

Assessment of Coastal Vulnerability Along the Kakinada Coast Using a GIS-Based Coastal Vulnerability Index— a case study of the Kakinada district Coast, Andhra Pradesh, India

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Abstract—This study assesses the physical coastal vulnerability of the Kakinada coast, Andhra Pradesh, India, using a GIS-based Coastal Vulnerability Index (CVI) approach. Five key parameters—geomorphology, coastal slope, shoreline change rate, spring tide range, and significant wave height—were integrated using multi-temporal satellite data, remote sensing, and secondary sources. The CVI was computed using a geometric mean method and classified into five vulnerability categories. Results indicate that most of the coastline falls under moderate to high vulnerability, with very high vulnerability concentrated along erosion-prone sectors such as Uppada and near Kakinada Port. These areas are characterized by low coastal slope, unconsolidated landforms, and persistent shoreline retreat. The study confirms that the GIS-based CVI method is an effective tool for identifying vulnerable coastal stretches and supports its application for coastal management and planning.

Index Terms—Coastal Vulnerability Index; Shoreline Change Rate; Coastal Slope; Significant Wave Height; Spring Tide Range; Kakinada Coast

I. INTRODUCTION

Coastal zones are among the most dynamic and sensitive environments, continuously shaped by the interaction of geological, oceanographic, and climatic processes. Factors such as shoreline erosion, wave action, tidal dynamics, and sea-level variability play a significant role in determining the stability of coastlines. In recent decades, several studies have reported that these processes are intensifying due to climate change and increasing anthropogenic pressures, thereby enhancing the vulnerability of coastal regions (FitzGerald et al., 2008; IPCC, 2014).

To systematically evaluate coastal susceptibility, the Coastal Vulnerability Index (CVI) has been widely adopted as a quantitative framework that integrates multiple physical parameters into a single indicator of relative vulnerability. Early applications of the CVI focused on parameters such as geomorphology, coastal slope, shoreline change, tides, and wave height to identify erosion- and inundation-prone coastal sectors (Thieler and Hammar-Klose, 2000; Nageswara Rao et al., 2008). More recent studies have combined remote sensing data with Geographic Information System (GIS) techniques to generate spatially explicit vulnerability maps that support coastal planning and management (Pramanik et al., 2016; Kantamaneni et al., 2019).

Along the Indian east coast, several CVI-based studies have documented high levels of vulnerability in deltaic and sediment-deficient environments, where low coastal relief, unconsolidated sediments, and energetic wave conditions coexist. Studies conducted along the Andhra Pradesh coast have reported severe shoreline erosion and coastal instability at locations such as Uppada, Kakinada, and adjacent deltaic stretches (Pal and Rao, 2008; Kankara et al., 2015). Despite these findings, a comprehensive GIS-based coastal vulnerability assessment focusing specifically on the Kakinada district coast using multi-decadal shoreline data remains limited.

The present study addresses this gap by developing a GIS-based Coastal Vulnerability Index for the Kakinada district coast using five key physical parameters: geomorphology, coastal slope, long-term shoreline change rate, spring tide range, and significant wave height. Multi-temporal satellite

imagery covering the period from 1995 to 2025, along with ancillary geospatial datasets, was integrated to assess spatial variations in physical coastal vulnerability within a 10 km coastal buffer. The

primary objective of the study is to identify and map vulnerable coastal stretches and to provide a scientific baseline for future coastal monitoring and management in the Kakinada district region.

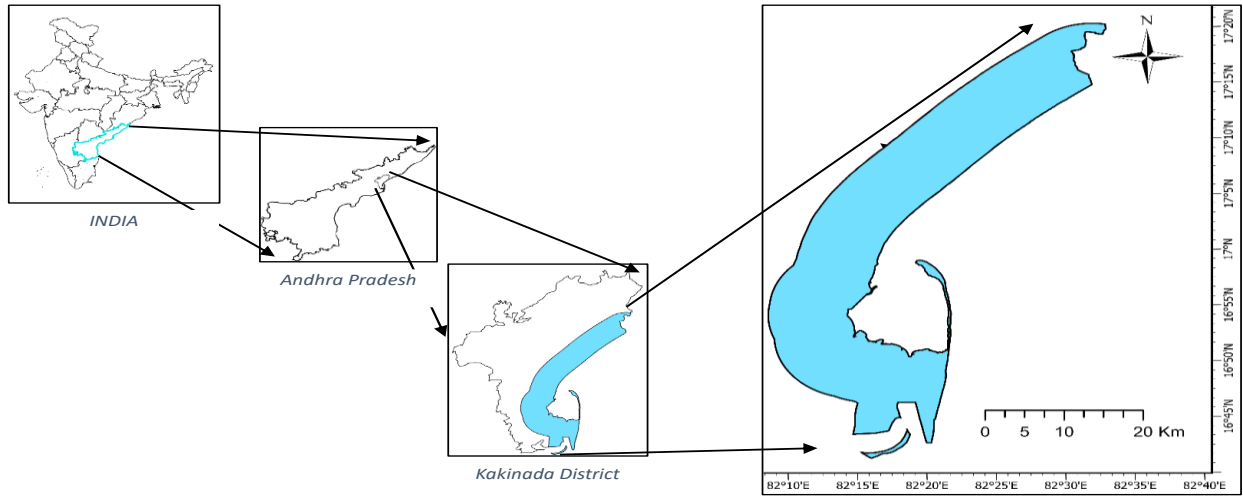


Figure 1 Location map of the Kakinada district coast showing regional, state, district and 10 km coastal buffer zone

a. Study Area

The Kakinada district coast which is approximately 144 km along the east coast of India has been chosen for the study (Figure 1). This 144 km shoreline falls entirely within a major fluvio-deltaic plain dominated by mudflats, tidal creeks, mangrove islands, beach-swale complexes, and extensive aquaculture and port developments. Elevations are predominantly below 5 m above mean sea level, making the region highly susceptible to storm surges, cyclone inundation, and sea-level rise. The coastline is semi-diurnal with significant spring tide amplifications, and the wave climate is driven by monsoon winds and tropical cyclones, producing moderate to high nearshore wave energy. Historical surveys report chronic shoreline retreat north of Kakinada Port (especially at Uppada) and localized accretion near sheltered estuarine and mangrove areas around Coringa and Yanam. Economically, the area hosts the Kakinada deep-water port, oil and gas facilities, and extensive shrimp farms, underscoring the need for risk-informed planning and hazard mitigation.

II. MATERIALS AND METHODS

a. Data Sources and Preparation

Multi-source spatial data has been collected to develop the CVI parameter layers, the details of the sources and

the corresponding period related to the data are shown here in Table 1.

The methodology used in the study is presented in Figure 2 and the details detailed description preparing each layer such as geomorphology, coastal slope, spring tide range, significant wave height, shoreline change rate are described as below

b. Geomorphology

Geomorphology constitutes a primary determinant of coastal vulnerability, as it reflects the inherent resistance of coastal landforms to marine and atmospheric forcing. The geomorphological framework of the Kakinada districts coast is predominantly deltaic in nature, shaped by long-term sediment deposition from the Godavari River system and continuous reworking by waves, tides, and currents. To capture this variability, geomorphological information was compiled from published coastal geomorphology maps obtained from the National Remote Sensing Centre (NRSC), supplemented by interpretation of multi-temporal satellite imagery and high-resolution Google Earth data. Survey of India topographic sheets were additionally used to validate landform boundaries and drainage patterns.

Distinct geomorphic units such as beaches, beach ridges, swales, tidal flats, mangrove swamps, estuarine islands, younger and older deltaic plains, floodplains,

pediplains, and residual uplands were identified and digitized within a 10 km landward buffer from the shoreline using . These units were classified based on sediment composition, degree of consolidation, elevation, and exposure to hydrodynamic processes. Highly dynamic and unconsolidated features such as sandy beaches, mudflats, spits, and beach ridge–swale complexes were assigned higher vulnerability ranks due to their susceptibility to erosion and inundation. In contrast, relatively stable landforms such as pediplains, older deltaic plains, and consolidated uplands were assigned lower vulnerability ranks. The finalized geomorphology layer was converted to raster format and reclassified into a standardized five-class vulnerability scale to ensure compatibility with other CVI parameters.

c. Coastal Slope

Coastal slope is a critical factor influencing the extent of inundation, storm surge penetration, and flood duration along low-lying coastlines. Even minor variations in slope can significantly alter coastal response during extreme events, particularly in deltaic

environments such as Kakinada. To quantify coastal slope characteristics, a Shuttle Radar Topography Mission (SRTM) Digital Elevation Model with 30 m spatial resolution was obtained from NASA–USGS repositories. The DEM was subjected to preprocessing steps including sink filling and surface smoothing to remove artefacts and improve elevation continuity.

Slope values were derived in degrees and the resulting slope raster revealed that much of the Kakinada coastal plain is characterized by extremely gentle gradients, often less than one degree, which enhances vulnerability to tidal inundation and storm surge flooding. Based on established coastal vulnerability literature, lower slope values were considered indicative of higher vulnerability. The slope raster was therefore classified into five vulnerability classes, with slopes less than or equal to 1° representing very high vulnerability, and progressively steeper slopes representing lower vulnerability categories. The classified slope layer was normalized to the common CVI scale and prepared for integration with other physical parameters.

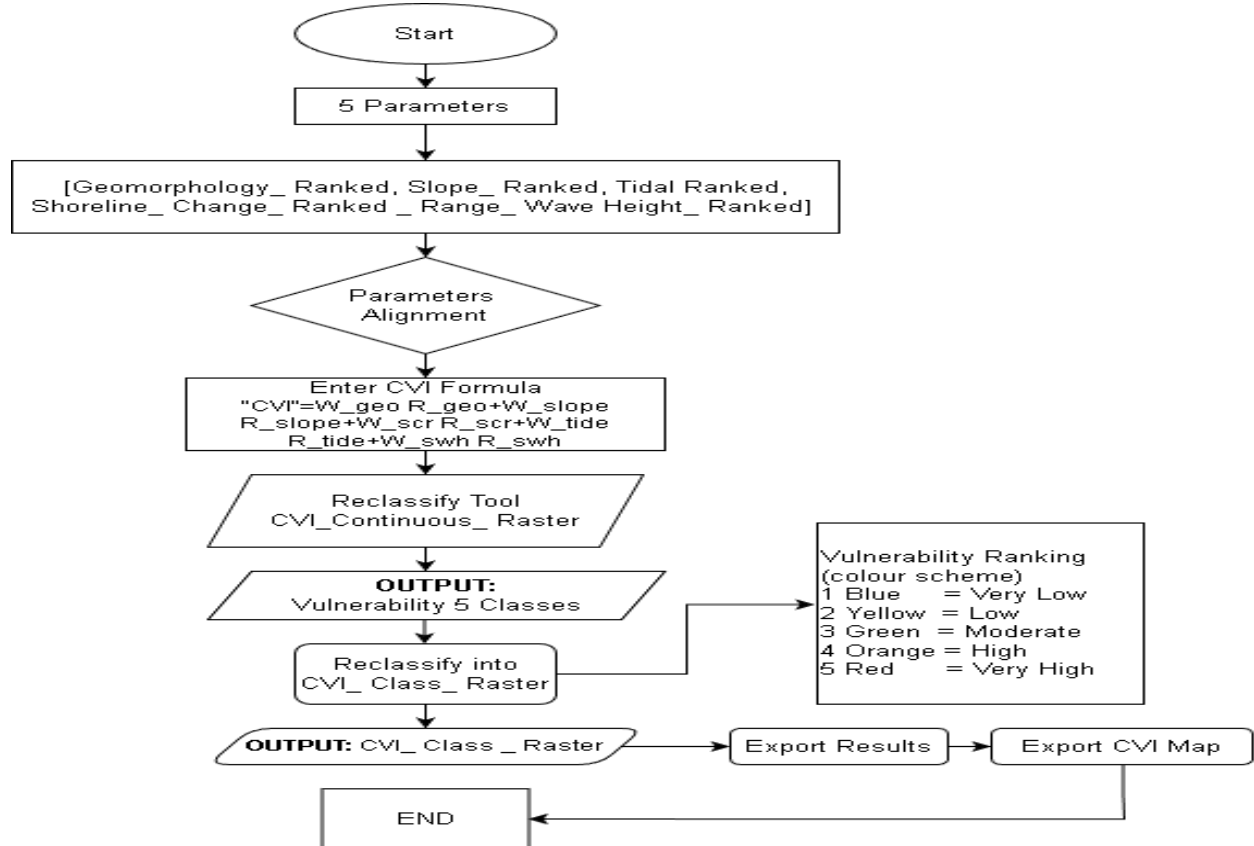


Figure 2 Overall methodological framework adopted for Coastal Vulnerability Index (CVI) computation along the Kakinada district coast.

Table 1. Data sources and specifications.

Dataset / Parameter	Source / Agency	Year(s)	Resolution/Type	Purpose
Landsat 5, 7, 8, 9 Imagery	USGS Earth Explorer	1995–2025	30 m multispectral	Shoreline extraction and change analysis
SRTM Digital Elevation Model	NASA / USGS	2014 (latest)	30 m DEM	Coastal slope calculation
Tidal Range Data (Spring)	INCOIS, Survey of India	2023–2024	Point measurements	Spring tide raster interpolation
Significant Wave Height (SWH)	INCOIS / ECMWF (ERA5 Reanalysis)	2022–2024	Satellite-assimilated numerical wave model data	Wave climate characterization and CVI input
NRSC Coastal Landform Maps	National Remote Sensing Centre	Latest	Vector landform datasets	Geomorphology classification
Administrative Boundaries	Survey of India	Latest	Vector shapefiles	Study area demarcation

d. Tidal Range

Tidal dynamics significantly influence coastal flooding, sediment transport, and estuarine circulation patterns. The Kakinada district coast experiences semi-diurnal tides, with spring tides producing maximum water level fluctuations that exacerbate inundation during storm events. Spring tidal range data were obtained from tide gauge records provided by the Indian National Centre for Ocean Information Services (INCOIS) and supporting hydrographic sources.

Point-based tidal range observations representing maximum spring tide amplitudes were compiled and spatially interpolated using ordinary kriging to generate a continuous tidal range raster. Areas experiencing higher tidal ranges were considered more vulnerable due to increased flood depth, prolonged water retention, and enhanced erosion potential, particularly over low-slope deltaic terrain. The interpolated tidal range raster was classified into five vulnerability categories, with higher tidal amplitudes assigned higher vulnerability ranks. The final tidal range layer was normalized and aligned spatially with other CVI parameter rasters.

e. Significant Wave Height

Significant wave height (SWH) represents the average height of the highest one-third of waves and is a primary indicator of wave energy impacting coastal erosion and sediment transport. In this study, SWH data were derived from satellite-assimilated numerical

wave model outputs (ERA5 reanalysis) accessed through INCOIS. The selected parameter represents the significant height of combined wind waves and swell, which corresponds to the standard oceanographic definition of significant wave height (Hs) and captures the total wave energy influencing the coastline.

The wave dataset was available at discrete spatial locations and at a coarser resolution relative to the narrow coastal buffer adopted in this study. To generate a spatially continuous and high-resolution wave height surface suitable for Coastal Vulnerability Index (CVI) integration, representative wave height values were spatially interpolated using ordinary kriging. The kriged surface was converted to raster format and clipped to the 10 km coastal buffer to restrict the analysis to the coastal influence zone. The resulting SWH raster exhibited moderate spatial variation along the coast and was subsequently reclassified into five vulnerability classes, with higher wave heights assigned higher vulnerability ranks.

f. Shoreline Change Analysis (DSAS)

Shoreline change analysis provides direct insight into the long-term stability of the coast and reflects the cumulative effects of waves, tides, sediment supply, and human interventions. In this study, shoreline change along the Kakinada district coast was quantified using the Digital Shoreline Analysis System (DSAS), a GIS-based extension developed by the United States Geological Survey. Multi-temporal

Landsat satellite images acquired between 1995 and 2025 were used to extract historical shoreline positions at decadal and sub-decadal intervals.

All shoreline datasets were georeferenced to a common coordinate system and digitized consistently along the wet-dry boundary to minimize positional errors. A baseline was established parallel to the general orientation of the coastline, and shore-normal transects were generated at 100 m spacing. The Linear Regression Rate (LRR) method was applied to compute long-term shoreline change rates, as it provides statistically robust estimates by considering all available shoreline positions over time. Negative LRR values indicate erosional trends, while positive values indicate accretion.

The computed shoreline change rates revealed extensive erosion along exposed stretches near Uppada, Kothapalem, and the Kakinada port region, while limited accretion was observed in sheltered areas influenced by sediment trapping. The LRR values were interpolated to generate a continuous shoreline change raster, which was subsequently classified into five vulnerability ranks, with high erosion zones assigned very high vulnerability and accretion-dominated zones assigned low vulnerability. The classified SWH raster was standardized to the common vulnerability scale to facilitate integration within the CVI framework.

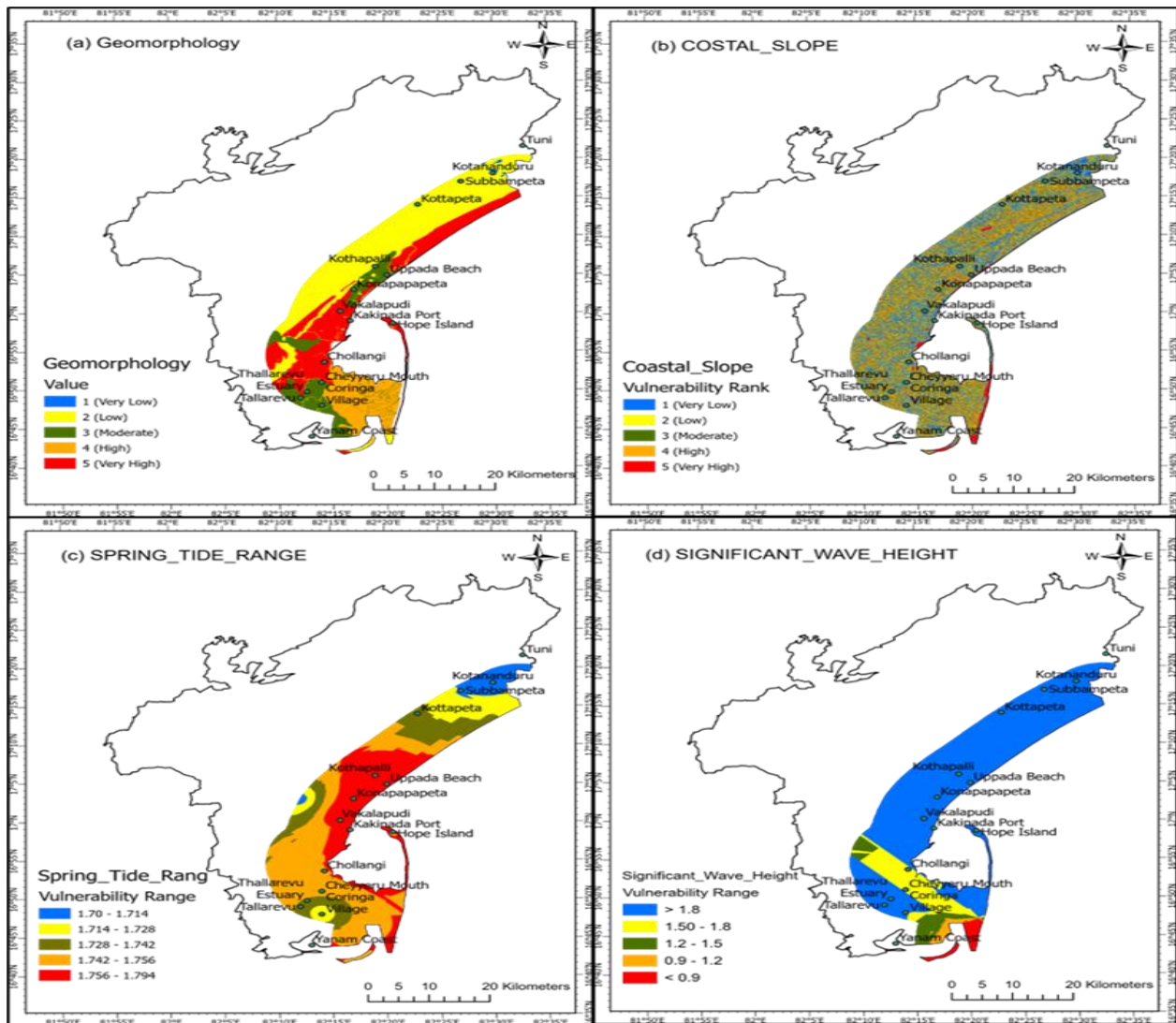


Figure 3 shows the spatial distribution of the four physical variables: (a) geomorphology, (b) coastal slope, (c) spring tidal range, and (d) significant wave height.

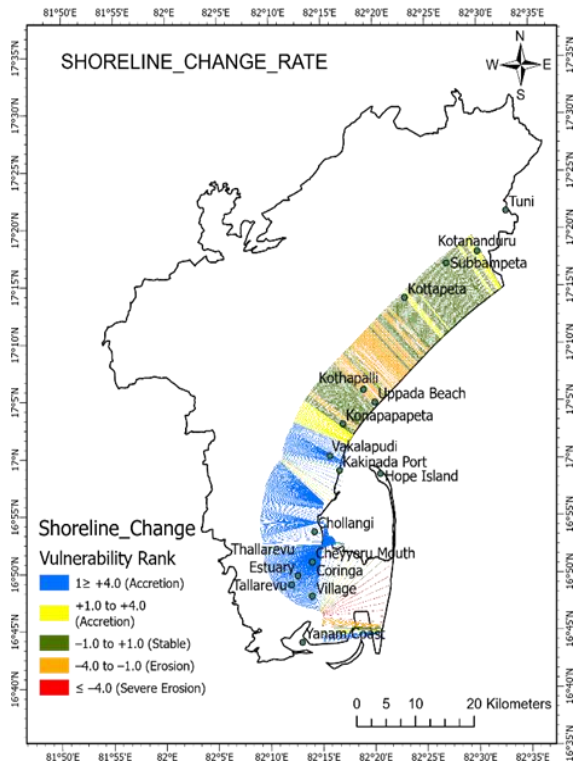


Figure 4 Map shows Shoreline change rate during 30-year period between 1995-2025

g. Analytic Hierarchy Process (AHP) Integration
 To integrate the five parameters into a single CVI, we used a weighted linear combination (WLC) model with weights derived from the Analytical Hierarchy Process. A pairwise comparison matrix was constructed based on expert judgement and literature consensus (giving greater importance to shoreline change and geomorphology in this deltaic context). The resulting normalized weights were: geomorphology (0.32), shoreline change rate (0.28), coastal slope (0.14), significant wave height (0.14), and tidal range (0.12). Each parameter raster was first rescaled to a common 1–5 vulnerability scale, then multiplied by its AHP weight using GIS Raster Calculator. The weighted rasters were summed to produce a continuous CVI raster.

h. CVI Classification
 The continuous CVI values were classified into five vulnerability categories using the Natural Breaks (Jenks) method, with manual adjustment for consistency. The final classes and value ranges are given in Table 2.

The weighted overlay integration ensured that each normalized parameter contributed proportionally to the final CVI.

Table 2: CVI Vulnerability Classes.

CVI Value Range	Vulnerability Class
1.28 – 2.053	Very Low
2.053– 2.494	Low
2.494 – 2.934	Moderate
2.934 – 3.428	High
3.428 – 4.68	Very High

Integration Workflow All parameter rasters were aligned to the same 30 m grid (WGS 84 UTM 44N). The following steps were performed during the GIS-based integration:

- Each parametric raster was normalized to a 1–5 vulnerability scale.
- Each normalized raster was multiplied by its AHP weight (using Raster Calculator).
- The weighted rasters were summed cell-by-cell to generate the continuous CVI raster.
- The CVI raster was normalized to values between 1.28 and 4.68 and then classified into the five vulnerability classes (Table 2).

This process produced a final vulnerability map ready for analysis.

III. RESULTS

a. Parametric Layer Outcomes

The five physical parameters exhibit clear spatial variability along the Kakinada district coast. Geomorphological mapping indicates that large sections of the northern and central coast are dominated by unconsolidated sandy beaches, beach ridges, and tidal flats, which were assigned higher vulnerability ranks, while relatively stable deltaic plains and mangrove-dominated sectors show lower vulnerability. Coastal slope analysis reveals that most of the shoreline is characterized by very gentle slopes (<2°), particularly along the central and southern sectors, resulting in predominantly high to very high vulnerability rankings.

Shoreline change analysis using DSAS indicates that erosion and accretion patterns vary distinctly along the coast. The northern Uppada sector and areas adjacent to Kakinada Port exhibit persistent erosion, whereas accretionary trends dominate near Hope Island and

within the Coringa mangrove region. Importantly, the observed long-term rates are moderate in magnitude, with no extreme erosion exceeding -4 m/yr, consistent with the transect-based LRR statistics derived from multi-temporal shoreline data.

Spring tide range and significant wave height layers display moderate spatial gradients along the coast. Higher tidal ranges and wave exposure are observed along the open northern shoreline, while reduced values occur within estuarine and mangrove-protected

environments, contributing to comparatively lower vulnerability in these sheltered zones.

b. Shoreline Change Characteristics (LRR-Based)

Based on the corrected DSAS results and transect statistics, shoreline change patterns were summarized by coastal sector in terms of rate ranges and affected shoreline length (Table 3). The results indicate that erosional stretches are spatially limited but persistent, whereas accretionary segments are more extensive in the southern and mangrove-dominated regions.

Table 3. Shoreline Change (LRR) Class Distribution Along Kakinada Coast

LRR Class (m/yr)	Process Category	Shoreline Length (km)
$\geq +4.0$	Strong Accretion	37.1
+1.0 to +4.0	Moderate Accretion	9.5
-1.0 to +1.0	Stable	25.7
-4.0 to -1.0	Erosion	12.1
≤ -4.0	Severe Erosion	0.8
Total		85.2 km

c. Distribution of Vulnerability in Terms of Shoreline Length

The classified CVI raster was intersected with shoreline transects to quantify vulnerability in terms of coastal stretch length (km). Moderate and high vulnerability classes account for the largest proportion of the coastline, while very low vulnerability is restricted to short, discontinuous segments.

Table 4. Distribution of shoreline length across CVI vulnerability classes

CVI Class	Shoreline Length (km)	Proportion of Coast
Very Low	37.1	Minimal
Low	5.1	Limited
Moderate	13	Dominant
High	28.1	Extensive
Very High	1.9	Localized hotspots

High and very high vulnerability stretches are primarily concentrated along the Uppada coast and exposed sectors east of Kakinada Port, whereas accretion-dominated and mangrove-influenced areas correspond to lower vulnerability classes.

d. Coastal Vulnerability Index (CVI) Map

Integration of the five physical parameters resulted in the final Coastal Vulnerability Index (CVI) raster for

the Kakinada district coast, with values ranging from approximately 1.28 to 4.68. The classified CVI map (Figure 5) reveals pronounced spatial variability in coastal vulnerability governed by the combined influence of geomorphology, coastal slope, shoreline change, tidal range, and significant wave height.

When expressed in terms of shoreline length, the very low vulnerability class occupies the largest stretch of the coast (37.1 km), corresponding mainly to sheltered deltaic and estuarine segments. This is followed by the high vulnerability class (28.1 km), which is concentrated along exposed open-coast sectors. The moderate vulnerability class extends over 13.0 km, representing transitional zones where low relief and unconsolidated sediments are present but shoreline change rates are comparatively moderate.

Very high vulnerability is confined to a limited shoreline stretch of only 1.9 km, appearing as localized hotspots where multiple adverse factors coincide, notably along the Uppada open coast. These segments are characterized by ultra-low coastal slopes, unconsolidated beach-ridge systems, and persistent erosional trends. In contrast, the low vulnerability class accounts for 5.1 km of shoreline, largely associated with relatively stable coastal segments.

The Kakinada Port region exhibits mixed vulnerability characteristics. While localized accretion is observed in sheltered areas near Hope Island and in the lee of

port structures, adjacent exposed segments display elevated vulnerability due to low coastal relief and altered sediment transport pathways. This spatial heterogeneity reflects the strong influence of anthropogenic structures on nearshore sediment dynamics rather than uniform erosion across the port sector.

Mangrove-dominated estuarine environments such as Coringa and Yanam consistently fall within low to very low vulnerability classes, underscoring the stabilizing role of vegetation, reduced wave energy, and enhanced sediment trapping. Overall, the shoreline-length-based CVI representation provides a clearer and management-relevant depiction of coastal risk, highlighting that although very high vulnerability affects a relatively short stretch of coastline, these segments represent critical priority zones for coastal management and intervention.

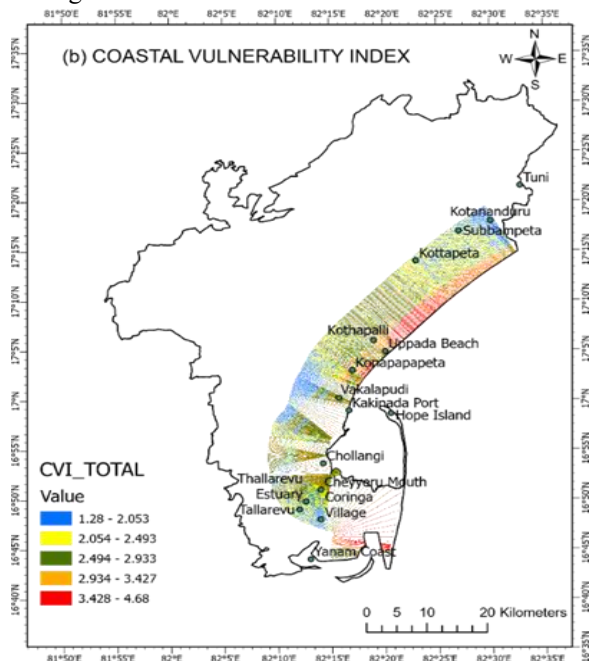


Figure 5. Final classified CVI map of the Kakinada district coast.

IV. DISCUSSION

The Coastal Vulnerability Index (CVI) results reveal a coherent spatial pattern along the Kakinada district coast, governed primarily by geomorphological setting and shoreline dynamics. Open-coast sectors such as the Uppada shoreline consistently exhibit elevated vulnerability due to the concurrence of unconsolidated sandy geomorphology, extremely low

coastal slopes, and persistent erosional trends. These findings align with long-standing field observations and previous regional studies that identify Uppada as one of the most erosion-prone stretches along the Andhra Pradesh coast.

In contrast, estuarine and mangrove-dominated regions, particularly around Coringa and Yanam, display low to very low vulnerability levels. The reduced vulnerability in these zones reflects the combined effects of sediment trapping, vegetation-induced wave attenuation, and relatively stable shoreline behaviour. This highlights the critical role of natural buffers in moderating coastal risk within deltaic environments.

The Kakinada Port region exhibits spatially variable vulnerability, rather than uniform erosion. While DSAS-derived shoreline change rates indicate localized accretion in sheltered zones, especially near Hope Island and in the lee of port structures, adjacent exposed segments register higher vulnerability due to low relief and altered sediment transport pathways. This spatial heterogeneity underscores the influence of anthropogenic interventions on nearshore sediment redistribution, rather than a simple erosion-dominated regime.

Overall, the AHP-weighted CVI integration effectively emphasizes the dominant physical controls on vulnerability. Parameters assigned higher weights—geomorphology and shoreline change rate—exert a strong influence on the final index, consistent with the sediment-starved nature of the Kakinada delta system. The resulting CVI map therefore provides a realistic representation of present-day physical vulnerability, rather than an overgeneralized hazard depiction.

V. CONCLUSION

This study presents a GIS-based Coastal Vulnerability Index (CVI) assessment for the Kakinada district coast by integrating five key physical parameters: geomorphology, coastal slope, shoreline change rate, spring tide range, and significant wave height. The adopted AHP-based multi-criteria framework successfully captures the spatial variability of coastal vulnerability along this dynamic deltaic coastline.

The results identify Uppada and adjacent open-coast stretches as the most vulnerable zones, driven by persistent erosion, unconsolidated sediments, and

ultra-low coastal slopes. In contrast, mangrove-fringed estuaries and sheltered coastal segments exhibit lower vulnerability due to their geomorphic stability and attenuated hydrodynamic conditions. The Kakinada Port sector demonstrates mixed vulnerability characteristics, reflecting the combined effects of engineered structures, localized accretion, and modified sediment transport.

By limiting the analysis to present physical conditions, this study provides a robust baseline assessment of coastal vulnerability without introducing speculative future scenarios. The CVI framework developed here offers a practical decision-support tool for identifying priority zones for monitoring, conservation, and coastal zone management. Importantly, the methodology remains flexible and can be updated with higher-resolution data or additional parameters to support future reassessments as coastal conditions evolve.

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