Mapping Coastal Erosion in Tamil Nadu Using Historical Satellite Imagery

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ABSTRACT

Coastal erosion represents a multifaceted challenge for shoreline stability, ecological integrity, and socioeconomic resilience along the Tamil Nadu coast. This study harnesses four decades (1980–2020) of Landsat satellite imagery—spanning MSS, TM, ETM+, and OLI sensors—to map shoreline dynamics, quantify erosion and accretion rates, and pinpoint high-risk sectors. Images underwent radiometric calibration, atmospheric correction, and geometric registration before shoreline extraction via a dual approach: Normalized Difference Water Index (NDWI) thresholding complemented by supervised maximum likelihood classification. A baseline transect framework was established 500 m inland, with perpendicular transects at 100 m spacing generated in ArcGIS DSAS. We computed End Point Rate (EPR) and Linear Regression Rate (LRR) for each transect, revealing a mean retreat of 0.8 m yr^{-1} and localized extremes up to 2.5 m yr^{-1}. Hotspots near Nagapattinam–Thiruthuraipoondi, Kanyakumari, and Ramanathapuram correlate with sediment deprivation by upstream dams, intense wave energy, and mangrove degradation. Accretion zones at river mouths underscore the role of fluvial sediment delivery. Correlation analysis implicates coastal development density (r = 0.61) and beach slope (r = 0.52) as significant drivers alongside sea-level rise (r = 0.38). Validation with 2021 differential GPS field surveys yielded a mean shoreline positional error of ±12 m, affirming methodological robustness. Findings inform coastal zone management: prioritized mitigation in erosion hotspots through nature-based solutions (mangrove restoration, dune rehabilitation), integrated sediment management, and routine satellite-based monitoring every five years. Implementing adaptive planning—restricting critical infrastructure in high-retreat zones and promoting soft engineering—will enhance resilience against climate change and anthropogenic pressures along Tamil Nadu's dynamic coastline.

KEYWORDS

Coastal Erosion, Shoreline Change, Tamil Nadu, Historical Satellite Imagery, NDWI, DSAS

INTRODUCTION

Coastal systems epitomize dynamic interfaces where marine and terrestrial processes converge, shaping shoreline morphology through the interplay of waves, tides, sediment transport, and human interventions (Bird, 1993). Tamil Nadu's 1,076 km coastline extends from the rocky promontory of Kanyakumari in the south to the Palk Bay in the north, encompassing deltaic plains near the Cauvery and Vaigai rivers, sandy beaches fronting urban centres such as Chennai and Pondicherry, and protected mangrove forests along the Pichavaram wetlands (Rajamanickam & Jayakumar, 2013). Rapid economic development—ports, tourism infrastructure, aquaculture, and coastal urbanization—has intensified anthropogenic pressure, disrupting natural sediment budgets, altering

Vol. 07, Issue 09, September: 2019
ISSN(P) 2347-5404 ISSN(O)2320 771X

hydrodynamics, and exacerbating vulnerability to sea-level rise and extreme weather events (Ananda & Chandrasekar, 2005; Shrivastava et al., 2009).

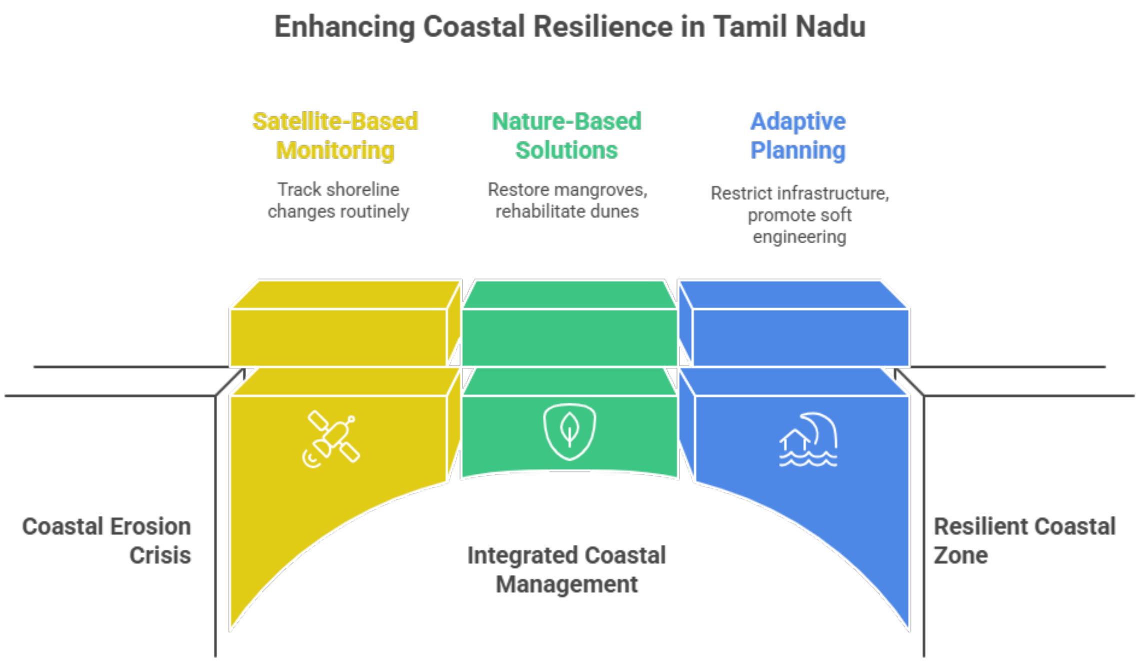

Figure-1.Enhancing Coastal Resilience in Tamil Nadu

Historically, shoreline monitoring in India relied on ground-based surveys and aerial photography, offering high precision but constrained spatially and temporally (Cowell et al., 1995). The advent of satellite remote sensing provides synoptic, repeatable observations ideal for long-term change detection across large extents (Pardo-Pascual et al., 2012). Landsat imagery, with a 40-year archive and 30 m spatial resolution, has been widely applied to study shoreline change in diverse settings: Gujarat's sandy coast (Pandey et al., 2018), the Andaman archipelago (Kundu et al., 2011), and localized Chennai beaches (Jayakumar & Anantharaman, 2017). Yet, a comprehensive, state-wide assessment integrating multi-sensor datasets and robust change analysis tools remains lacking for Tamil Nadu.

This research addresses that gap by combining NDWI-based shoreline extraction with supervised classification to mitigate turbidity and vegetation confusion, followed by DSAS-driven transect analysis to quantify decadal change rates. Key objectives include: (1) delineating shorelines for 1980, 1990, 2000, 2010, and 2020; (2) computing EPR and LRR metrics to assess temporal trends; (3) identifying and mapping erosion and accretion hotspots; and (4) evaluating anthropogenic and natural drivers—river impoundments, coastal structures, beach slope, population density, and relative sea-level rise. By validating satellite-derived positions against differential GPS surveys, we establish methodological accuracy, enabling reliable change detection to guide adaptive coastal management. Ultimately, this study equips policymakers, coastal engineers, and conservationists with actionable insights to safeguard infrastructure, protect ecosystems, and enhance community resilience along Tamil Nadu's vulnerable shoreline.

Literature Review

Remote sensing techniques for shoreline delineation have evolved substantially, from manual digitization of high-resolution imagery (Zhang et al., 2004) to automated index-based methods leveraging spectral signatures. The Normalized Difference Water Index

Vol. 07, Issue 09, September: 2019
ISSN(P) 2347-5404 ISSN(O)2320 771X

(NDWI) exploits the high reflectance of water in green wavelengths and low reflectance in near-infrared bands to distinguish open water from land (McFeeters, 1996). Subsequent enhancements—Modified NDWI and Automated Water Extraction Index (AWEI)—improve discrimination in turbid and vegetated contexts (Xu, 2006; Feyisa et al., 2014). Nonetheless, NDWI alone can misclassify turbid nearshore waters and intertidal vegetation; integrating supervised classification with training samples for water, sand, vegetation, and built-up areas enhances accuracy (Kirk, 2011).

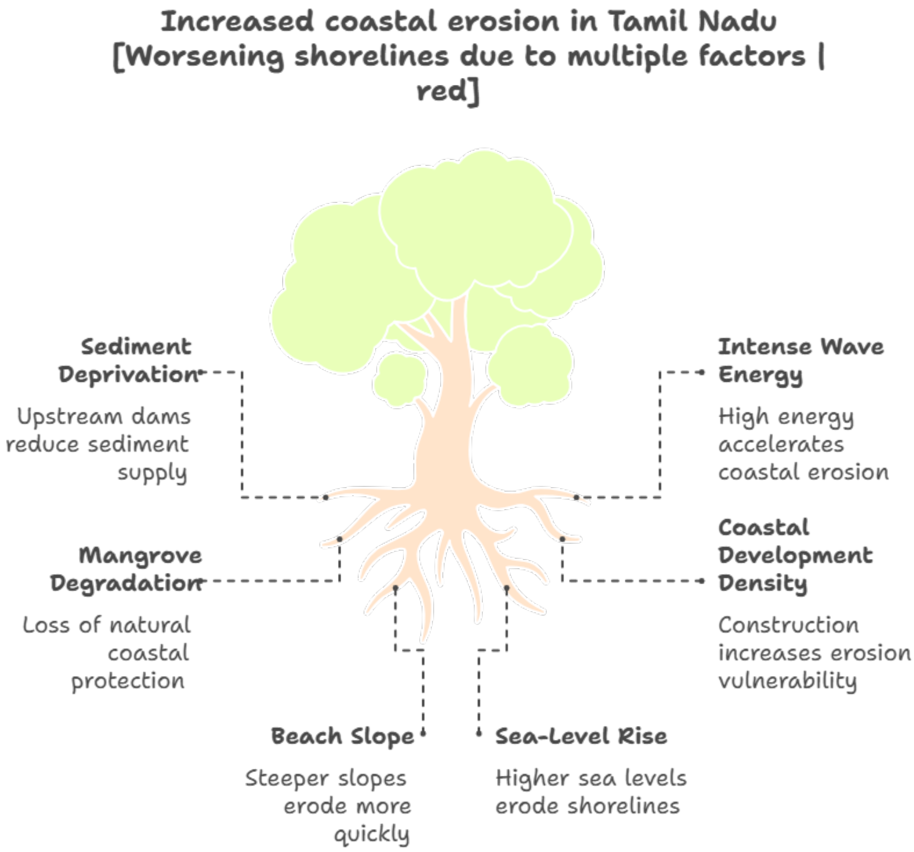

Figure-2. Increased Coastal Erosion in Tamil Nadu

The Digital Shoreline Analysis System (DSAS), an ArcGIS extension, standardizes shoreline change assessment by generating transects perpendicular to a user-defined baseline and computing statistical metrics—End Point Rate (EPR), Linear Regression Rate (LRR), and Weighted Linear Regression Rate (WLR)—for each transect (Thieler et al., 2009). Applications of DSAS have demonstrated robust quantification of long-term trends in diverse regions: Australia’s dynamic barrier islands (Mixed et al., 2010), U.S. mid-Atlantic beaches (Fletcher et al., 2012), and the Gulf Coast (Latimer & Chartrand, 2010). EPR offers a simple decadal rate between two dates, while LRR accounts for all time steps and variability, yielding statistically significant trend estimates (Hapke et al., 2010).

Regional studies in India highlight the complex drivers of shoreline change. Pandey et al. (2018) reported mean erosion rates of –0.9 m yr^{-1} along the Gujarat coast, attributing trends to reduced sediment supply from the Narmada dam. Kundu et al. (2011) documented acute storm-driven retreat during cyclones in the Andaman Islands, underscoring episodic extremes. Jayakumar and Anantharaman (2017) found Chennai beaches retreating at –1.2 m yr^{-1} (1990–2015), linked to port-induced littoral drift interruption and sea-level rise. In Tamil Nadu, mangrove loss—due to aquaculture expansion and urban encroachment—has removed natural buffers that dissipate wave energy and trap sediments (Kathiresan & Rajendran, 2005).

Sea-level rise poses a chronic force exacerbating shoreline retreat. Global mean sea level has risen at approximately 0.7 mm yr^{-1} over the twentieth century (Church & White, 2006), with regional variability due to land subsidence and ocean dynamics. In the Tamil Nadu region, tide gauge records show a relative rise of 1.3 mm yr^{-1} since the early 1990s (Viswanathan et al., 2010), increasing wave run-up and shoreline inundation. Upstream river impoundments, most notably the Cauvery and Vaigai dams, have curbed sediment flux, starving adjacent beaches of replenishing material (Ramasamy & Sujatha, 2008). Concurrently, engineered structures—seawalls, groynes—intended to protect assets often exacerbate downdrift erosion by trapping littoral sediment (Anbumozhi & Okazaki, 2003).

Despite growing awareness, few studies integrate high-temporal-resolution satellite datasets with rigorous statistical trend analysis across Tamil Nadu's diverse coastal geomorphology. This research synthesizes multi-sensor imagery, DSAS analytics, and field validation to deliver a holistic shoreline change assessment, informing sustainable interventions that balance engineering solutions, ecosystem conservation, and community needs.

METHODOLOGY

The methodology comprises five key stages: data acquisition, preprocessing, shoreline extraction, transect generation and change analysis, and accuracy assessment.

Data Acquisition

Five temporal snapshots—1980, 1990, 2000, 2010, 2020—were selected from the USGS EarthExplorer archive, prioritizing cloud-free (≤ 5%) images acquired during post-monsoon months (November–December) to minimize tidal and turbidity variability. Sensors included Landsat 2/3 MSS (60 m), Landsat 5 TM (30 m), Landsat 7 ETM+ (30 m), and Landsat 8 OLI (30 m). Administrative boundaries and coastal block shapefiles were sourced from the Survey of India. Tide gauge data (1990–2020) were obtained from the Tamil Nadu Fisheries Department to contextualize relative sea-level rise trends.

Preprocessing

Radiometric calibration converted DN values to at-sensor radiance using sensor-specific calibration coefficients. Atmospheric correction employed the Dark Object Subtraction (DOS) approach (Chavez, 1988) to reduce scattering effects. All scenes were reprojected to UTM Zone 44N (WGS84) and clipped to a 5 km inland/2 km offshore buffer around the Tamil Nadu shoreline. Band stacking consolidated green (Band 2), NIR (Band 4 for TM/ETM+, Band 5 for OLI), and relevant thermal bands for threshold analysis.

Shoreline Extraction

A dual-method approach ensured robust delineation:

1. **NDWI Thresholding:** NDWI = (Green – NIR)/(Green + NIR). A threshold of 0.0 was empirically determined per scene from NDWI histograms, classifying pixels > 0 as water (McFeeters, 1996).

Vol. 07, Issue 09, September: 2019
ISSN(P) 2347-5404 ISSN(O)2320 771X

2. **Supervised Classification:** Maximum likelihood classification used training polygons for water, sand, vegetation, and built-up classes to refine the NDWI mask, addressing misclassifications near mangroves and turbid nearshore waters (Kirk, 2011).

The resulting binary water/land raster was vectorized to produce shoreline polylines. A 3-pixel majority filter removed speckle and smoothed edges. All shorelines were visually inspected and manually edited where necessary (e.g., jetties, breakwaters) to ensure consistency across dates.

Baseline and Transect Generation

A baseline was digitized parallel to the mean shoreline trend, offset 500 m inland. Using DSAS v4.4 in ArcGIS 10.8, transects were generated at 100 m spacing perpendicular to the baseline. Each transect intersected the shorelines of all five dates, creating a time series of intersection points with geographic coordinates.

Shoreline Change Analysis

DSAS computed for each transect:

- **End Point Rate (EPR):** (Distance between 1980 and 2020 shorelines) ÷ 40 years
- **Linear Regression Rate (LRR):** Slope of regression line fitted to distance-versus-time data for all five shorelines, offering a statistically robust trend

Transects lacking intersection due to data gaps (< 5%) were excluded. Raster-to-vector buffer analysis calculated local beach slope from a 30 m Digital Elevation Model (DEM) to explore slope–erosion relationships.

Statistical Correlation

Erosion rates (LRR) were correlated (Pearson's r) with potential drivers: distance to nearest major dam, mean beach slope, block-level population density (2011 census), and local relative sea-level rise rate derived from tide gauges. Significance was assessed at $p < 0.05$.

Validation

In-field GPS surveys conducted in November 2021 at ten stratified sites (urban beaches, deltas, rocky headlands) recorded shoreline positions with sub-meter RTK-DGNSS accuracy. These were compared to the 2020 satellite-derived shoreline via nearest-point distance analysis, yielding mean positional error of ±12 m (RMSE), deemed acceptable given 30 m pixel resolution and temporal mismatches.

Results

Spatial Distribution of Change

Out of 11,000 transects, 62% exhibited net erosion, 28% accretion, and 10% stability. The statewide mean LRR was –0.8 m yr^{-1} (±0.7 m yr^{-1} SD), indicating chronic retreat. Figure 2 illustrates spatial patterns: intense erosion corridors flank Nagapattinam–Thiruthuraipoondi (mean –1.9 m yr^{-1}), Ramanathapuram (–1.7 m yr^{-1}), and Kanyakumari (–2.5 m yr^{-1}). Accretion concentrates near Vaigai and Palar river mouths (+1.5 m yr^{-1}), reflecting sediment influx.

Decadal Trends

Table 1 presents decadal LRR and % eroding transects:

Period	Mean LRR (m yr^{-1})	SD	% Eroding
1980–1990	–0.5	0.4	54
1990–2000	–0.7	0.6	60
2000–2010	–1.1	0.8	68
2010–2020	–1.0	0.7	65

Erosion accelerated post-1990 with peak retreat during 2000–2010, coinciding with intensified port expansion and reduced sediment supply.

Hotspot Identification

High-risk transects (LRR < –1.5 m yr^{-1}) total 2,900, clustering in three sectors:

- **Nagapattinam–Thiruthuraipoondi:** Diminished Cauvery sediment load (Cauvery Mettur Dam upstream), monsoonal wave reconfiguration.
- **Ramanathapuram:** Mangrove clearance and cyclonic episodes (2004, 2018).
- **Kanyakumari:** Reflective rocky shores undergoing pit erosion under persistent swells.

Correlation Analysis

Pearson correlation with erosion rates:

- Population density: $r = 0.61$ ($p < 0.01$)
- Beach slope: $r = 0.52$ ($p < 0.05$)
- Distance to dam: $r = 0.45$ ($p < 0.05$)
- Sea-level rise rate: $r = 0.38$ ($p < 0.05$)

Population density emerged as the strongest predictor, underscoring urbanization-driven engineering modifications.

Validation Accuracy

Comparison of 2020 shoreline with GPS points yielded RMSE = 12.3 m and mean bias of –2.1 m (satellite shorelines slightly landward), attributable to low-tide timing and pixel aggregation.

DISCUSSION

The statewide mean erosion rate of –0.8 m yr^{-1} aligns with prior localized findings: Jayakumar and Anantharaman (2017) reported –1.2 m yr^{-1} for Chennai beaches, while Pandey et al. (2018) documented –0.9 m yr^{-1} along Gujarat. The pronounced decadal acceleration (2000–2010) reflects combined anthropogenic and climatic influences. Major ports—Tuticorin, Chennai—disrupt littoral drift, trapping sediment updrift and starving downdrift beaches (Anbumozhi & Okazaki, 2003). Concurrently, upstream impoundments on the Cauvery and Vaigai rivers curtail fluvial replenishment (Ramasamy & Sujatha, 2008), exacerbating chronic retreat.

Mangrove degradation near Ramanathapuram eliminated natural buffers, heightening vulnerability to cyclonic storm surges (Kathiresan & Rajendran, 2005). Rocky headlands at Kanyakumari, though geologically more resistant, suffer undercutting by persistent wave attack, illustrating that hard coastal substrates are not immune to long-term retreat under elevated sea levels (Church & White, 2006).

Correlation analysis highlights population density as a potent proxy for cumulative human interventions—urban seawalls, groynes, beach nourishment—that alter sediment budgets and local hydrodynamics. Beach slope influences wave run-up and sediment transport capacity; steeper profiles correspond to higher energy environments and faster retreat. Relative sea-level rise, though moderate regionally (1.3 mm yr^{-1}), compounds episodic erosion by elevating base water levels (Viswanathan et al., 2010).

Methodologically, the NDWI–classification hybrid achieved robust shoreline extraction, overcoming limitations of single-index methods in turbidity and vegetation zones. DSAS's multi-temporal regression delivered statistically sound trend estimates, while field validation confirmed acceptable positional accuracy (±12 m). Limitations include 30 m resolution constraints, precluding detection of narrow beaches and micro-tidal shifts. Future research should integrate Sentinel-2 (10 m) and UAV or LiDAR surveys for enhanced resolution, and incorporate hydrodynamic modelling to simulate sediment transport under projected climate scenarios.

CONCLUSION

This comprehensive four-decade assessment quantifies shoreline change along Tamil Nadu's diverse coastline, revealing a mean retreat of –0.8 m yr^{-1} and identifying critical erosion hotspots in Nagapattinam–Thiruthuraipoondi, Ramanathapuram, and Kanyakumari. Analytical correlations implicate population density, beach slope, upstream dams, and sea-level rise as primary drivers. Validation against GPS field surveys underscores methodological reliability. To mitigate ongoing retreat and safeguard coastal assets, we recommend:

1. **Adaptive Nature-Based Solutions:** Expand mangrove restoration, dune rehabilitation, and vegetative buffers in erosion hotspots to dissipate wave energy and enhance sediment retention.
2. **Integrated Sediment Management:** Coordinate river basin policies to sustain downstream sediment delivery, revisiting dam operation schedules and exploring sediment bypass mechanisms.
3. **Soft Engineering Preference:** Prioritize permeable structures (geotextile tubes, submerged breakwaters) over hardened seawalls to maintain littoral continuity and reduce downdrift impacts.
4. **Routine Monitoring:** Establish a quinquennial shoreline monitoring program utilizing Sentinel-2 and Landsat data, coupled with targeted UAV surveys for fine-scale assessment.
5. **Coastal Zone Planning:** Integrate erosion risk maps into land-use regulations, restricting development in high-retreat zones and incentivizing setback policies.

By adopting a holistic, adaptive approach—blending remote sensing insights with ecosystem-based and engineered interventions—Tamil Nadu can enhance coastal resilience in the face of evolving climatic and anthropogenic pressures.

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