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Shoreline Change Analysis Along The Thoothukudi District Coast, Tamil Nadu, India Using Remote Sensing, GIS And Digital Shoreline Analysis System (DSAS)

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ABSTRACT
Shoreline change analysis is one of the most crucial components in determining coastal erosion and accretion, as well as in studying coastal morphodynamics. Coastal zones are becoming more vulnerable to coastal devastation as a result of coastal erosion and accretion. The sensitivity of research on shoreline monitoring is justified due to high population density, climate change impacts, and intensified development, all of which are squeezing the ecosystem of coastal zones worldwide. The emerging fields of optical remote sensing, such as source medium and high-resolution satellite imagery combined with avenue programming of Digital Shoreline Analysis System (DSAS) are widely used extended tools for analysing the rate of coastal erosion and deposition. The study has been conducted along the coast of the Thoothukudi district to evaluate two decadal changes with the help of multi-temporal satellite images of 2000, 2010 and 2021. The erosion and accretion rates have been calculated using the Digital Shoreline Analysis System (DSAS V 5.0). The rates of shoreline changes are automatically quantified by using statistical parameters like Linear Regression Rate (LRR), End Point Rate (EPR), and Net Shoreline Movement (NSM) methods. A total of 163 km of shoreline ranked as erosion, accretion and no change zones. About 41.44 km of coastline was found to be accreting with an average of +1.9 m/yr followed by 70.56 km of coastline eroding with an average of -3 m/yr and a stable coastline of 51 km was found. This study demonstrates that the combined use of satellite imagery and statistical methods is beneficial for erosion monitoring and preventive measures. It is also useful in facilitating an in-depth analysis of the temporal and historical movement of shoreline positions.

Keywords: Shoreline change, Coastal erosion and accretion, Digital Shoreline Analysis System (DSAS), Remote sensing and GIS.

INTRODUCTION
Shorelines are the interface between land and sea, which change erratically in response to morphological, climatic or geological factors (Hunt et al. 2023). As a borderline between land and sea, shorelines are subjected to continuous change due to their dynamic environmental setting (Woodroffe et al. 2023). Sediment movement in the littoral zone, both along and across the coast, as well as changes in water level causes shoreline position shifts with time. Shoreline features depend on the interactions among waves, tides, rivers, storms, tectonic and physical processes (Das 2022). Today coastal zones have become the habitation of a large fraction of the world's population, with over 60% geographically located within 100 km of coastal areas (Mikhaylov & Plotnikova 2021). These zones are continuously subjected to both natural and anthropogenic forcing factors such as sea-level rise, shoreline changes, river runoff, coastal bathymetry and land use modifications (Sahavacharin et al. 2022). For coastal zone monitoring, shoreline change mapping is a fundamental requirement and it is necessary to study the spatio-temporal analysis of shoreline changes in the context of global climate change and sea level rise (Adebisi et al. 2021; Komolafe et al. 2021; Ankrah, Monteiro & Madureira 2022; Boussetta et al. 2022).
Numerous researchers have employed the Digital Shoreline Analysis System (DSAS) extension by Environmental System Research Institute (ESRI) ArcGIS, to measure, quantify, compute and monitor coastline rate-of-change statistics from various historic shoreline positions (Himmelstoss et al. 2021). DSAS is designed to compute shoreline change and provide rate-of-change data and mathematical information needed to ensure the consistency of computed results (Abd-Elhamid et al. 2023). It has three main components that define a baseline, generate orthogonal transects showing separation along the

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coast and compute rates of change using different statistical methods including linear regression rate, endpoint rate and net shoreline movement. Statistical change metrics available in DSAS include Shoreline Change Envelope (SCE), End Point Rate (EPR), Net Shoreline Movement (NSM), Linear Regression Rate (LRR) and Weighted Linear Regression Rate (WLR) based on the evaluation of shoreline positions over time (Ledheng & Hano'e 2023). The DSAS derivation of past rate of change trends as an indicator of future trends has been used to forecast patterns of shoreline behaviour, assuming continuity in the physical, natural or anthropogenic forces driving historical change.
From the coastal vulnerability perspective, areas subjected to accretion are considered less vulnerable as they move toward the water with addition of land areas, whereas coastal erosion zones are considered most vulnerable because of loss of public and individual properties, also reducing the distance between coastal inhabitation and the ocean Hastuti et al. 2022. Along most shorelines across the world, beach erosion and accretion as well as shifting shorelines and sea level rise have been chronic concerns for millennia (Adebisi et al. 2021; Ankrah et al. 2022). The present study deals with shoreline changes along the Thoothukudi district coast using remote sensing and GIS techniques for the years 2000, 2010 and 2021.This study aims to identify zones of erosion, accretion and stability, thereby providing baseline information for coastal zone management and planning.

MATERIALS AND METHODS

Study Area

The study area is the coastal stretch of Thoothukudi district, Tamil Nadu, India, falling within latitudes 8°19'N and 9°20'N and longitudes 77°40'E and 78°10'E. Thoothukudi is a port city on the Gulf of Mannar, approximately 125 km north of Cape Comorin. It is bounded on the north by Virudhunagar and Ramanathapuram districts, in the east by the Bay of Bengal and by Tirunelveli district in the west and southwest. The total geographical area covers 4590 sq. km, administratively divided into 8 taluks, 12 blocks and 41 firkas. The coastline extends from Vembar in the north to the south of Manapad, approximately covering 163 km. The district population is estimated at 1849365. The Thamirabarani river originating from the Western Ghats controls the drainage network of the district, while Vaippar, Nambiyar and Karamanaiyar are other major rivers draining the district. All rivers are ephemeral with runoff generated only during heavy rainfall periods. The district's average yearly temperature is 30.28°C at an elevation of 4.22 metres above sea level. The region has a well-developed litho package of metasedimentary rocks inter-banded with the Charnockite group. Estuaries, mudflats, beaches and woodlands form part of the Gulf of Mannar Marine National Park area, which supports numerous noteworthy species including coral reefs, seagrass beds, seaweed, salt marshes and mangroves (Fig. 1).

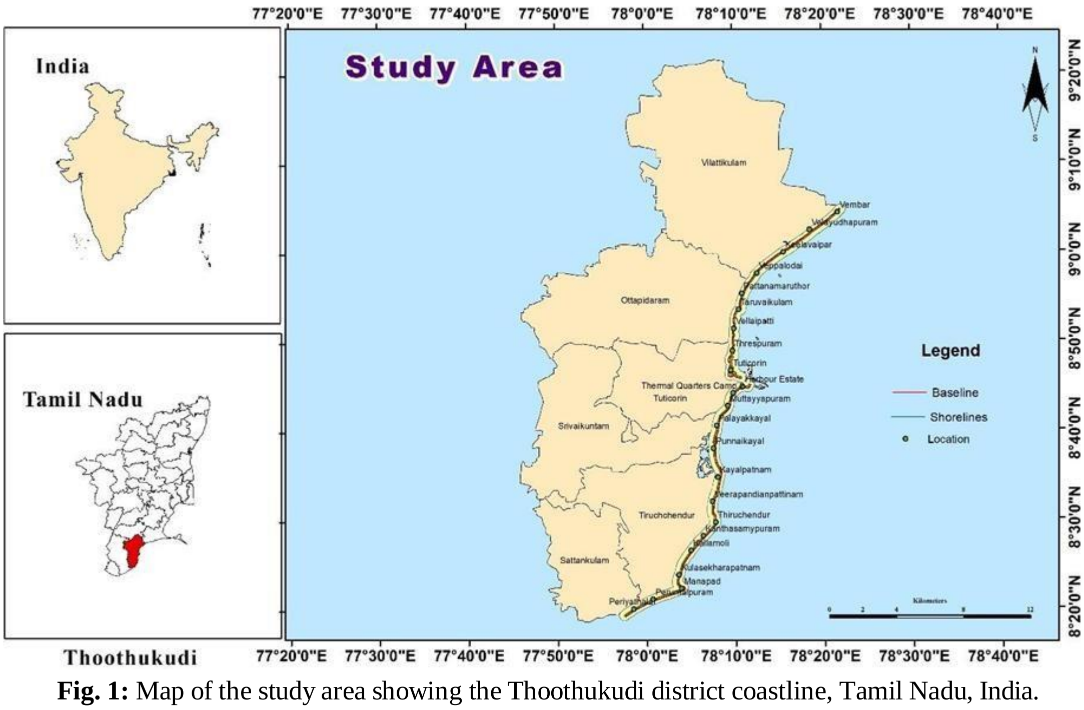

Fig. 1: Map of the study area showing the Thoothukudi district coastline, Tamil Nadu, India.

Data Source and Processing

Shoreline change rate determination was carried out using multi-resolution and multi-temporal satellite data of Landsat 8. All downloaded satellite images were in UTM projection with zone 43N and WGS 1984 datum. These datasets acquired on cloud-free days over the chosen period (2000 to 2021) were digitized manually at 1:50,000 scale using ArcMap 10.8. The shorelines were extracted from satellite imagery based on the land-water boundary delineation using band combination techniques and visual interpretation methods.

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Digital Shoreline Analysis System (DSAS)
The United States Geological Survey developed the GIS-based Digital Shoreline Analysis System (DSAS) (Thieler et al. 2009). DSAS records the distances between coastline sites over specific time intervals, providing fundamental information for computing shoreline changes. The system controls coastline characteristics including historical coastline dynamics, shoreline change, cliff retreat and erosion, shoreline measurement and modelling. A total of 1126 transects were positioned perpendicular to the shore at an interval of 100 m along the entire shoreline from the baseline with a smoothing distance of 2500 m using the cast transects tool in DSAS. The erosion and accretion rates were grouped into three categories: Erosion (< −1 m/yr), Stable (−1 to +1 m/yr) and Accretion (> +1 m/yr) (Thieler & Hammar-Klose 2000).

Shoreline Change Analysis Using Statistical Methods
Three statistical parameters were employed for quantifying shoreline change rates: Linear Regression Rate (LRR), Net Shoreline Movement (NSM) and End Point Rate (EPR).

Linear Regression Rate (LRR): A linear regression rate-of-change statistic is determined by fitting a least-squares regression line to all shoreline points for a transect (Thieler et al. 2009). The linear regression rate is the slope of the fitted line:

$$L = b + mx \quad (1)$$

where L is the dependent variable representing the shoreline's geographic location (distance from baseline in metres), x is the independent variable of time (year), m is the slope representing the rate of shoreline change (LRR, in m/yr) and b is the y-intercept. The slope is solved by minimizing the sum of squared residuals:

$$m = [n\sum(x_i y_i) - \sum x_i \sum y_i] / [n\sum(x_i^2) - (\sum x_i)^2] \quad (2)$$

where n is the number of shoreline dates, x_i are the time values and y_i are the corresponding shoreline positions. The coefficient of determination (R^2) quantifies the goodness of fit:

$$R^2 = 1 - [\sum(y_i - \hat{y}_i)^2 / \sum(y_i - \bar{y})^2] \quad (3)$$

where $\hat{y}_i$ are the predicted values and $\bar{y}$ is the mean of observed shoreline positions. LRR is considered the most statistically robust metric as it uses all available data points (Himmelstoss et al. 2018).

Net Shoreline Movement (NSM): NSM enumerates the actual distance between the oldest and youngest shoreline for each transect (Himmelstoss et al. 2021):

$$NSM = d(t_2) - d(t_1) \quad (4)$$

where $d(t_2)$ is the shoreline position at the most recent date (2021) and $d(t_1)$ is the shoreline position at the oldest date (2000). Positive NSM values indicate accretion (seaward movement) and negative values indicate erosion (landward retreat). Its unit is in metres.

End Point Rate (EPR): EPR is calculated by dividing the NSM by the time elapsed between the oldest and most recent shoreline (Himmelstoss et al. 2021):

$$EPR = [d(t_2) - d(t_1)] / [t_2 - t_1] \quad (5)$$

where t_1 and t_2 represent the earliest and latest shoreline dates, respectively, and $d(t_1)$ and $d(t_2)$ are the corresponding shoreline positions. EPR is expressed in m/yr. While computationally simple, EPR only considers two shoreline dates and may not capture intermediate trends.

Shoreline Change Envelope (SCE): SCE represents the total distance of shoreline movement regardless of direction:

$$SCE = d(max) - d(min) \quad (6)$$

where d_{max} and d_{min} are the maximum and minimum shoreline distances from the baseline, respectively. SCE provides a measure of total variability in shoreline position over the study period.

RESULTS
For effective spatial data modelling, the entire 163 km shoreline was divided into two segments: from Vembar to Tuticorin harbour (Segment A) and from Tuticorin harbour to Manapad (Segment B). Segment A was further divided into three sub-zones: Zone 1 (Vembar to Vepalodai), Zone 2 (Vepalodai to Taruvaikulam) and Zone 3 (Taruvaikulam to North Tuticorin harbour). Likewise, Segment B was divided into Zone 1 (Tuticorin harbour to Punnakayal), Zone 2 (Punnakayal to Kallamoli) and Zone 3 (Kallamoli to Manapad). Positive and negative values of LRR, NSM and EPR indicate accretion and erosion, respectively.

Linear Regression Rate (LRR) Analysis
The LRR results for both segments are presented in Figs. 2 and 3. The LRR method uses all available shoreline positions to compute a best-fit regression line, providing the most statistically robust assessment of long-term shoreline change trends.

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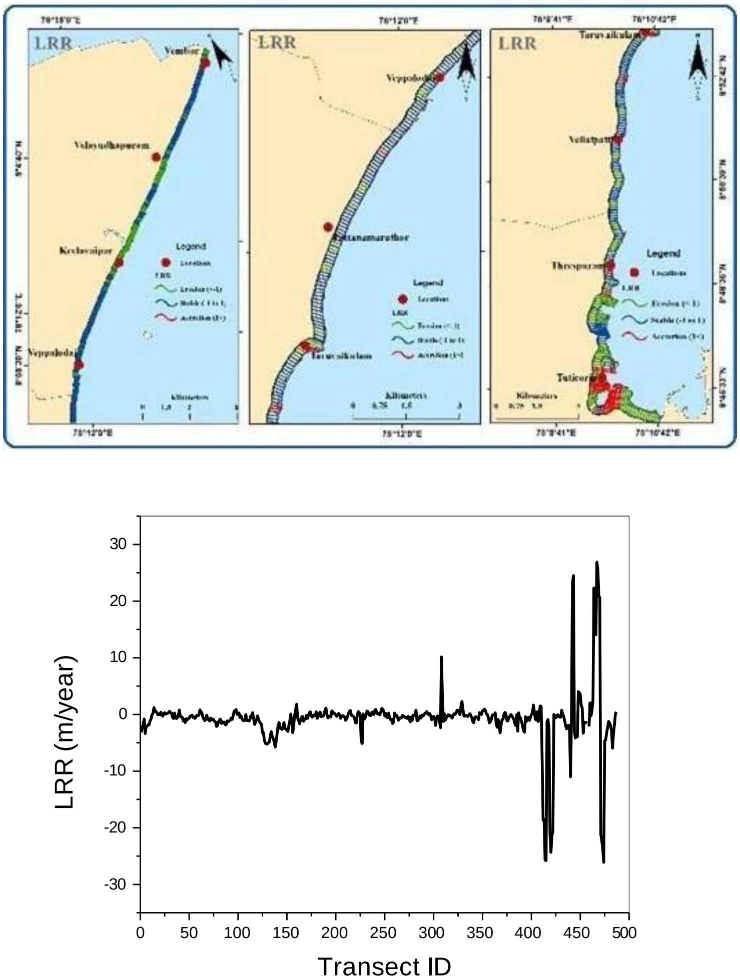
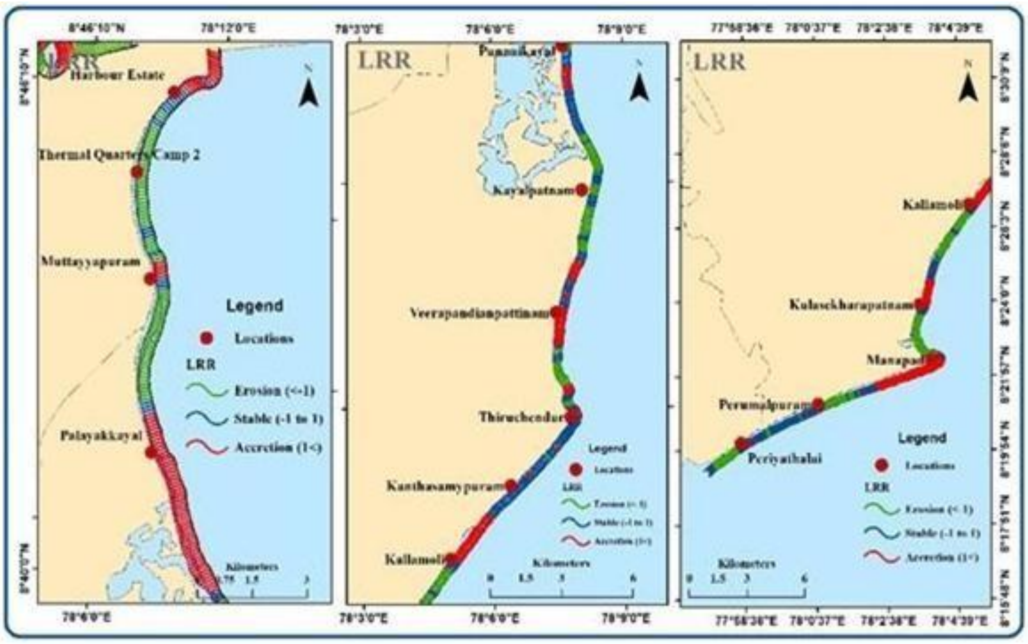


Fig2. Shore line change rates (LRR) from Vembar to Thoothukudi Harbour

(SegmentA)



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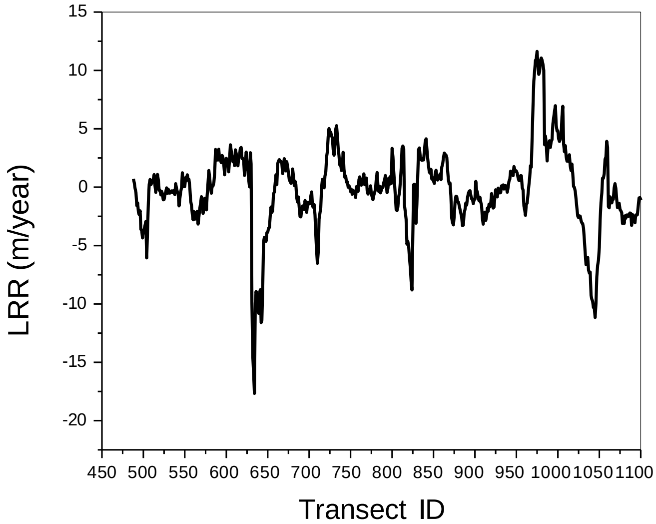

Fig3. Shore line change rates (LRR) from Thoothukudi Harbour to Manapad (Segment B)

Shoreline Change Rates: Segment A
The location-wise statistics of Segment A are presented in Table 1.

Table 1: Shoreline change rates of Segment A

Section Name	Transect ID & Location	LRR (m/year)	EPR (m/year)	NSM (m)
Zone 1	138 (Keelavaippar river)	−5.76	−5.91	−119.9
(Vembar to Vepalodai)	160 (Sippikulam)	+1.81	+1.70	+34.57
Zone 2	227 (Vepalodai)	−5.14	−5.01	−101.67
(Vepalodai to Taruvaikulam)	308 (Taruvaikulam)	+10.14	+10.34	+209.97
Zone 3	474 (Thoothukudi Port)	−26.10	−25.56	−518.98
(Taruvaikulam to N. harbour)	467 (TTPS)	+26.88	+26.11	+530.16

In Segment A, Zone 1 and Zone 2 exhibited dominant erosion with an average erosional rate of −3.55 m/year. The highest erosional rate was found in Zone 3 near Thoothukudi Port (−26.10 m/yr LRR), whereas the least erosion was found in Zone 2. Zone 3 also showed the highest accretion rate (+26.88 m/yr LRR) near the Tuticorin Thermal Power Station (TTPS), indicating significant anthropogenic influence on shoreline dynamics. The NSM showed an average positive distance of +19.86 m and average negative distance of −70.84 m, confirming that erosional processes dominate over accretional processes in Segment A.

Shoreline Change Rates: Segment B
The shoreline change statistics for Segment B are presented in Table 2.

Table 2: Shoreline change rates of Segment B

Section Name	Transect ID & Location	LRR (m/year)	EPR (m/year)	NSM (m)
Zone 1	606 (Manapad)	+3.12	+3.16	+64.16
(Harbour to Punnakayal)	634 (Manapad)	−17.67	−17.39	−353.15

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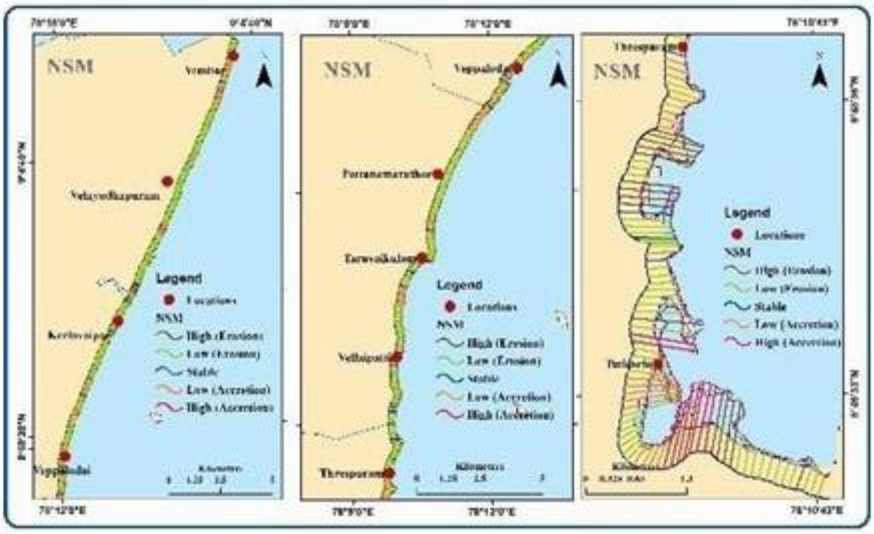
Zone 2	732 (Alanthalai)	+4.95	+4.45	+107.67
(Punnakayal to Kallamoli)	824 (Veerapandiyapattanam)	−8.81	−8.64	−175.47
Zone 3	975 (Punnakayal)	+11.63	+10.69	+233.26
(Kallamoli to Manapad)	1045 (Muttayapuram)	−11.16	−11.11	−225.55

In Segment B, Zones 1 and 3 exhibited dominant erosion with an average erosional rate of −2.39 m/year. The highest erosional rate was found in Zone 1 near Manapad (−17.67 m/yr LRR), whereas the least erosion was found in Zone 2. The NSM showed an average positive distance of +45.05 m and average negative distance of −48.49 m.

Net Shoreline Movement (NSM) Analysis
The NSM results for both segments are presented in Figs. 4 and 5. NSM measures the total distance of shoreline displacement between the oldest (2000) and youngest (2021) shoreline positions. Maximum seaward advancement (+530.16 m) was observed near TTPS in Segment A, attributed to land reclamation and port-related activities, while maximum landward retreat (−518.98 m) occurred at Thoothukudi Port, likely due to wave energy concentration and sediment transport disruption by harbour structures.



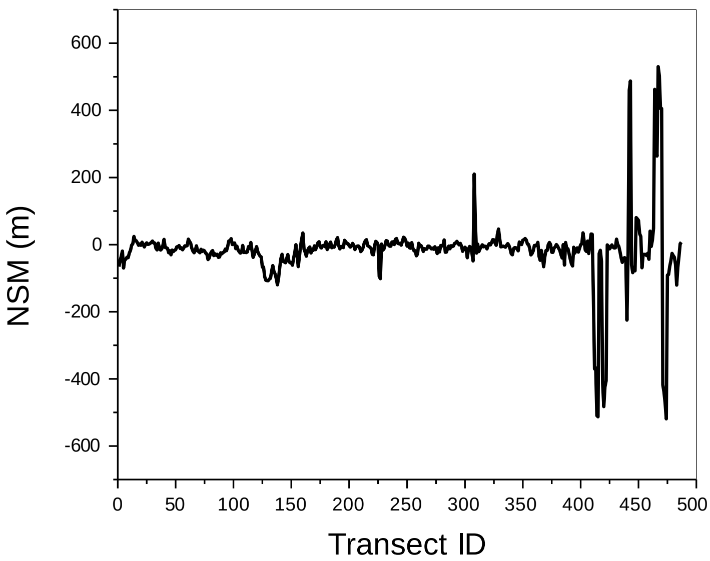


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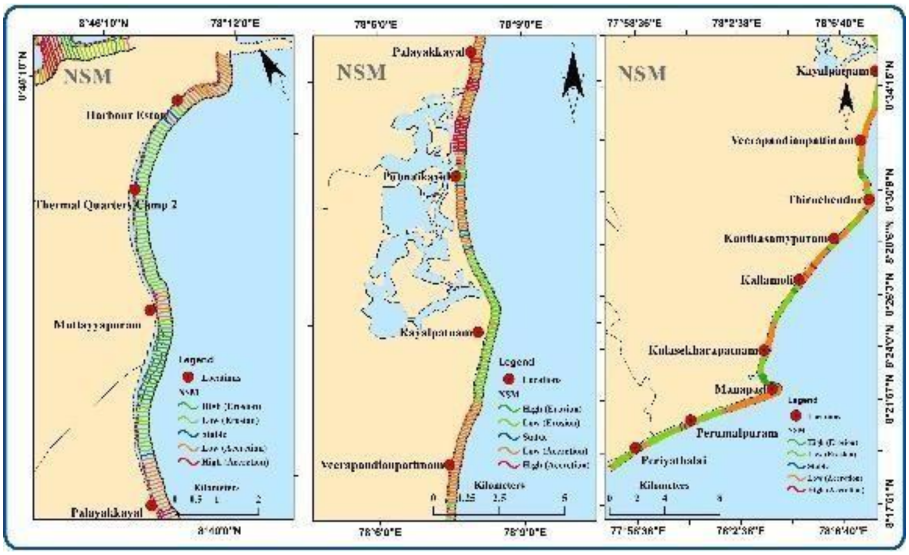
Fig4. Shore line change rates (NSM) from Vembar to Thoothukudi Harbour (SegmentA)



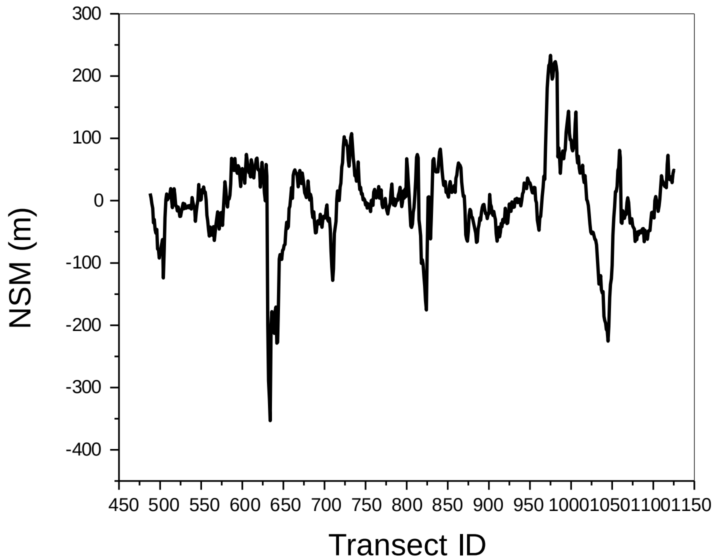


Fig. 5: Net Shoreline Movement (NSM) from Thoothukudi harbour to Manapad (Segment B).

End Point Rate (EPR) Analysis

The EPR results for both segments are shown in Figs. 6 and 7. EPR values closely corroborated the LRR findings, confirming the spatial distribution of erosion and accretion zones. The concordance between EPR and LRR values validates the consistency and reliability of the shoreline change measurements. Slight differences at certain transects reflect the influence of intermediate shoreline positions (2010) captured by LRR but not by EPR, which only considers the two extreme dates.

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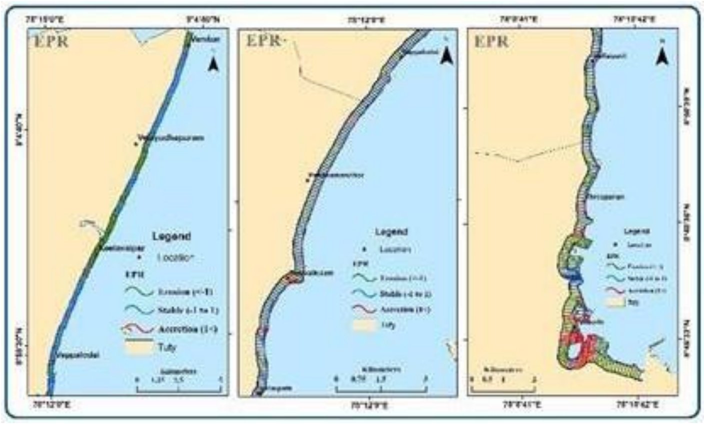


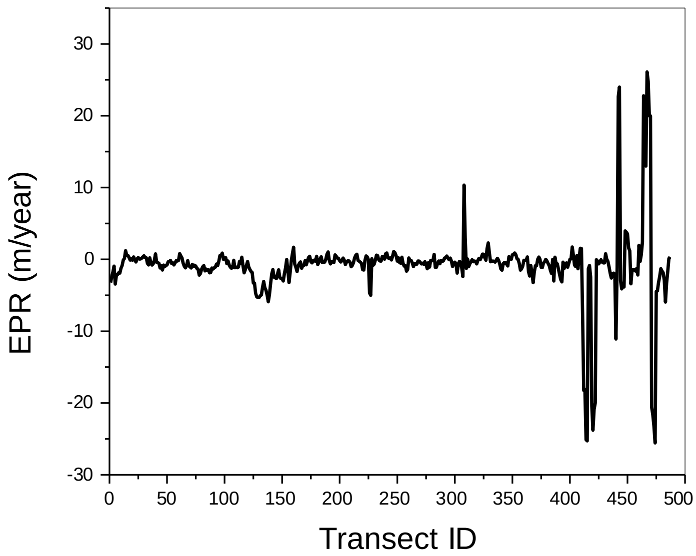
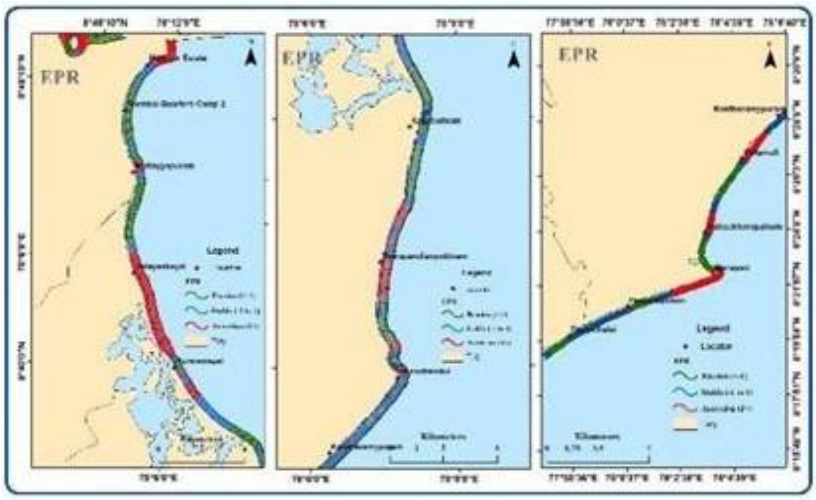


Fig.6 Shore line change rates (EPR) from Vembar to Thoothukudi Harbour (Segment A)



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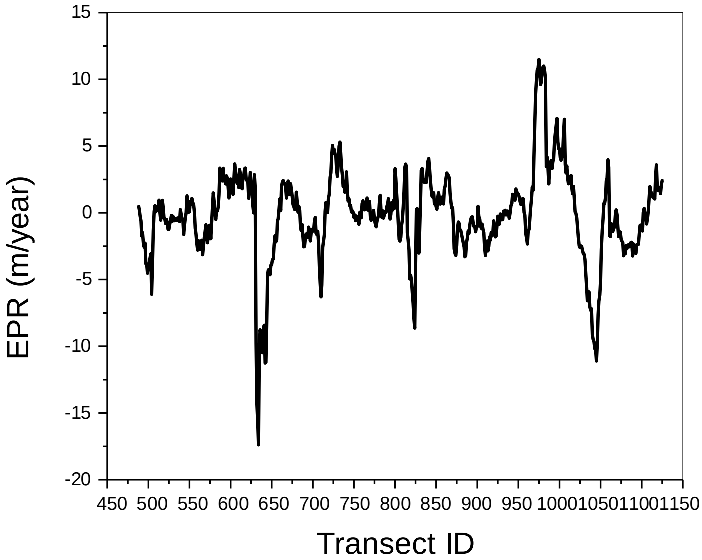

Fig.7 Shore line change rates (EPR) from Thoothukudi Harbour to Manapad (Segment B)

Overall Shoreline Change Assessment

The integrated analysis of LRR, EPR and NSM reveals that out of 1126 transects, approximately 63% exhibited erosional trends, indicating that overall erosional activities are significantly higher than accretional activities along the Thoothukudi coast. The predominance of erosion can be attributed to multiple interacting factors including sediment transport dynamics influenced by the Tamiraparani river system, wave action during the northeast monsoon season, longshore current patterns in the Gulf of Mannar and anthropogenic modifications to the coastal zone. Accretion was primarily concentrated near artificial structures such as Tuticorin harbour breakwaters and TTPS, where sediment trapping occurs on the updrift side. The stable zones (51 km) were generally located in sheltered embayments or areas with balanced sediment budgets. The observed erosion rates near river mouths (particularly the Vaippar river at Keelavaippar coast) align with regional patterns of reduced fluvial sediment supply due to dam construction and sand mining upstream. The combination of natural processes (tidal action, monsoon-driven wave energy) and anthropogenic activities (port expansion, coastal infrastructure development) creates a complex erosion-accretion pattern necessitating integrated coastal zone management strategies.

DISCUSSION

Anthropogenic Control on Extreme Shoreline Morphodynamics

The extreme erosion-accretion couplet documented adjacent to Thoothukudi Port infrastructure (−26.10 m/yr erosion versus +26.88 m/yr accretion) represents rates nearly an order of magnitude greater than natural baseline erosion rates observed along unmodified segments of the Gulf of Mannar coastline. These magnitudes substantially exceed typical tropical coast erosion rates (−2 to −4 m/yr) reported across the Indo-Pacific region (Luijendijk et al. 2018; Mentaschi et al. 2018), confirming that coastal engineering structures exert disproportionate influence on littoral sediment budgets. Harbour breakwaters function as high-efficiency sediment traps that intercept northward longshore drift driven by northeast monsoon wave climate, generating pronounced updrift accretion while simultaneously inducing severe downdrift sediment starvation, ubiquitous phenomenon along engineered coastlines globally. The spatial symmetry of maximum erosion and accretion zones mirroring port geometry rather than natural coastal compartmentalization demonstrates that structure-induced wave diffraction patterns and littoral current deflection override natural sediment transport equilibria. Similar infrastructure-driven morphodynamic perturbations have been documented along India's west coast ports, where sediment circulation cells extend 10-15 km from major harbour structures (Mahapatra, Ratheesh & Rajawat 2014). The juxtaposition of localized extreme rates against basin-wide erosional dominance (63% of transects) suggests that anthropogenic structures redistribute sediment within a system experiencing regional sediment budget deficit rather than creating new sinks in an otherwise balanced coastal system.

Fluvial Supply Constraints and Upstream Modifications

The predominance of erosional trends across 63% of transects along the Thoothukudi coast reflects systematic regional sediment supply reduction rather than localized process variability, consistent with basin-scale sediment starvation patterns documented across monsoon-influenced tropical coasts of South and Southeast Asia (Anthony et al. 2015; Besset, Anthony & Bouchette 2019). Erosion hotspots near river mouths, particularly the Vaippar River at Keelavaippar (−5.76 m/yr LRR), provide direct evidence of fluvial sediment supply curtailment linked to upstream dam construction and intensive sand mining activities within catchment areas. Recent studies quantifying sediment retention behind India's reservoir network estimate 60–80% reduction in fluvial sediment delivery to coastal systems over the past four decades (Adebisi et al. 2021; Abd-Elhamid et al. 2023). The Tamiraparani River, historically a primary sediment source for this coastal segment, has experienced similar sediment flux reduction following construction of multiple check dams and weirs across its drainage basin. The NSM asymmetry between Segment A (average negative distance −70.84 m) and Segment B (−48.49 m) suggests differential sediment supply vulnerability, with northern segments experiencing more severe fluvial sediment deficits. Climate-driven alterations in monsoon precipitation patterns compound this sediment crisis by modifying fluvial discharge regimes and sediment mobilization capacity (Ranasinghe 2020). The stable zones (51 km, ~31% of coastline) concentrated in sheltered embayments indicate that localized wave energy attenuation and sediment retention mechanisms partially buffer regional sediment deficit impacts, highlighting the critical role of coastal geomorphology in mediating erosion susceptibility.

Implications for Climate-Adaptive Strategies

The complex erosion-accretion mosaic documented along Thoothukudi's 163 km coastline necessitates spatially differentiated coastal management strategies that acknowledge both anthropogenic forcing and natural process variability. The concordance between LRR, EPR and NSM methodologies validates the robustness of multi-metric shoreline change assessment frameworks for policy formulation, consistent with best practices in coastal vulnerability mapping (Nikolakopoulos et al. 2019; Himmelstoss et al. 2021). Priority intervention zones should target compound vulnerability hotspots where infrastructure-induced erosion intersects with high population density and critical coastal infrastructure, particularly near Thoothukudi Port and Manapad. Nature-based solutions including beach nourishment programs sourced from offshore sand deposits, hybrid grey-green infrastructure combining submerged breakwaters with mangrove/seagrass restoration, and managed sediment bypass systems around harbour structures offer cost-effective alternatives to conventional hard stabilization. The successful implementation requires addressing root causes of sediment budget deficit through integrated river basin-coastal zone management linking upstream sediment retention mitigation with downstream shoreline protection. Climate change projections indicating intensified cyclone frequency and sea-level rise acceleration (3.1–3.7 mm/yr for Gulf of Mannar) will exacerbate existing erosion trends, necessitating adaptive management frameworks incorporating regular shoreline monitoring, dynamic setback line adjustments and strategic retreat from high-risk zones. The methodology presented provides a replicable template for data-scarce tropical coasts requiring evidence-based coastal adaptation planning aligned with sustainable development objectives.

CONCLUSION

Shoreline changes along the Thoothukudi coast for the period 2000 to 2021 were effectively detected and computed using remote sensing and geospatial techniques. Out of 1126 transects, nearly 63% were erosional, indicating that overall erosional activities are higher than accretional activities in the study area. Accretion was found along the coast of Sippikulam, Taruvaikulam, Punnakayal, Kallamoli, Veerapandiyapattinam and Manapad. Erosion was found along the coast of Keelavaippar, Vepalodai, Kayalpattinam and Perumalpuram, while both accretion and erosion were observed in the Tuticorin port areas. The highest erosion rates were observed near the Vaippar river on the Keelavaippar coast due to sediment transport dynamics of the Tamiraparani river, tidal action during the northeast monsoon season and wind effects. Both accretion and erosion in Tuticorin Port areas were attributed to anthropogenic activities like port expansion and natural activities like sediment transport from Tamiraparani estuary during the southwest monsoon. Special attention should be paid to low-lying coastal areas vulnerable to sea level rise. Improvements in land management, erosion control, dune reinforcement, protection of existing natural barriers and strengthening of infrastructure are the best adaptation options. Accurate coastal zone regulation should be strictly implemented and it is recommended to derive change analysis studies at regular intervals.

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CONFLICT OF 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.

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