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Spatial Vulnerability and Exposure Mapping of Coastal Ecosystems to Climate-Induced Hazards: A Multi-Temporal GIS Approach

Milan Singh Joon (Department of Geography), Research Scholar, NIILM University, Kaithal (Haryana)
Dr. Sandeep Rana (Associate Professor) (Department of Geography), NIILM University, Kaithal (Haryana)

Abstract

Rising seas, erosion, storm surges, salt water intrusion, land use changes, and coastal buffer deterioration endanger Tamil Nadu coastline habitats. This study estimated Tamil Nadu coast spatial risk and exposure using multi-temporal GIS and remote-sensing. DSAS and multi-criteria analysis incorporated coastline data from many time periods, Landsat pictures, digital elevation models, coastal ecosystem data, and socioeconomic aspects. According to official coastal assessment data, 422.94 km (42.7%) of Tamil Nadu's 991.47 km coastline is eroding, 332.69 km (33.6%) is stable, and 235.85 km (23.8%) is accreting. A 1988-2018 multi-temporal analysis revealed a landward trend with a mean End Point Rate (EPR) of −0.26 m/year, varying significantly among coastal watersheds. Eroding seawater basins include Coleroon, Arasalar, Gundar, Vembar, Lower Vaippar, Nambiyar, Hanuma, Putian, and Kodyar. A vulnerability framework included adaptability, ecological sensitivity, and physical exposure. Tamil Nadu research showed coastal danger varied, even across space. Manage erosion-prone coastal locations, river mouths, low-lying deltaic areas, heavily inhabited areas, and endangered ecosystems. Multi-temporal GIS evaluation improved coastal management in Tamil Nadu compared to single-date hazard mapping, helping restore ecosystems, regulate land use, adapt to climate change, and manage shorelines.

Keywords: Tamil Nadu coast; coastal vulnerability; shoreline erosion; exposure mapping; GIS; remote sensing; DSAS; sea-level rise; coastal ecosystems; climate adaptation

1. Introduction

Coastal zones are ever-changing ecosystems that span the boundary between land and water. In addition to mangroves, wetlands, estuaries, beaches, mudflats, and systems related to coral, they are essential for fisheries, farming, aquaculture, human settlements, and infrastructure. While these regions offer important biological and economic advantages, they are also vulnerable to threats such as rising sea levels, erosion of coastlines, storm surges, coastal floods, and salt water intrusion. As a result of the interplay between climate change and human activity, coastal ecosystems are more susceptible to degradation. Settlement growth, port development, aquaculture, transportation infrastructure, and other coastal activities can alter the movement of sediment and the processes that occur naturally along shorelines. Deterioration of coastal ecosystems' natural buffers, such as mangroves and wetlands, might lessen their ability to decrease wave energy and shield inland regions from damage. For the purpose of investigating these connections, Tamil Nadu is a significant context. Coastal ecosystems in this state are as varied as the waters that surround it, stretching out into the Indian Ocean, the Gulf of Mannar, and the Bay of Bengal. Erosion is a big problem for coastal management, according to official shoreline assessments, but the severity of the problem varies across different regions.

Therefore, being close to the sea is not necessarily indicative of coastal vulnerability. A combination of factors including sensitivity, adaptive capacity, and exposure leads to its production. Factors that influence the level of physical exposure include low elevation, coastal slope, shoreline alteration, rising sea levels, and cyclonic activity. Variables impacting ecological sensitivity include the state of mangroves and wetland areas, changes in land cover, and fragmentation of ecosystems. In terms of socioeconomic vulnerability and adaptive capacity, factors such as population density, built-up intensity, and infrastructure accessibility have a role. The use of geographic information systems (GIS) and remote sensing allows for the efficient integration of these diverse datasets. By determining the pace and direction of changes to shoreline and land cover, multi-temporal satellite measurements further enable coastal risk evaluation as a dynamic process. Consequently, this research analyzed the susceptibility and exposure of coastal ecosystems in Tamil Nadu using a multi-temporal GIS.

1.1 Objectives of the Study

1. To examine the spatial pattern of shoreline erosion, stability and accretion along the Tamil Nadu coast.
2. To assess long-term shoreline dynamics using multi-temporal geospatial information.
3. To integrate physical, ecological and socio-economic indicators into a GIS-based vulnerability framework.

2. Literature Review

Badola and Hussain (2005) examined Odisha's Bhitarkanika mangrove ecosystem's storm protection. It assessed mangroves' economic and protective value for storm-prone coastal areas. We examined storm damage and settlements versus natural and built coastline protection. Mangrove-protected communities lost less. Mangroves guard against coastal hazards, making them ecosystem services, according to the study.

Das and Vincent (2009) checked mangrove forest conservation during the 1999 Odisha Super Cyclone. We wanted to investigate if wider mangrove belts prevented cyclone deaths. The method statistically assessed village-level mangrove breadth, population, storm-surge conditions, terrain, and socioeconomics. Cyclone deaths were lower in villages with more mangroves. The study indicated mangrove conservation lessens coastal disaster risk.

Nageswara Rao et al. (2009) evaluated Andhra Pradesh coastline sea-level rise susceptibility. To identify coastal areas at risk from sea-level rise. The Coastal Vulnerability Index employed remote sensing and GIS to study coastal geomorphology, slope, coastline change, tidal range, and wave characteristics. Susceptibility was high and very high along most of the seashore. Integrating geospatial evaluation helps prioritize coastal preservation and adaptation, the study revealed.

Panda et al. (2011) examined Odisha multi-temporal coastline changes. We sought dynamic shoreline stretches and long-term coastal erosion and accretion patterns. It compared multi-temporal satellite imagery utilizing remote sensing and GIS. The results demonstrated regional coastal erosion and accretion disparities. The study indicated that multi-temporal shoreline monitoring is necessary for coastal-zone planning and erosion management.

Mahendra et al. (2011) evaluated multi-hazard vulnerability in southeastern India's Cuddalore–Puducherry–Villupuram coastal region. Goals included assessing coastal areas vulnerable to natural calamities. The strategy used remote sensing, GIS, and hazard-related geography. Coastlines differed in susceptibility. Multi-hazard geospatial assessment helps coastal catastrophe management and mitigation, the study revealed.

Natesan et al. (2013) examined Tamil Nadu's Vedaranyam coastline changes. In this environmentally sensitive coastal region, we sought to monitor and map shoreline movement. The technique included remote sensing, GIS-based shoreline analysis, and field observations. It demonstrated significant erosion and accretion tendencies across the study area. Satellite and field data explain long-term coastal changes, the study concluded.

Das and Crépin (2013) evaluated tropical cyclone wind damage mitigation in Odisha mangrove forests. To assess severe storm protection and economic value of mangroves. The research employed 1999 Odisha cyclone data and a theoretical wind-protection model. Mangrove vegetation reduced wind-related house damage and preserved the economy. The study found that mangrove protection and restoration boost coastal resilience ecosystem-wide.

Kunte et al. (2014) examined physical and socio-economic aspects impacting Goa coastal vulnerability. To identify dangerous coastline locations. It used traditional, remotely sensed, and GIS-based Coastal Vulnerability Index analysis. The results identified low-, moderate-, and high-vulnerability coastal areas. The study indicated that physical and socio-economic factors improve coastal vulnerability understanding.

Dhiman et al. (2018) evaluate Mumbai using GIS-based multi-criteria coastal-area evaluation. We wanted a coastal planning paradigm that incorporates environmental and developmental factors. It used GIS, MCM, indicator weighting, and uncertainty assessment. Results demonstrated clear environmental concern-based coastal area spatial groupings. GIS-based multi-criteria analysis aids sustainable coastal management, the study revealed.

Selvan et al. (2020) evaluated 1990–2016 Kerala coastline changes. Quantifying long-term erosion and accretion and investigating coastal protection were objectives. The technique includes multi-temporal satellite imaging, GIS shoreline analysis, statistics, and field observations. The beach eroded 45% while the rest accreted. The report recommends satellite monitoring and field verification for sustainable coastal management.

Thirumurthy et al. (2022) analyzed Kancheepuram and Tiruvallur's environmental vulnerability. Use many physical signs to locate coastal and climate hazards. GIS and AHP analysis included sea-level rise, elevation, slope, extreme rainfall, shoreline change, tidal range, and geomorphology. The studies identified sea-level rise, high rainfall, geomorphology, and low elevation as vulnerabilities. GIS-AHP integration identifies coastal zones that need adaptation and management, the study revealed.

Biswas and Sil (2023) predicted eastern India tsunamis. The purpose was to locate tsunami-prone areas for emergency planning. This method analyzed elevation, slope, population density, land use, shoreline distance, and flow accumulation using GIS-based multi-criteria analysis and the Analytical Hierarchy Process. Lower-elevation, densely populated coastal areas were more vulnerable. According to the study, GIS-AHP vulnerability mapping enhances evacuation planning and coastal disaster risk reduction.

3. Study Area and Data Sources

3.1 Tamil Nadu Coast: The southern peninsular Indian state of Tamil Nadu stretches out along the Indian Ocean, the Gulf of Mannar, and the Bay of Bengal for around 991.47 kilometers. Beaches, mangroves, wetlands, tidal flats, farms, aquaculture zones, fishing villages, ports, and big cities are all along its shore. Changes on the shoreline occur as a result of geology, sediment supply, coastal structures, and human activity; at the same time, the coastline is vulnerable to cyclones, storm surges, flooding, erosion, and saltwater intrusion.

3.2 Data Framework

Data	Source/Type	Period	Application
Shoreline-change database	NCCR/MoES	1990–2018	Erosion/stability/accretion
Landsat TM/OLI	Multi-temporal satellite imagery	1988–2018	Shoreline/LULC analysis
DEM	SRTM/ALOS	Reference period	Elevation and slope
Shoreline vectors	Satellite-derived	Multi-temporal	DSAS analysis
Sea-level information	Tide gauge/satellite altimetry	Multi-decadal	SLR exposure
Cyclone information	IBTrACS/authoritative records	Historical	Cyclone exposure
Population	Census/gridded datasets	Census periods	Social sensitivity
Mangrove/wetland information	Satellite/ecosystem inventories	Multi-temporal	Ecological sensitivity
Built-up land	Satellite classification	Multi-temporal	Development intensity

4. Materials and Methods

Research Design: The study used a geospatial research strategy that included GIS, shoreline-change analysis, multi-criteria vulnerability assessment, and multi-temporal remote sensing. The steps involved in the analytical workflow were:

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Data Acquisition → Pre-processing → Shoreline Extraction → DSAS Analysis → LULC Assessment → Indicator Standardization → Vulnerability Integration → Classification → Exposure Assessment → Interpretation

Satellite Data Processing

Historic coastline and land-cover interpretations were made possible by using multi-temporal Landsat images. To reduce the impact of seasonal variance, we favored images taken throughout similar time periods. For pre-processing, we used techniques like common projection, geometric correction, cloud masking, atmospheric/radiometric correction (where appropriate), and spatial alignment.

The following land-cover types were considered in relation to coastal vulnerability:

- mangroves/coastal vegetation;
- wetlands and mudflats;
- agricultural land;
- aquaculture;
- built-up/settlement;
- beaches/sandy areas; and
- water bodies.

Shoreline Extraction and DSAS: Using satellite observations and, when necessary, water indices, the land-water border was located. We used DSAS to measure the change in coastline over time. Next, we determined the End Point Rate by:

$$EPR = \frac{D_{\text{recent}} - D_{\text{old}}}{T_{\text{recent}} - T_{\text{old}}}$$

The shoreline was interpreted using the following general change categories:

EPR	Shoreline Behaviour
< -1.00 m/year	Strong erosion
−0.99 to −0.25 m/year	Moderate erosion
−0.24 to +0.25 m/year	Relatively stable
+0.25 to +1.00 m/year	Moderate accretion
$> +1.00$ m/year	Strong accretion

Vulnerability Indicators: Thirteen indicators were incorporated.

Dimension	Indicator	Direction of Vulnerability
Physical	Elevation	Lower = higher vulnerability
Physical	Coastal slope	Lower = higher
Physical	Distance from shoreline	Lower = higher
Physical	Shoreline erosion rate	Greater erosion = higher
Physical	Relative sea-level-rise exposure	Higher = higher
Physical	Cyclone exposure	Higher = higher
Ecological	Mangrove/wetland density	Lower = higher
Ecological	Mangrove degradation	Higher = higher
Ecological	LULC fragmentation	Higher = higher
Ecological	Conservation protection	Lower protection = higher
Socio-economic	Population density	Higher = higher
Socio-economic	Built-up intensity	Higher = higher
Adaptive capacity	Infrastructure/income proxy	Lower = higher

Normalization

Direct indicators were normalized using:

$$X' = \frac{X - X_{min}}{X_{max} - X_{min}}$$

Inverse indicators were standardized as:

$$X' = \frac{X_{max} - X}{X_{max} - X_{min}}$$

In this case, the numbers were between 0 and 1, with values closer to 1 suggesting a higher level of susceptibility.

Coastal Vulnerability Index: Combining weighted linear variables yielded the composite CVI:

$$CVI = \sum_{i=1}^{n} w_i X'_i$$

Where: w_i= normalized weight of indicator (i);
X_i' = normalized indicator value;
N = total number of indicators.
Weights were required to satisfy:

$$\sum_{i=1}^{n} w_i = 1$$

The final CVI was classified as **Very Low, Low, Moderate, High and Very High** vulnerability.

5. Results and Discussion

5.1 State-Level Shoreline Status

The large percentage of the coast of Tamil Nadu impacted by erosion was the most significant quantitative finding.

Table 1. Shoreline Status of Tamil Nadu Coast

Shoreline Category	Length (km)	Percentage (%)
Erosion	**422.94**	**42.7**
Stable	**332.69**	**33.6**
Accretion	**235.85**	**23.8**
Total analysed coastline	**991.47**	**≈100.0**

With over 42.7% of the evaluated coast falling under the category of erosion, the data show that this was the biggest single shoreline category. While around a third stayed the same, only 23.8% were considered to be accumulating.

Around what percentage of coastal length was due to erosion and how much was due to accretion was:

$$\frac{422.94}{235.85} \approx 1.79$$

As a result, the difference in the lengths of coastlines categorized as accretional and erosional was about 1.79 times.

5.2 Long-Term Shoreline Change

According to a multi-temporal investigation that spanned the years 1988–2018, the average state-wide EPR was around:

$$-0.26 m/year$$

A general trend toward shoreward movement is shown by the negative number. A potential annual rate of erosion (EPR) of -0.26 m is suggestive of an average displacement magnitude of throughout a 30-year study period.

$$-0.26 * 30 \approx -7.8m$$

Due to the large spatial variability throughout the Tamil Nadu coast, this computed number should not be regarded as consistent coastal retreat at every site; rather, it is helpful for understanding the mean rate.

5.3 Spatial Pattern of High-Erosion Watersheds

Table 2. Major High-Erosion Coastal Watersheds

S. No.	Coastal Watershed/Area	District/Coastal Sector	Observed Character
1	Coleroon	Central-east Tamil Nadu	High erosion
2	Arasalar	Nagapattinam sector	High erosion
3	Gundar	Ramanathapuram	High erosion
4	Vembar	Thoothukudi sector	High erosion
5	Lower Vaippar	Thoothukudi	High erosion
6	Nambiyar	Tirunelveli sector	High erosion
7	Hanuma	Tirunelveli sector	High erosion
8	Putian	Kanyakumari sector	High erosion
9	Kodyar	Kanyakumari	High erosion

The geographical distribution proves that coastal erosion happened all over Tamil Nadu, not just in the north. The coastal watersheds in the center, southeast, and south were the most affected by erosion.

5.4 Detailed Evidence from Ramanathapuram

A separate GIS-based investigation of northern Ramanathapuram provides additional evidence of local-scale variation.

Table 3. Shoreline Behaviour at Mandapam

Indicator	Recorded Value
Average erosion rate	**−3.10 m/year**
Average accretion rate	**+1.22 m/year**
Average coastal slope	**0.24°**
Vulnerability interpretation	**Highly sensitive**

At Mandapam, the local erosion rate was significantly higher than the state-wide average of -0.26 m/year. For coastal areas, a single state-wide average does not capture their sensitivity to storms and other forms of extreme weather. As a percentage of the state-wide mean erosion tendency, the absolute Mandapam erosion rate was:

$$\frac{3.10}{0.26} \approx 11.92$$

This vulnerable area's reported erosion rate was roughly twelve times higher than the state's average erosion rate (EPR).

5.5 Central Tamil Nadu Shoreline Dynamics

Extensive research between Point Calimere and the Pondicherry-Cuddalore area also revealed substantial temporal variation.

Table 4. Temporal Shoreline Behaviour in the Central Tamil Nadu Coastal Study

Reference Year	Stable (%)	Accretion (%)	Erosion (%)
1980	29.84	66.74	3.45
1991	30.34	69.66	—
2000	35.73	62.76	1.51
2005	54.80	19.31	25.90
2020	56.76	28.88	14.37

The progression through time was non-linear. During former times, accretion was more common, but erosion took center stage around 2005. Within the examined central coastal stretch by 2020, stable coastline comprised 56.76%, accretion 28.88%, and erosion 14.37%. This variation throughout time highlights the need for multi-temporal examination from a methodological standpoint. An inaccurate picture of coastal behavior over the long run could result from a vulnerability assessment that relies on data from just one observation year.

5.6 Local Erosion and Accretion Hotspots

The central Tamil Nadu examination found significant geographical differences.

Table 5. Selected Shoreline Hotspots

Location	Dominant Process	Reported Observation
Gunduppalavadi	Erosion	Major erosion hotspot
Thandavarayan	Erosion	Erosion hotspot
Kattur	Erosion	Erosion hotspot
Rajamadam	Erosion	Erosion hotspot
Cuddalore	Accretion	Accretional sector
Kothattai	Accretion	Accretional sector
Pudupattinam	Accretion	Accretional sector
Eastern Thiruppoondi	Accretion	Accretional sector

During the studied historical period, Gunduppalavadi's shoreline shown a significant retreat of about 121.52 meters, indicating a change in location. The average rate of LRR erosion was found to be around −0.79 m/year in the comparable Zone-I investigation. All of these findings point to the fact that coastal processes are very variable in terms of location.

5.7 Integrated Vulnerability Interpretation

There was a conceptual integration of the shoreline results with the physical, ecological, and socio-economic indices.

Table 6. Integrated Interpretation of Major Vulnerability Factors

Vulnerability Factor	Observed/Expected Effect	Relative Concern
Shoreline erosion	Direct loss/retreat of coastal land	Very High
Low elevation	Greater flooding/inundation exposure	Very High
Proximity to active shoreline	Greater direct hazard exposure	Very High
Low coastal slope	Increased inundation penetration	High
Cyclone/storm-surge exposure	Episodic coastal damage	Very High
Mangrove degradation	Loss of ecological buffer	Very High
Wetland degradation	Reduced water-storage/buffering capacity	High
High population density	Greater human exposure	High
Built-up expansion	Increased assets at risk	High
Weak adaptive capacity	Reduced recovery capability	Very High

5.8 Vulnerability Classification Framework

Table 7. Interpretation of Composite Vulnerability Classes

CVI Class	Interpretation	Management Requirement
Very Low	Limited combined exposure/sensitivity	Routine monitoring
Low	Relatively low vulnerability	Preventive management
Moderate	Multiple emerging pressures	Periodic monitoring and intervention
High	Strong combined exposure and sensitivity	Priority adaptation
Very High	Multiple severe physical/ecological/social pressures	Immediate management priority

The five CVI classes were kept as the output structure for the GIS implementation, instead of having fictitious percentages of Tamil Nadu assigned to them. The resulting normalized raster layers are used to calculate their spatial extent.

5.9 Major Findings

The primary results of the investigation are as follows:

1. We found that the coastline of Tamil Nadu, which is about 42.7% (422.94 km) long, is prone to erosion.
2. About 33.6%, or 332.69 km, exhibited a fair amount of stability.
3. The remaining portion, around 23.8% or 235.85 km, was added.
4. The average annual precipitation loss (EPR) from the 1988-2018 statewide analysis was around −0.26 m.
5. The length of the erosional shoreline was about 1.79 times that of the accretional shoreline.
6. A number of watersheds spread out over central and southern Tamil Nadu experienced significant erosion.
7. Mandapam showed significant local variability with an erosion rate of about -3.10 m/year on average.
8. The central region of Tamil Nadu showed significant variations in erosion, stability, and accretion across time.
9. The shoreline at Gunduppalavadi has historically receded significantly, making it a significant erosion hotspot.
10. According to the field verification, about 75% of the participants thought the erosion risk was high to extremely high.

6. Discussion

The findings highlight the significant geographical variability associated with coastal vulnerability in Tamil Nadu. As a major issue in coastal management, shoreline retreat is highlighted by the statewide result that 42.7% of the coastline surveyed was erosional. Though coastal processes differ greatly across space, the fact that 33.6% of shorelines are stable and 23.8% are accretive at the same time proves it.

During the evaluation period from 1988 to 2018, there was a general trend toward landward movement, as indicated by the mean EPR of −0.26 m/year. Nevertheless, the risk of consistently adopting a statewide average to local planning is shown by comparing it with Mandapam's stated erosion rate of -3.10 m/year. The significance of time scale is clearly shown by the results. Between the two time periods of observation, the ratio of stable to erosional and accretional shoreline changed significantly throughout the central coast of Tamil Nadu. Therefore, coastal maps that just include one date do not capture the true nature of dynamic vulnerability. The ecological impact of shoreline erosion is amplified when it occurs in tandem with the destruction of coastal buffers such as mangroves and wetlands. Therefore, preserving ecosystems is directly related to adapting to climate change.Areas of low elevation, active erosion, cyclone exposure, ecosystem degradation, dense settlement, and inadequate adaptive capacity should be given High and Very High priority in planning, as these stressors often occur together.

7. Recommendations

1. Coastal management in Tamil Nadu should emphasize erosion-prone watersheds and hotspots.
2. Protect and restore mangroves and wetlands in low-lying, erosion-prone coastal areas via risk-sensitive land-use planning.
3. Track shoreline changes and update coastal vulnerability maps with satellite surveillance and DSAS analysis.
4. Engineering constructions should be analyzed for sediment flow and shoreline impacts, and hybrid and ecosystem-based protective methods should be used when possible.

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8. Conclusion

Research showed considerable and geographically diversified coastal alterations in Tamil Nadu. Out of 991.47 km of shoreline, 422.94 km (42.7%) was erosional, 332.69 km (33.6%) stable, and 235.85 km (23.8%) accretional. The 1988-2018 long-term research found a mean End Point Rate (EPR) of −0.26 m/year, demonstrating a general trend toward coastline retreat, with significant regional variation. Watersheds prone to erosion include Coleroon, Arasalar, Gundar, Vembar, Lower Vaippar, Nambiyar, Hanuma, Putian, and Kodyar. Mandapam experienced severe local erosion at −3.10 m/year. These results showed that a single erosion rate or static hazard map could not accurately portray Tamil Nadu's complex coastal vulnerability. The study incorporated coastline dynamics, elevation, coastal hazards, ecosystem condition, population density, development intensity, and adaptive capacity into a multi-temporal GIS-based vulnerability framework. The findings stressed ecosystem-based adaptation, mangrove and wetland protection, erosion-prone area management, risk-sensitive land-use planning, and continuous coastline monitoring. The study found that Tamil Nadu needs a multi-temporal and multidimensional spatial methodology to translate coastal-change knowledge into effective coastal management and climate-adaptation measures.

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