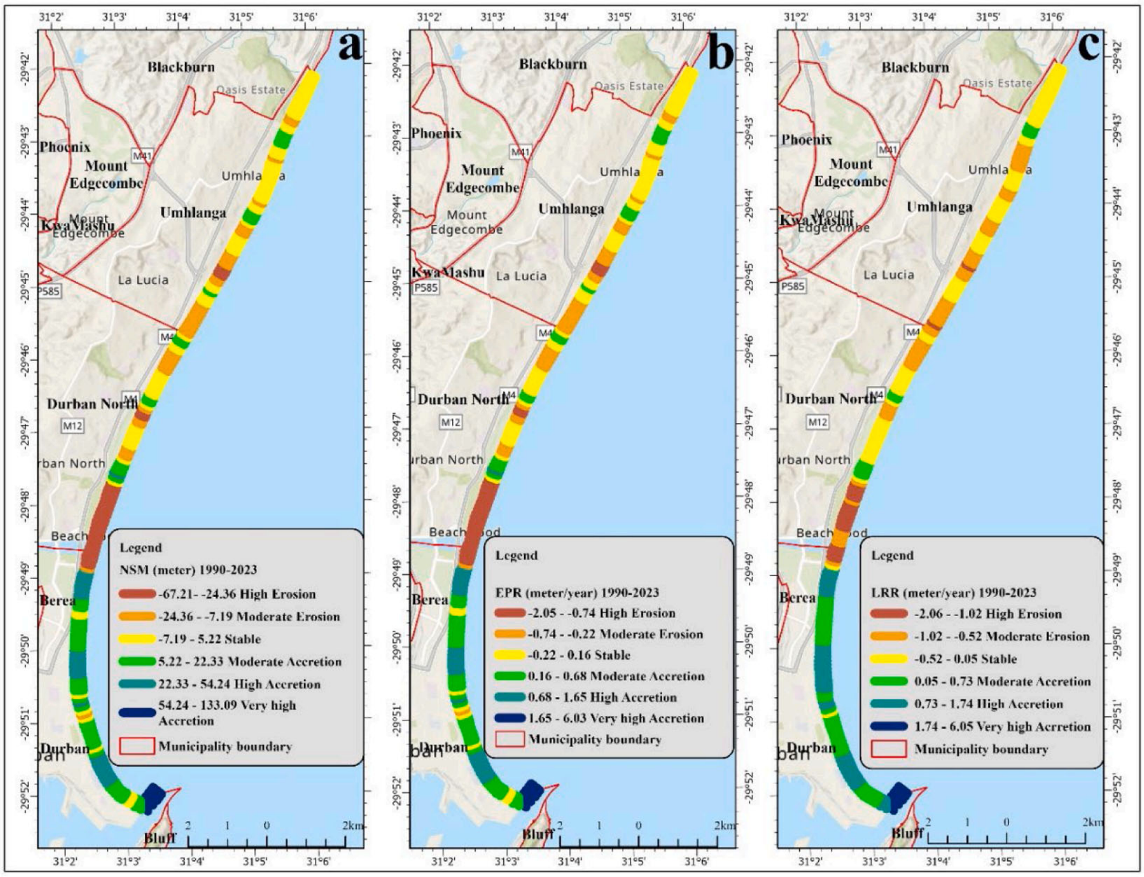

Fig. 3. Shoreline change based on Net Shoreline Movement 1990–2023 (a), End Point Rate 1990–2023 (b), and Linear Regression Rate 1990–2023 (c) of Durban North.

Erosion and accretion distance

The number of transects analyzed is almost equal in both areas, with 208 transects in Durban North and 207 in Durban South, ensuring a comparable analysis. The average NSM in the North is positive (+2.49 m), indicating a slight overall shoreline advancement or accretion. The NSM average in the South is negative (−7.42 m), showing significant shoreline retreat or erosion. This suggests that Durban South is experiencing more erosion than Durban North. 122 transects (53.85 %) show negative movement in the North, implying that over half of the transects in this area are eroding. 149 transects (71.9 %) in the South erode, indicating that erosion is more widespread in this region than in Durban North.

The maximum negative distance in the North is −67.21 m, and the average negative distance across eroding transects is −13.98 m. These values suggest localized hotspots of significant erosion, but overall erosion is moderate. The maximum negative distance is smaller at −39.54 m, yet the higher percentage of eroding transects indicates more consistent and widespread erosion in the South. The average negative distance (−12.98 m) is slightly lower than in Durban North.

The North, with 96 transects (46.15 %), shows positive NSM, representing shoreline advancement. The maximum positive distance (133.09 m) and the average positive distance (21.71 m) suggest occasional significant accretion events. Only 58 transects (28.02 %) show positive NSM in the North, indicating that shoreline advancement is less common. The maximum positive distance (29.58 m) and the average positive distance (6.86 m) are substantially lower than in Durban North, reflecting minimal accretion in this region.

Durban North balances erosion and accretion, with relatively larger positive distances compensating for localized erosion. This may indicate coastal management strategies, as seen in Durban Central, which has some seawalls built to protect the most affluent part of the coastline. The predominance of negative NSM and limited accretion in Durban South suggest a net erosional trend, which could result from higher wave energy, reduced sediment supply, or human activities like coastal development that exacerbate erosion.

Although erosion is present, the relatively high percentage of accreting transects and significant accretion distances provide opportunities for targeted management to enhance shoreline stability in the North. The consistent and widespread erosion in the South requires urgent attention. Coastal management strategies such as beach nourishment, erosion control structures, or ecosystem restoration could be necessary to mitigate shoreline retreat and protect infrastructure and ecosystems

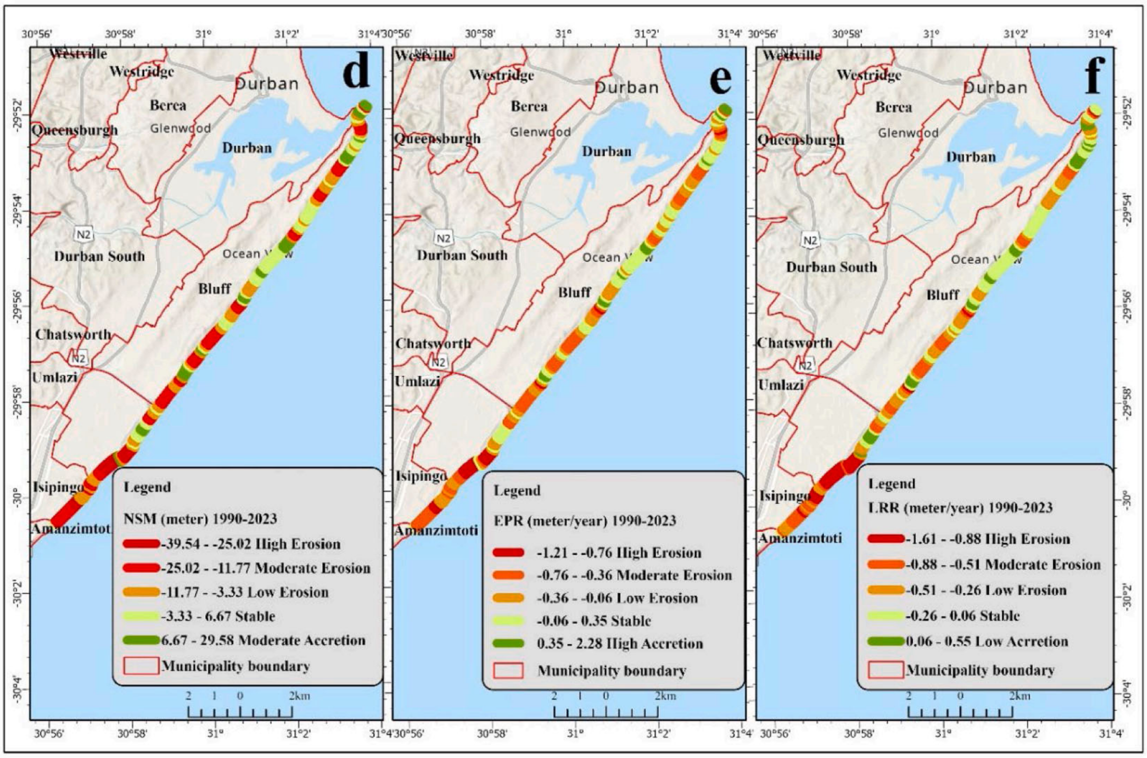

Fig. 4. Shoreline change based on Net Shoreline Movement 1990–2023 (a), End Point Rate 1990–2023 (b), and Linear Regression Rate 1990–2023 (c) of Durban North.

End point rate (EPR)

The endpoint rate (EPR) analysis for coastal transects in Durban North and Durban South reveals significant differences in erosion and accretion patterns between the two areas. Figs. 3b and 3e revealed the EPR of Durban's north and south coastline.

Erosion and accretion rates

Durban North shows an average erosion rate of 0.09 m/year, while Durban South has a negative average rate of −0.22 m/year, indicating a net loss of shoreline in Durban South.

The maximum erosion values are −2.05 m/year for Durban North and −1.21 m/year for Durban South, suggesting that Durban North's most severe erosion occurs despite its overall positive average rate. A total of 208 transects were analyzed in Durban North, with 53.85 % classified as erosional, whereas 71.98 % of the 207 transects in Durban South are erosional. Statistically significant erosion was observed in 18.75 % of transects in Durban North compared to 29.95 % in Durban South, indicating a higher prevalence of significant erosion events in the latter.

In terms of accretion, Durban North has a higher percentage of accretional transects at 46.15 %, compared to only 28.02 % in Durban South. The maximum accretion observed is significantly higher in Durban North at 6.03 m/year, compared to 2.28 m/year in Durban South, reflecting a more dynamic coastal process favoring accretion in this region.

The data indicates that while both regions experience erosion, Durban South is notably more affected by erosional processes, with a greater percentage of transects exhibiting significant erosion compared to Durban North. Conversely, Durban North benefits from higher rates of accretion, which may mitigate some of the erosional impacts observed. This disparity highlights the importance of localized coastal management strategies to address the unique challenges faced by each area, particularly in regions like Durban South, where significant erosion is prevalent.

Linear regression rate (LRR)

The linear regression analysis of the coastline erosion and accretion rates for Durban's northern and southern regions reveals significant differences in coastal dynamics. Figs. 3c and 3f revealed the LRR of Durban's north and south coastline.

Erosion and accretion rates

Durban North had 208 transects, while Durban South had 206, indicating a relatively similar sample size for both regions. The

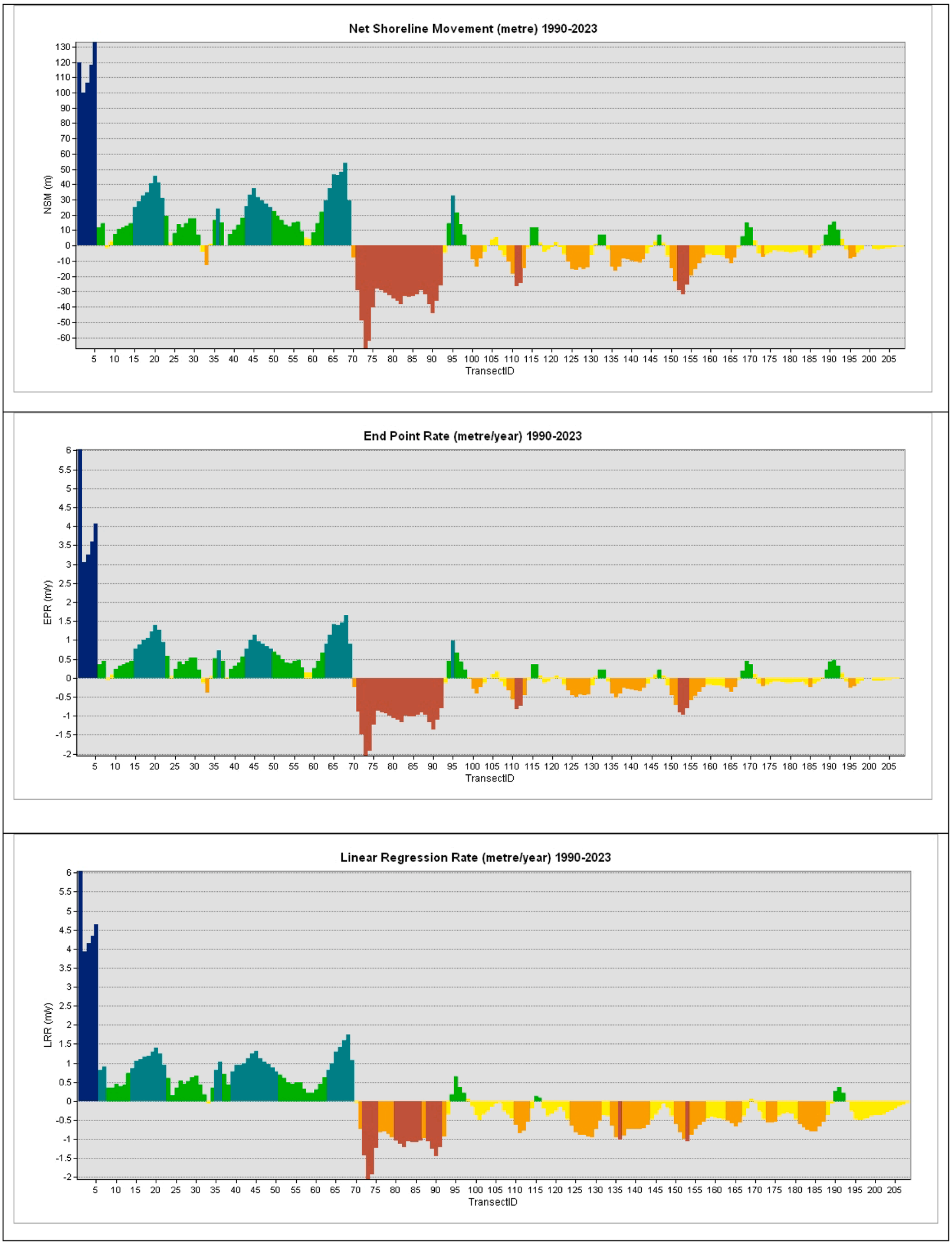

Fig. 5. Erosion and Accretion based on NSM, EPR, and LRR 1990–2023 of Durban North.

average erosion rate for Durban North is slightly positive at −0.01 m/year, suggesting minimal erosion. In contrast, Durban South shows a more pronounced negative average rate of −0.37 m/year, indicating significant erosion in that area. Durban North has 129 erosional transects (62.02 %), while Durban South has 171 (83.01 %). This suggests a higher prevalence of erosion in the southern region. Only 0.48 % of transects in Durban North show statistically significant erosion, compared to 0 % in Durban South. This may indicate that erosion is more common in the south but is not statistically significant across the sampled transects. The maximum recorded erosion values are −2.06 m for Durban North and −1.61 m for Durban South, highlighting that the most severe erosion events occurred in the northern region.

There are 79 accretional transects in Durban North (37.98 %) versus 35 in Durban South (16.99 %), indicating that accretion is

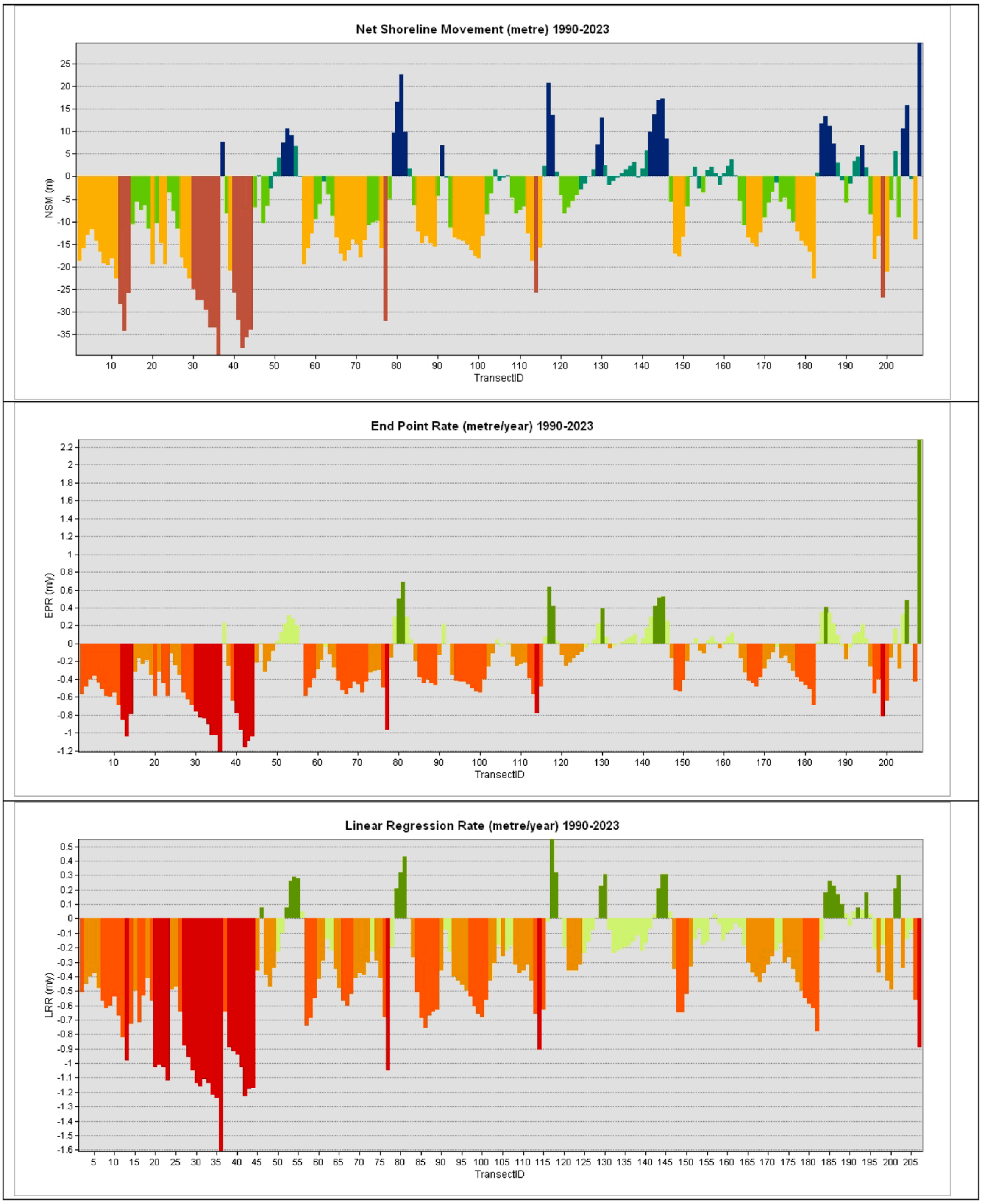

Fig. 6. Erosion and Accretion based on NSM, EPR, and LRR 1990–2023 of Durban South.

more common in the northern area. The maximum accretion value is notably higher in Durban North at 6.05 m, compared to only 0.55 m in Durban South. This suggests that while both regions experience accretion, it is significantly more pronounced in the north.

Durban North experiences minimal erosion with significant areas of accretion, showcasing a relatively stable coastline. Conversely, Durban South faces considerable erosion challenges with a lower tendency for accretion, leading to concerns about coastal stability and potential impacts on infrastructure and ecosystems.

These findings have critical implications for coastal management strategies. The pronounced erosion in Durban South necessitates targeted interventions to mitigate further loss and protect coastal habitats and human development. In contrast, the stability observed in Durban North may allow for different management approaches focused on maintaining current conditions while monitoring potential changes due to external factors such as climate change or human activity. Understanding these dynamics is essential for effective coastal planning and management, particularly in light of ongoing environmental changes affecting sea levels and coastal processes.

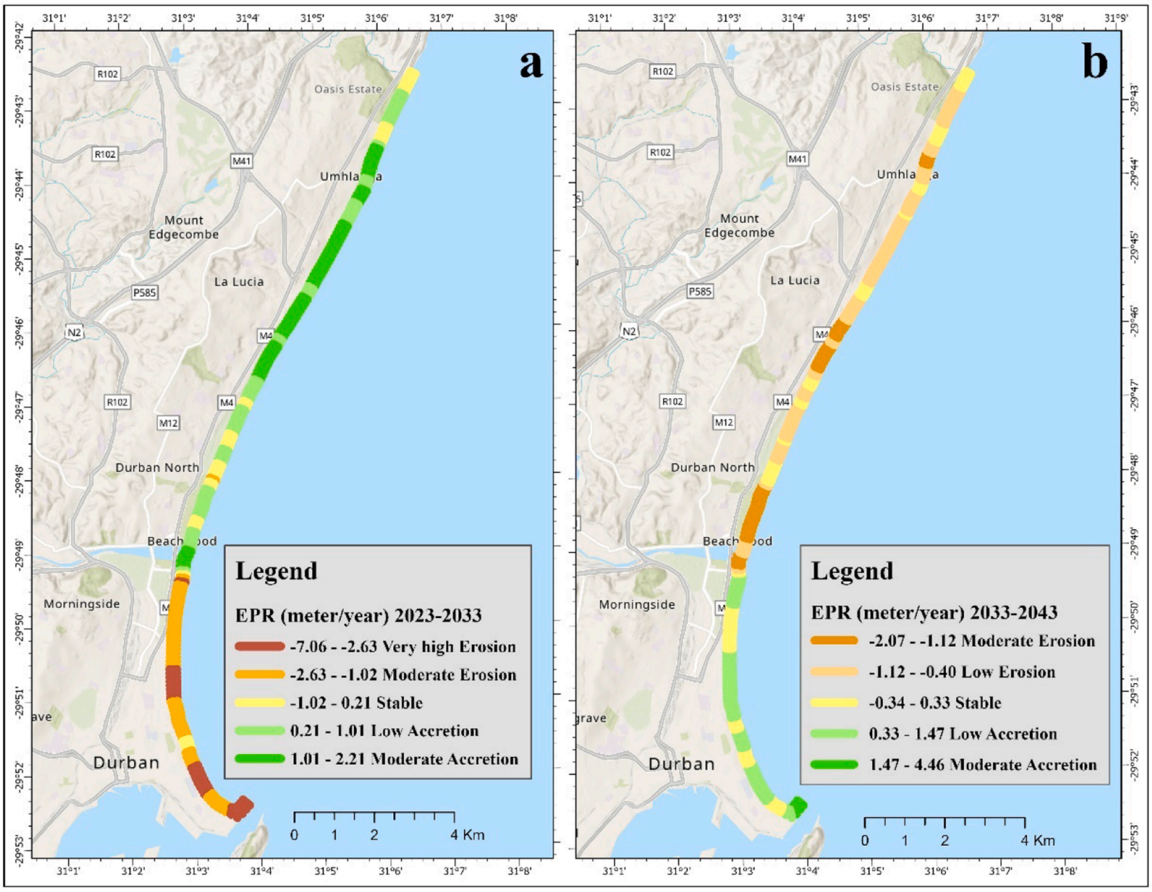

Fig. 7. Predicted Shoreline change based on End Point Rate 2023–2033 (short term) (a) and 2033–2043 (Long term) (b) of Durban North.

A comparative Analysis of the Prediction of Future Shoreline Change Rate Based on End Point Rate 2023–2033 (short term) and 2033–2043 (Long term) of Durban North and South

Erosion trends in durban north

In the short-term (2023–2033), the average erosion rate is −0.18 m/year, which worsens to −0.3 m/year long-term (2033–2043). The percentage of erosional transects increases significantly from 39.3 % to 68.66 %, indicating a worsening erosion trend. The number of statistically significant erosional transects drops from 25.87 % to 8.46 %, suggesting that while erosion increases in extent, fewer areas show significant statistical trends. Maximum erosion intensity decreases from −7.06 m/year to −2.07 m/year, implying a reduction in peak erosion rates. The average of all erosional rates also decreases from −1.93 m/year to −0.77 m/year, showing less aggressive but more widespread erosion.

Accretion trends in durban north

The percentage of accretional transects decreases from 60.7 % to 31.34 %, indicating a reduction in coastal build-up. Statistically significant accretional transects drop from 13.43 % to 2.49 %, suggesting less confidence in accretional trends over time. The maximum accretion rate increases from 2.21 m/year to 4.46 m/year, showing that while accretion is less frequent when it occurs, it is more intense. The average accretion rate slightly decreases from 0.96 m/year to 0.74 m/year.

Erosion trends in durban south

The average erosion rate improves significantly from −0.92 m/year in 2023–2033 to 0.3 m/year in 2033–2043, indicating a shift from erosion to overall accretion. The percentage of erosional transects declines drastically from 90.24 % to 16.1 %, suggesting that erosion becomes much less prominent over time. Statistically significant erosional transects disappear entirely (from 20.98 % to 0 %), reinforcing the trend reversal. Maximum erosion intensity decreases from −4.73 m/year to −0.54 m/year. The average of all erosional rates also declines from −1.06 m/year to −0.18 m/year, supporting the shift towards accretion.

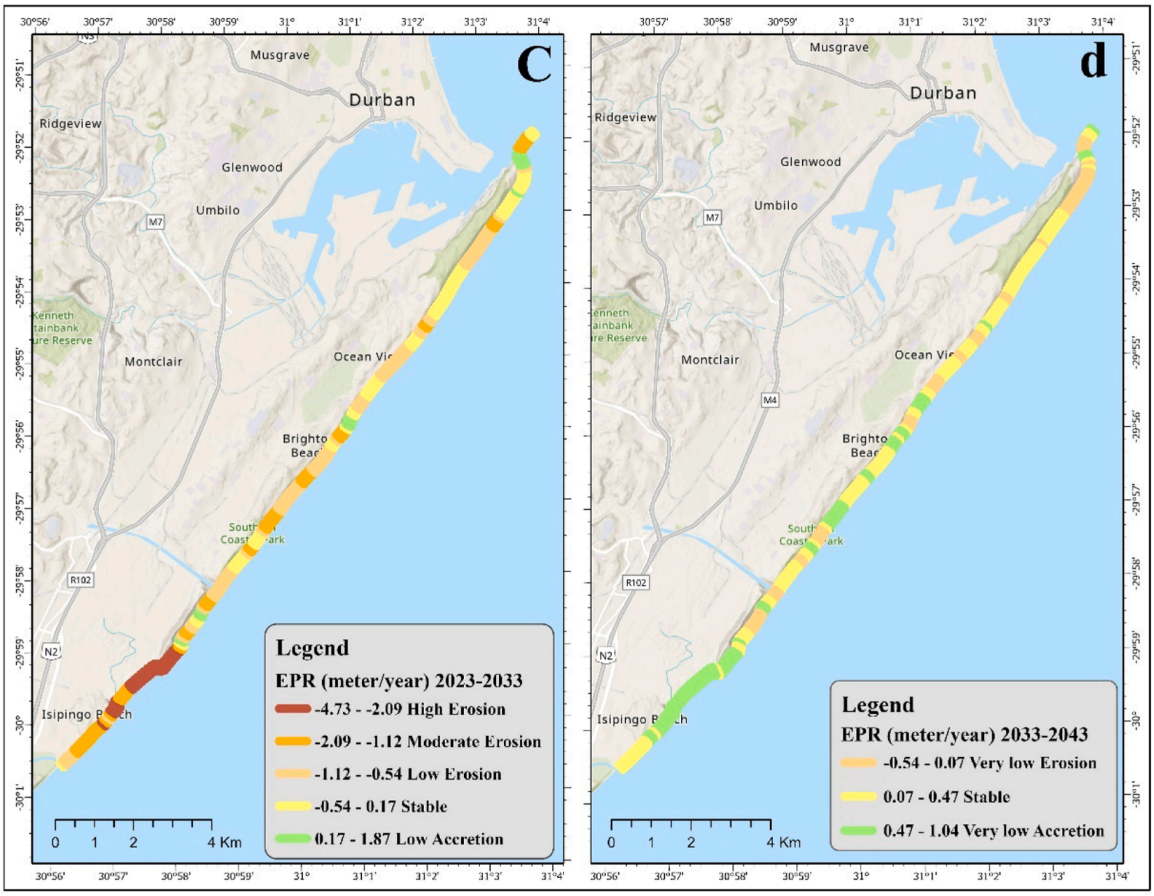

Fig. 8. Predicted Shoreline change based on End Point Rate 2023–2033 (short term) (a) and 2033–2043 (Long term) (b) of Durban South.

Table 3
NSM shoreline change statistics.

Statistics	Durban North	Durban South
Total number of transects	208	207
Average distance (m)	2.49	−7.42
Number of transects with negative distance	122	149
Percent of all transects that have a negative distance (%)	53.85	71.9
Maximum negative distance (m)	−67.21	−39.54
Average of all negative distances (m)	−13.98	−12.98
Number of transects with positive distance	96	58
Percent of all transects that have a positive distance (%)	46.15	28.02
Maximum positive distance (m)	133.09	29.58
Average of all positive distances (m)	21.71	6.86

Table 4
EPR shoreline change statistics.

Statistics	Durban North	Durban South
Total number of transects	208	207
Average rate (m/year)	0.09	−0.22
Number of erosional transects	112	149
Percent of all transects that are erosional (%)	53.85	71.98
Percent of all transects that have statistically significant erosion (%)	18.75	29.95
Maximum value erosion (m/year)	−2.05	−1.21
Average of all erosional rates (m/year)	−0.43	−0.4
Number of accretional transects	96	58
Percent of all transects that are accretional (%)	46.15	28.02
Percent of all transects that have statistically significant accretion (%)	24.04	3.38
Maximum value accretion (m/year)	6.03	2.28
Average of all accretional rates (m/year)	0.69	0.23

Table 5
LRR shoreline change statistics.

Statistics	Durban North	Durban South
Total number of transects	208	206
Average rate	−0.01	−0.37
Number of erosional transects	129	171
Percent of all transects that are erosional	62.02 %	83.01 %
Percent of all transects that have statistically significant erosion	0.48 %	0 %
Maximum value erosion	−2.06	−1.61
Average of all erosional rates	−0.59	−0.48
Number of accretional transects	79	35
Percent of all transects that are accretional	37.98 %	16.99 %
Percent of all transects that have statistically significant accretion	0 %	0 %
Maximum value accretion	6.05	0.55
Average of all accretional rates	0.94	0.18

Table 6
EPR shoreline change statistics 2023 – 2033 and 2033 – 2043 for the North and South Durban coastline.

	Durban North		Durban South	
Statistics	2023 – 2033	2033 – 2043	2023 – 2033	2033 – 2043
Total number of transects	201	201	205	205
Average distance (m/year)	−0.18	−0.3	−0.92	0.3
Number of erosional transects	79	138	185	33
Percent of all transects that are erosional (%)	39.3	68.66	90.24	16.1
Percent of all transects that have statistically significant erosion (%)	25.87	8.46	20.98	0
Maximum value erosion (m/year)	−7.06	−2.07	−4.73	−0.54
Average of all erosional rates (m/year)	−1.93	−0.77	−1.06	−0.18
Number of accretional transects	122	63	20	172
Percent of all transects that are accretional (%)	60.7	31.34	9.76	83.9
Percent of all transects that have statistically significant accretion (%)	13.43	2.49	0.49	0
Maximum value accretion (m/year)	2.21	4.46	1.87	1.04
Average of all accretional rates (m/year)	0.96	0.74	0.39	0.39

Accretion trends in durban south

The percentage of accretional transects increases dramatically from 9.76 % to 83.9 %, showing a complete shift from erosion to accretion. Statistically significant accretional transects remain low (0.49 % to 0 %). Maximum accretion remains relatively stable (1.87 m/year to 1.04 m/year) but with increased spatial coverage. The average accretion rate remains constant at 0.39 m/year.

The northern sector shows persistent but weakening erosion, while the south experiences a complete regime shift from erosion to accretion. This aligns with observed sediment transport patterns in Durban Bight, where longshore currents create localized accretion zones [61]. Both regions show reduced erosion intensity as affected areas expand (North) or contract (South), suggesting system-wide adjustments in sediment distribution. The decline in statistically significant erosion/accretion percentages (e.g., Durban North's significant erosion dropping from 25.87 % to 8.46 %) implies gradual stabilization, consistent with predictive models for managed shorelines [61,62].

In comparing the results from the two zones within the short and long term, Durban North experiences worsening erosion in the long term, with a higher percentage of erosional transects but decreasing maximum and average erosion rates. Durban South transitions from an erosional to an accretional environment over time, showing a dramatic decline in erosional transects and increased accretion. Erosion intensity is higher in the short term for both regions, but the long-term trend differs, worsening in Durban North and improving in Durban South. Accretion in Durban North becomes less widespread but more intense in localized areas, while Durban South shifts from erosion to dominance of accretion.

Discussion

The shoreline, the physical interface between land and sea, continuously changes its position in response to sediment transport, climate change effects, and variations in sea level, the tidal cycle, and human activity. These factors have contributed to significant coastal accretion and erosion patterns over time [2,15]. However, their impact on the Durban shoreline between 1990–2023 and their future implications for 2023–2043 remains unclear. The present study contributes to mapping Durban shoreline change based on NSM, EPR, and LRR statistics to improve the coastline management approach.

Analysis of the shoreline change along the Durban coastlines revealed significant spatial variability in erosion and accretion rates over the study period. The results show that the northern coastline predominantly experiences localized accretion, whereas the southern coastline is undergoing more erosion. The higher percentage of negative distances in Durban South (71.9 %) compared to Durban North (53.85 %) highlights the greater vulnerability of the southern coastline to erosion. Additionally, the average negative distances in both regions suggest notable losses in the shoreline area, with the southern coastline showing a more consistent erosional trend across a more significant proportion of the transects, particularly around Stanvac, Amanzimtoti, and Isipingo Beach area (Fig. 2d-g). The higher erosion rate on the southern coastline can be attributed to increased wave energy and sediment depletion caused by anthropogenic activities such as harbour development and sand mining. These findings are consistent with the works of Leuci et al. [26], who identified erosion hotspots along urbanized coastlines. However, our results differed in identifying significant accretion trends in the northern section, which may reflect localized sediment management practices not considered in earlier studies [63]. Daud et al. [22], found that sand mining was responsible for high rates of erosion along the Selangor coast of Malaysia, the Moroccan Kenitra coast [21], and along the Gulf of California in the United States [24].

Conversely, the accretion observed in the northern segment, especially around the Durban Beach and Point waterfront segments, could have resulted from sediment deposition facilitated by longshore drift and the Umgeni River deposits. However, the presence of hard engineering structures such as Breakwaters, Groynes, and seawalls in the northern segment accounts for the low erosion rate in this area compared to the Durban South. These results are validated by Hossain et al. [2], who found that engineering structures like Groynes and seawalls contributed significantly to stabilizing the Purba coastline in India. While these structures provide significant protection, they can also have negative impacts, including disrupting sediment transport, the need for regular maintenance, and worsening erosion in the adjacent southern segments of the Durban coast. Recent trends in coastal management emphasize the importance of integrating hard and soft engineering solutions [15,64]. For instance, using geotextile sand-filled containers combines soft engineering principles with structural support, providing a flexible and effective defense against erosion while minimizing environmental impact [65]. Inadequate coastline management, particularly for areas affected by erosion, was found to increase the risk of coastal hazards such as flooding, environmental degradation, and loss of valuable land for human settlements along the Digha Coast of India [15,66]. Furthermore, frequent cyclonic activities, such as cut-off low along Durban's southeast coast, contributed significantly to shoreline erosion [31]. In this light, such a study is critical to prepare the Durban coastal communities for the impacts of climate change. However, the contrasting patterns of shoreline change between the two coastlines emphasize the need for tailored coastal management strategies that address each of these coastal segments' specific erosion and accretion dynamics.

Shoreline changes along the Durban coastline have significant future implications for coastal communities, particularly in light of ongoing climate change and development pressures. Rising sea levels are expected to reduce the surface area of beaches, which could adversely affect local tourism, a crucial economic driver for the region. As beaches shrink, the infrastructure supporting tourism may also be compromised, leading to economic losses and reduced recreational opportunities for residents and visitors alike [62,67].

The dynamics of erosion and accretion can lead to increased vulnerability to risks associated with the coast, like storm surges and flooding. Communities in areas experiencing significant erosion may face greater risks, necessitating urgent measures for disaster preparedness and response [31,68]. The construction of new ports and other developments could alter sediment dynamics, potentially exacerbating erosion in certain areas. This necessitates careful planning and management to protect the existing infrastructure while accommodating new developments [61,68]. Coastal ecosystems, such as beaches and dunes, play a crucial role in protecting coastlines by providing habitats for wildlife and mitigating the impact of storms. Alterations in shoreline dynamics may disrupt these ecosystems, affecting biodiversity and their services to local communities [69].

The findings of this study underscore the importance of adopting an integrated approach to coastal management. This includes implementing setback lines for new developments, enhancing natural buffers, and considering hard and soft engineering solutions to mitigate the impacts of shoreline change [68,69]. The implications of shoreline change for Durban coastal communities are multi-faceted and affect economic, environmental, and social dimensions. Thus, proactive management and adaptation strategies will be essential to address these challenges and protect the livelihoods and well-being of coastal residents.

Conclusion

The analysis of Net Shoreline Movement (NSM), Endpoint Rate (EPR), and Linear Regression Rate (LRR) for Durban North and Durban South reveals significant spatial and temporal variations in shoreline dynamics, which are shaped by both natural processes and human activities. Durban North exhibits a relatively balanced interplay between erosion and accretion, with moderate overall shoreline advancement and occasional significant accretion events. Despite localized erosion hotspots, accretional processes, including higher maximum and average positive distances, contribute to a relatively stable coastline. This stability may result from effective coastal management strategies, such as constructing protective structures. However, the region is not immune to erosion risks, particularly in areas with statistically significant shoreline retreats. In contrast, Durban South faces a pronounced net erosional trend, with widespread and consistent shoreline retreat evident in the higher percentage of eroding transects. The prevalence of erosion and the limited extent of accretion suggest that Durban South is more vulnerable to coastal instability. Factors such as reduced sediment supply, higher wave energy, and human-induced pressures exacerbate the challenges in this region. The projection of future shoreline dynamics (2023–2033 and 2033–2043) based on EPR further underscores the contrasting trends. These findings have critical implications for coastal management. Durban North requires targeted erosion control measures and monitoring to maintain its relatively stable coastline. Strategies such as beach nourishment and ecosystem restoration could enhance resilience. Durban South, however, demands urgent interventions to address widespread erosion, protect coastal habitats, and safeguard infrastructure. Implementing adaptive management plans that consider localized dynamics, climate change impacts, and the socio-economic significance of these coastlines will be essential for long-term sustainability.

CRediT authorship contribution statement

Zachariah H. Mshelia: Conceptualization, Methodology, Formal analysis, Writing – original draft. **Ekang C. Amatebelle:** Resources, Data curation, Writing – original draft. **Johanes A. Belle:** Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

[1] S. Subbarayan, D. Abijith, Shoreline change detection using geo-spatial techniques- A case study for Cuddalore Coast, Journal of Geography and environmental science 3 (5) (2018) 15–34.

[2] S.A. Hossain, I. Mondal, S. Thakur, N.T.T. Linh, D.T. Anh, Assessing the multi-decadal shoreline dynamics along the Purba Medinipur-Balasore coastal stretch, India by integrating remote sensing and statistical methods, Acta Geophysica 70 (4) (2022) 1701–1715, https://doi.org/10.1007/s11600-022-00797-5.

[3] M.A. Dereli, E. Tercan, Assessment of shoreline changes using historical satellite images and geospatial analysis along the lake salda in turkey, Earth Sci Inform 13 (3) (2020) 709–718, https://doi.org/10.1007/s12145-020-00460-x.

[4] D. Dutta, T. Kumar, C. Jayaram, W. Akram, Shoreline change analysis of hooghly estuary using multi-temporal landsat data and digital shoreline analysis system, in: Y. Zhang, Q. Cheng (Eds.), Geographic Information Systems and Applications in Coastal Studies, IntechOpen, 2022, https://doi.org/10.5772/intechopen.103030.

[5] A. Nath, B. Koley, S. Saraswati, T. Choudhury, J.-S. Um, B.C. Ray, Geospatial analysis of short-term shoreline change behavior between Subarnarekha and Rasulpur estuary, east coast of India using intelligent techniques (Dsas), GeoJournal 88 (S1) (2022) 255–275, https://doi.org/10.1007/s10708-022-10683-8.

[6] C. Goksel, G. Senel, A.O. Dogru, Determination of shoreline change along the Black Sea coast of Istanbul using remote sensing and GIS technology, Desalination Water Treat 177 (2020) 242–247, https://doi.org/10.5004/dwt.2020.24975.

[7] S. Kermani, M. Boutiba, M. Guendouz, M.S. Guettouche, D. Khelfani, Detection and analysis of shoreline changes using geospatial tools and automatic computation: case of jijelian sandy coast (East algeria), Ocean Coast Manag 132 (2016) 46–58, https://doi.org/10.1016/j.ocecoaman.2016.08.010.

[8] L.C. Allison, M.D. Palmer, I.D. Haigh, Projections of 21st century sea level rise for the coast of South Africa, Environmental Research Communications 4 (2) (2022) 025001, https://doi.org/10.1088/2515-7620/ac4a90.

[9] A. Emran, Md.A. Rob, Md.H. Kabir, Coastline change and erosion-accretion evolution of the sandwip island, bangladesh, International Journal of Applied Geospatial Research 8 (2) (2017) 33–44, https://doi.org/10.4018/IJAGR.2017040103.

[10] K. Appeaning Addo, Shoreline morphological changes and the human factor. Case study of Accra Ghana, Journal of Coastal Conservation 17 (1) (2013) 85–91, https://doi.org/10.1007/s11852-012-0220-5.

[11] J.F. Ekow, Coastal Erosion In Ghana: A Case Of The Elmina-Cape Coast-Moree Area (2015). PhD thesis, https://ir.knust.edu.gh/handle/123456789/6882.

[12] I. Mondal, S. Thakur, A. De, J. Bandyopadhyay, T.K. De, Estimating water quality of sundarban coastal zone area using landsat series satellite data, Springer River Health and Ecology in South Asia (2022) 155–176, https://doi.org/10.1007/978-3-030-83553-8_8.

[13] K.K. Basheer Ahammed, A.C. Pandey, Assessment and prediction of shoreline change using multi-temporal satellite data and geostatistics: a case study on the eastern coast of India, Journal of Water and Climate Change 13 (3) (2022) 1477–1493, https://doi.org/10.2166/wcc.2022.270.

[14] N. Bushra, R.B. Mostafiz, R.V. Rohli, C.J. Friedland, M.A. Rahim, Technical and social approaches to study shoreline change of kuakata, bangladesh, Front Mar Sci 8 (2021) 730984, https://doi.org/10.3389/fmars.2021.730984.

[15] L. Natarajan, N. Sivagnanam, T. Usha, L. Chokkalingam, S. Sundar, M. Gowrappan, P.D. Roy, Shoreline changes over last five decades and predictions for 2030 and 2040: a case study from Cuddalore, southeast coast of India, Earth Sci Inform 14 (3) (2021) 1315–1325, https://doi.org/10.1007/s12145-021-00668-5.

[16] O.O. Popoola, Spatio-temporal assessment of shoreline changes and management of the transgressive mud coast, nigeria, European Scientific Journal 18 (20) (2022) 99, https://doi.org/10.19044/esj.2022.v18n20p99. *ESJ*.

[17] N. Matin, G.M.J. Hasan, A quantitative analysis of shoreline changes along the coast of Bangladesh using remote sensing and GIS techniques, CATENA 201 (2021) 105185, https://doi.org/10.1016/j.catena.2021.105185.

[18] H.F. Abd-Elhamid, M. Zeleňáková, J. Barańczuk, M.B. Gergelova, M. Mahdy, Historical trend analysis and forecasting of shoreline change at the nile delta using rs data and gis with the dsas tool, Remote Sens (Basel) 15 (7) (2023) 1737, https://doi.org/10.3390/rs15071737.

[19] I.B. Isha, M.R.M. Adib, Application of geospatial information system (Gis) using digital shoreline analysis system (Dsas) in determining shoreline changes, IOP Conference Series: Earth and Environmental Science 616 (1) (2020) 012029, https://doi.org/10.1088/1755-1315/616/1/012029.

[20] M.R.I. Baig, I.A. Ahmad, M. Shahfahad Tayyab, A. Rahman, Analysis of shoreline changes in Vishakhapatnam coastal tract of Andhra Pradesh, India: an application of digital shoreline analysis system (DSAS), Ann GIS 26 (4) (2020) 361–376.

[21] M. Hakkou, M. Maanan, T. Belrhaba, D. El Ouai, A. Benmohammadi, Multi-decadal assessment of shoreline changes using geospatial tools and automatic computation in Kenitra coast, Morocco, Ocean Coast Manag 163 (2018) 232–239.

[22] S. Daud, P. Milow, R.M. Zakaria, Analysis of shoreline change trends and adaptation of Selangor Coastline, Using Landsat Satellite Data, J Indian Soc Remote Sens 49 (2021) 1869–1878.

[23] A. Masria, K. Nassar, M.G. Eltarabily, Assessment of North Sinai shoreline Morphodynamics using geospatial tools and DSAS technique. In *Geographic information systems and applications in coastal studies*, IntechOpen (2022).

[24] Y.G. Zambrano-Medina, W. Plata-Rocha, S.A. Monjardin-Armenta, C. Franco-Ochoa, Assessment and forecast of shoreline change using geo-spatial techniques in the gulf of california, Land (Basel) 12 (4) (2023) 782, https://doi.org/10.3390/land12040782.

[25] H.C. Cawthra, F.H. Neumann, R. Uken, A.M. Smith, L.A. Guastella, A. Yates, Sedimentation on the narrow (8 km wide), oceanic current-influenced continental shelf off Durban, Kwazulu-Natal, South Africa, Mar. Geol. 323–325 (2012) 107–122, https://doi.org/10.1016/j.margeo.2012.08.001.

[26] R. Leuci, E. Wiles, Z. Thackeray, G. Vella, Trends in sandy beach variability ethekwini municipality, south africa, J. Sea Res. 179 (2022) 102149, https://doi.org/10.1016/j.seares.2021.102149.

[27] J.A.G. Cooper, A.N. Green, Southern African sandy coasts in the context of near-future sea-level rise, Transactions of the Royal Society of South Africa 78 (3) (2023) 149–166, https://doi.org/10.1080/0035919X.2023.2272829.

[28] H. Burningham, J. French, Understanding coastal change using shoreline trend analysis supported by cluster-based segmentation, Geomorphology 282 (2017) 131–149, https://doi.org/10.1016/j.geomorph.2016.12.029.

[29] S. Maiti, A.K. Bhattacharya, Shoreline change analysis and its application to prediction: a remote sensing and statistics based approach, Mar. Geol. 257 (1–4) (2009) 11–23, https://doi.org/10.1016/j.margeo.2008.10.006.

[30] *NOAA*, Sea Level Trends—Noaa Tides & Currents, 2024 n.d.Retrieved from, https://tidesandcurrents.noaa.gov/sltrends/sltrends_station.shtml?id=430-091 [Accessed 25/01/24].

[31] F.M. Mashao, M.C. Mothapo, R.B. Munyai, J.M. Letsoalo, I.L. Mbokodo, T.P. Muofhe, W. Matsane, H. Chikoore, Extreme rainfall and flood risk prediction over the east coast of south africa, Water (Basel) 15 (1) (2022) 50, https://doi.org/10.3390/w15010050.

[32] South African Weather Service. (2023). Annual State of the climate of South Africa. Pretoria. South Africa.

[33] B.J. Palmer, R. Van der Elst, F. Mackay, A.A. Mather, A.M. Smith, S.C. Bundy, Z. Thackeray, R. Leuci, O. Parak, Preliminary coastal vulnerability assessment for kwazulu-natal, south africa, Journal of Coastal Research (2011) 1390–1395. https://www.jstor.org/stable/26482403.

[34] A. Smith, L.A. Guastella, A.A. Mather, S.C. Bundy, I.D. Haigh, KwaZulu-Natal coastal erosion events of 2006/2007 and 2011: a predictive tool? S. Afr. J. Sci. 109 (3) (2013) 1–4, https://doi.org/10.1590/sajs.2013/20120025.

[35] Wiebe de Boer, Yongjing Mao, Gerben Hagenaars, Sierd de Vries, Jill Slinger, Tiedo Vellinga, Mapping the Sandy Beach evolution around seaports at the scale of the African continent, J Mar Sci Eng 7 (5) (2019) 151, https://doi.org/10.3390/jmse7050151.

[36] K. Thieler, M.K. Tivey, Woods Hole Oceanographic Institution (WHOI) 2020 Summer Student Fellowship Remote Program: challenges and successes, in: AGU Fall Meeting Abstracts 2020, 2020, pp. ED035–E0008.

[37] S.S. Akay, O. Özcan, F.B. Şanlı, Quantification and visualization of flood-induced morphological changes in meander structures by UAV-based monitoring, Eng Sci Technol Int J 27 (2022) 101016.

[38] A. M.-Muslim, G.M. Foody, P.M Atkinson, Shoreline mapping from coarse–spatial resolution remote sensing imagery of Seberang Takir, Malaysia, Journal of Coastal Research 23 (6) (2007) 1399–1408.

[39] M. Esmail, W. Mahmod, H. Fath, Influence of coastal measures on shoreline kinematics along Damietta coast using geospatial tools, in: IOP Conference Series: Earth and Environmental Science 151, IOP Publishing, 2018 012027.

[40] M. Mishra, T. Acharyya, P. Chand, C.A.G. Santos, D. Kar, P.P. Das, T.V.M.D. Nascimento, Analyzing shoreline dynamicity and the associated socioecological risk along the Southern Odisha Coast of India using remote sensing-based and statistical approaches, Geocarto Int 37 (14) (2022) 3991–4027.

[41] A. Jutla, A.S. Akanda, A. Huq, A.S.G. Faruque, R. Colwell, S. Islam, A water marker monitored by satellites to predict seasonal endemic cholera, Remote Sens Lett 4 (8) (2013) 822–831, https://doi.org/10.1080/2150704X.2013.802097.

[42] C. Xu, J.J. Qu, X. Hao, M.H. Cosh, J.H. Prueger, Z. Zhu, L. Gutenberg, Downscaling of surface soil moisture retrieval by combining MODIS/Landsat and in situ measurements, Remote Sens 10 (2) (2018) 210.

[43] R. Dolan, M.S. Fenster, S.J. Holme, Temporal analysis of shoreline recession and accretion, J Coast Res 7 (3) (1991) 723–744.

[44] L.J. Moore, Shoreline mapping techniques, Journal of coastal research (2000) 111–124.

[45] R. Aedla, G.S. Dwarakish, D.V. Reddy, Automatic shoreline detection and change detection analysis of netravati-gurpurrivermouth using histogram equalization and adaptive thresholding techniques, Aquatic Procedia 4 (2015) 563–570.

[46] K. Nassar, W.E. Mahmod, H. Fath, A. Masria, K. Nadaoka, A. Negm, Shoreline change detection using DSAS technique: case of North Sinai coast, Egypt. Marine Georesources & Geotechnology 37 (1) (2019) 81–95.

[47] J.H. Ryu, J.S. Won, K.D. Min, Waterline extraction from Landsat TM data in a tidal flat: a case study in Gomso Bay, Korea. Remote sensing of Environment 83 (3) (2002) 442–456.

[48] Y. Tarabalka, J. Chanussot, J.A. Benediktsson, Segmentation and classification of hyperspectral images using minimum spanning forest grown from automatically selected markers, IEEE Transactions on Systems, Man, and Cybernetics, Part B (Cybernetics) 40 (5) (2009) 1267–1279.

[49] P. Godwyn-Paulson, M.P. Jonathan, P.D. Roy, P.F. Rodríguez-Espinosa, G. Muthusankar, N.P. Muñoz-Sevilla, C. Lakshumanan, Evolution of southern Mexican Pacific coastline: responses to meteo-oceanographic and physiographic conditions, Regional Studies in Marine Science 47 (2021) 101914.

[50] T.W.S. Warnasuriya, M.P. Kumara, S.S. Gunasekara, K. Gunaalan, R.M.R.M. Jayathilaka, An improved method to detect shoreline changes in small-scale beaches using Google Earth Pro, Marine Geodesy 43 (6) (2020) 541–572.

[51] J.A. Pollard, S.M. Brooks, T. Spencer, Harmonising topographic & remotely sensed datasets, a reference dataset for shoreline and beach change analysis, Sci Data 6 (1) (2019) 42.

[52] E.H. Boak, I.L. Turner, Shoreline definition and detection: a review, Journal of coastal research 21 (4) (2005) 688–703.

[53] P. Wernette, A. Shortridge, D.P. Lusch, A.F. Arbogast, Accounting for positional uncertainty in historical shoreline change analysis without ground reference information, Int J Remote Sens 38 (13) (2017) 3906–3922.

[54] R.S. Kankara, S.C. Selvan, V.J. Markose, B. Rajan, S. Arockiaraj, Estimation of long and short term shoreline changes along Andhra Pradesh coast using remote sensing and GIS techniques, Proc Eng 116 (2015) 855–862.

[55] R.A. Morton, T. Miller, L. Moore, Historical shoreline changes along the US Gulf of Mexico: a summary of recent shoreline comparisons and analyses, J Coast Res 21 (4) (2005) 704–709.

[56] A. Jana, S. Maiti, A. Biswas, Seasonal change monitoring and mapping of coastal vegetation types along Midnapur-Balasore Coast, Bay of Bengal using multi-temporal landsat data, Modeling Earth Systems and Environment 2 (2016) 1–12.

[57] S. Nayak, Coastal zone management in India− present status and future needs, Geo-spatial information science 20 (2) (2017) 174–183.

[58] M.A. Davidson, R.P. Lewis, I.L. Turner, Forecasting seasonal to multi-year shoreline change, Coastal Engineering 57 (6) (2010) 620–629.

[59] M.S. Fenster, R. Dolan, Historical shoreline trends along the Outer Banks, North Carolina: processes and responses, Journal of Coastal Research (1993) 172–188.

[60] C. Dilara, T. Tarik, Automatic detection of shoreline change by Geographical Information System (GIS) and remote sensing in the Gӧksu Delta Turkey, J Indian Soc Remote Sens (2019), https://doi.org/10.1007/s12524-019-00947-1.

[61] C. Rautenbach, A.K. Theron, Study of the Durban Bight shoreline evolution under schematised climate change and sand-bypassing scenarios, J. S. Afr. Inst. Civ. Eng. 60 (4) (2018) 2018, https://doi.org/10.17159/2309-8775/2018/v60n4a1, nMidrand Dec.

[62] J. Murray, E. Adam, S. Woodborne, D. Miller, S. Xulu, M. Evans, Monitoring shoreline changes along the Southwestern Coast of South Africa from 1937 to 2020 using varied remote sensing data and approaches, Remote Sens. 15 (2023) 317, https://doi.org/10.3390/rs15020317.

[63] H.G. Smith, R. Spiekermann, J. Dymond, L. Basher, Predicting spatial patterns in riverbank erosion for catchment sediment budgets, N Z J Mar Freshw Res 53 (3) (2019) 338–362.

[64] Murty, M.R., Kumar, C.R., Srinivasu, K., Kannan, R., & Sundar, B. Monitoring of coastal geo-environment for hazard mitigation: a case study of Machilipatnam Region, Andhra Pradesh, India.

[65] Corbella, S. and Stretch, D.D. (2012) Coastal defences on the KwaZulu-Natal coast of South Africa: a review with particular reference to geotextiles. On-line version ISSN 2309-8775.

[66] A. Jana, A. Biswas, S. Maiti, A.K. Bhattacharya, Shoreline changes in response to sea level rise along Digha Coast, Eastern India: an analytical approach of remote sensing, GIS and statistical techniques, Journal of Coastal Conservation 18 (3) (2014) 145–155, https://doi.org/10.1007/s11852-013-0297-5.

[67] A.A. Mather, Linear and nonlinear sea-level changes at Durban, South Africa, S. Afr. j. sci. 103 (2007) 11–12, nPretoriaOn-line version ISSN 1996-7489.

[68] A. Mather Andrew, Derek D. Stretch, A perspective on sea level rise and coastal storm surge from Southern and Eastern Africa: a case study near Durban, South Africa, Water (Basel) 4 (1) (2012) 237–259, https://doi.org/10.3390/w4010237.

[69] J.G. Bronwyn, Rudy van der Elst, Trends in coastal development and land cover change: the case of KwaZulu-Natal, South Africa Western Indian Ocean J. Mar. Sci. Vol. 11 (2) (2012) 193–204.