Assessment of Coastal Vulnerability Index and Shoreline Dynamics Along The Coast of Nagapattinam District, Tamil Nadu, India

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Abstract
Coastal regions are the most dynamic and vulnerable interfaces on Earth, supporting diverse ecosystems and significant human populations, yet facing escalating threats from climate change, natural hazards, and anthropogenic activities. This study evaluated the coastal vulnerability of the Nagapattinam coast, India, using a geospatially derived Coastal Vulnerability Index (CVI) to address the increasing risks of climate change, natural hazards, and anthropogenic pressures. Six key physical parameters, including geomorphology, Land Use/Land Cover (LULC), shoreline change rate, coastal slope, bathymetry, and mean tidal range, were integrated to compute the CVI. Multi-temporal Landsat TM and OLI satellite data (1994–2024) were analysed to assess shoreline dynamics, including erosion and accretion trends. The Digital Shoreline Analysis System (DSAS) was employed to calculate the endpoint rate (EPR), Net Shoreline Movement (NSM), and Linear Regression Rate (LRR). The coastal slope and bathymetry were derived using SRTM data and Naval Hydrographic Charts, respectively. The analysis revealed pronounced spatial variability in coastal vulnerability along the Nagapattinam coast. Villages, namely Nagapattinam, Vadakkupoigainallur, Therkupoigainallur, Velankanni, Prathabaramapuram, Thiruppoondi, Vizhunthamavadi, Vellapalam, Nalavedapathi, Pushpavanam, Periyakuthagai, and Vedaranyam, were identified as highly vulnerable, along with the coastal stretches of Kodiakarai and Point Calimere, which exhibited very high vulnerability owing to persistent shoreline changes and exposure to future sea-level rise. The results highlight significant landform dynamics driven by both natural processes and human intervention. This study provides a scientific basis for informed coastal zone management and risk mitigation planning. Future research can incorporate socioeconomic indicators, high-resolution climate projections, and real-time monitoring to enhance the predictive capability of the CVI framework. Such integrated approaches will support sustainable coastal development and strengthen resilience to evolving coastal hazards.

Keywords: Coastal Vulnerability Index, Remote Sensing, Coastal Dynamics, DSAS, GIS, Nagapattinam and Shoreline Changes.

Introduction

Vulnerability is extensively characterised as the propensity or predisposition to suffer adverse effects of climate change (Comte et al., 2019; Sudha Rani et al., 2015). A multitude of notions and elements are encompassed within the concept of vulnerability, including sensitivity or susceptibility to harm and a deficiency in the capacity to cope and adapt (Faivre and Mićunović, 2017; Kaniewski et al., 2016). Rapid population growth, along with natural and anthropogenic catastrophes and climate change, necessitates the implementation of innovative strategies (Bevacqua et al., 2018). These proactive designs can profoundly influence the safety and welfare of individuals and communities (Rus et al., 2018; Vandeweerd et al., 2002).

According to a comprehensive analysis by the Intergovernmental Panel on Climate Change, coastal regions adjacent to the land-sea boundary represent one of the most dynamic interfaces on the planet and host some of the most diverse and productive ecosystems (McCarthy et al., 2001; MCLAUGHLIN & COOPER, 2010). The current scenario highlights socioeconomic development but also impacts the coastal ecosystems (Arulbalaji&Gurugnanam, 2014a). Highly varied and productive ecosystems are located in coastal regions adjacent to the land-sea interface, rendering them among the most dynamic interfaces on the planet (Balica et al., 2012). Coastal plains, wetlands, sea cliffs, rocky shorelines, and reefs are examples of these varying geomorphological structures (Alcántara-Carrió et al., 2024; Isinkaralar et al., 2024). These coastal regions have emerged as the epicentre of significant urban development and tourism, rendering them susceptible to evolving physical dynamics that induce substantial alterations to the natural environment (Batzakis et al., 2024; Leka et al., 2022). Nearly 40% of the global population lives within 60 km of the coast, leading to severe health crises from coastal pollution. Issues such as deforestation, agricultural fertiliser runoff, and untreated sewage significantly impact human health and vital coastal ecosystems, including mangrove swamps and coral reefs (Šimac et al., 2023). Powerful and dynamic physical forces continuously influence coastal zones and their ecosystems, presenting risks to human activities (J & C, 2017; Villacís et al., 2025).

The concept of coastal vulnerability refers to the spatial identification of individuals and locations at risk of disruption by coastal hazards (Kaniewski et al., 2016). Shoreline modification is one of the most dynamic processes in coastal regions (Alves et al., 2013; Luo & Yang, 2024). The main factors contributing to shoreline changes include geomorphic processes such as erosion and accretion, human activities, waves, tides, winds, and frequent storms (J & C, 2017). Monitoring shorelines is essential for developing disaster-specific coastal management strategies and mitigating the effects on living organisms and environmental resources. Satellite imagery is beneficial for change detection using multi-date data to analyse changes (Raj et al., 2014), and geographic information systems (GIS) help evaluate multiple parameters simultaneously in mapping-related studies (Arulbalaji & Gurugnanam, 2014b; Gurugnanam et al., 2008; Nijagunappa et al., 2007; Palanisamy, 2016). Unlike conventional methods, integrating satellite imagery with GIS and a Digital Shoreline Analysis System (DSAS) for remote sensing enables a more precise assessment of shoreline changes over both short- and long-term periods (Asmorowati et al., 2025; ElKotby et al., 2024).

This study aimed to develop a comprehensive Coastal Vulnerability Index (CVI) for the Nagapattinam Coast in India by employing six relative risk indicators and integrated geospatial techniques, along with the measurement and analysis of erosion and accretion. The susceptibility of the study area was assessed to characterise the vulnerability of the coast to human activities and coastal processes.

Review of Literature

Coastal vulnerability is defined as the susceptibility of coastal systems to adverse impacts from natural hazards and climate change, particularly sea level rise and extreme events (Alves et al., 2013; Comte et al., 2019). The Intergovernmental Panel on Climate Change highlights that coastal zones are among the most dynamic and densely populated regions, making them highly vulnerable to climate change (Mccarthy et al., 2001). The Coastal Vulnerability Index (CVI) has been widely adopted as an effective tool to quantify shoreline risk by integrating multiple physical parameters (Joevivek et al., 2013). Early applications by the United States Geological Survey established the use of variables such as geomorphology, shoreline change, slope, and tidal range in vulnerability assessments. Advances in Remote Sensing and Geographic Information Systems have significantly improved coastal studies by enabling multi-temporal shoreline analysis (Arulbalaji & Gurugnanam, 2014b; Raj et al., 2014). Satellite datasets from the Landsat Program have been extensively used to detect shoreline changes over long periods. The Digital Shoreline Analysis System (DSAS) enhances accuracy by calculating statistical measures such as the EPR, NSM, and LRR (Sam & Gurugnanam, 2022).

In India, several studies along the Bay of Bengal coast have revealed high vulnerability due to low-lying deltaic geomorphology and intense human activities (Dwivedi et al., 2023; Palanisamy, 2016). Land Use/Land Cover (LULC) changes, including urbanisation and mangrove degradation, significantly increase coastal risk (Faria de Deus & Tenedório, 2021). Bathymetry and coastal slope influence wave energy and inundation potential, whereas tidal range affects sediment dynamics (Anfuso et al., 2021). Recent research emphasises the integration of climate projections and socioeconomic factors for comprehensive vulnerability assessments (Bevacqua et al., 2018). However, numerous studies have assessed coastal vulnerability along the southeast coast of India, limited by the use of short-term datasets, inadequate integration of DSAS-based shoreline change analysis, and insufficient consideration of anthropogenic factors. Village-level vulnerability assessments remain scarce. Therefore, this study addresses these limitations by applying a multi-decadal CVI framework to the Nagapattinam coast.

Materials and Methodology

Study Area

The Coastal District of Nagapattinam is situated on the eastern seaboard, adjacent to the Bay of Bengal. It is located approximately 326 km south of the state capital, Chennai, and 145 km from Trichy, which serves as a central town. The administrative centre of the district is situated between the northern latitudes of 10˚19′ and 10˚44′ and the eastern longitudes of 79˚36′ and 79˚52′ (Fig. 1). The coastline extends in a northeastward trajectory from Kollidam to Kodiakkarai and subsequently shifts to an east-west orientation fromKodiakkarai to Atirampattinam. Within the Cauvery River delta, this segment of the shoreline encompasses a limited expanse of sandy beaches. Salt pans are located near Tharangampadi and Thirumullaivasal in Tamil Nadu. The recorded minimum and maximum temperatures were 20°C and 34°C, respectively.

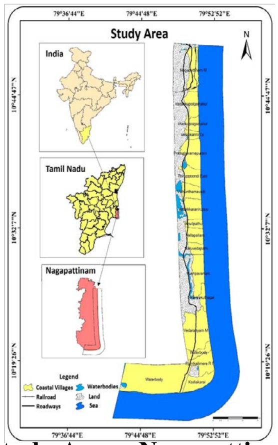

Figure 1 Study Area - Nagapattinam District

Coastal Vulnerability Index

The coastal vulnerability index is calculated based on six vulnerable parameters: shoreline change rate, coastal slope, relative sea level change, mean wave height, and mean tide range (Joevivek et al., 2013) (Figure 2).

CVI = (√a*b*c*d*e*f)/6

a = Geomorphology, b = Land use/land cover, c = Shoreline changes, d = coastal slope, e = Bathymetry, f = Mean tidal Range.

Satellite images were used to delineate each component in the CVI computation. ResourceSat-2 satellite data stored at the data collection site of the Bhuvan thematic dataset were used to demarcate geomorphology, as these data accurately capture significant geomorphic characteristics. The image classification approach in remote sensing is used to classify pixel-based Land Use and Land Cover categories (Arulbalaji & Gurugnanam, 2014b; Sam & Balasubramanian, 2023). This change-detection mapping can be used to identify surface changes in land physiography in a GIS environment with high precision (Kom et al., 2021; Phaisonreng Kom et al., 2023) The physiographical change classification in the research region for 1994, 2004, 2014, and 2024 was performed using Landsat TM and OLI imagery, employing a supervised classification approach to digitally interpret land cover into multiple classes. For a thorough and precise categorisation via visual and supervised classification, the satellite image is analysed in False Colour Composite (FCC) format. This technique uses pixel values in photographs to automatically categorise land cover.

The Digital Shoreline Analysis System (DSAS) measures shoreline alterations along the coastline. Shoreline datasets were derived from Landsat TM and OLI satellite imagery (1994, 2004, 2014, and 2024). The shoreline was extracted using a manual extraction method. Characteristics such as SHAPE, SHAPE Length, DATE, and UNCERTAINTY were used to calculate shoreline change rates in the DSAS. To determine the shoreline change rate, transects were generated, and statistical change rates were computed in DSAS to estimate the End Point Rate (EPR), Net Shoreline Movement (NSM), and Linear Regression Rate (LRR) (Chrisben Sam &Gurugnanam, 2022; Sam S &Gurugnanam, 2022). The slope map for this investigation was created from SRTM data at 30-meter resolution.

Bathymetry shows the depth from the coast to the vast ocean. The bathymetry outline for this study was created using a Naval Hydrographic Chart. After georeferencing using the Universal Transverse Mercator (UTM) projection framework with the WGS-84 datum, depth was generated using ArcGIS 10.5. The tidal chart provides the information required for the mean tide range in this study. This tidal chart calculates the tidal risk susceptibility rate and the most significant extreme amplitude for the coastal regions of India in a given year.

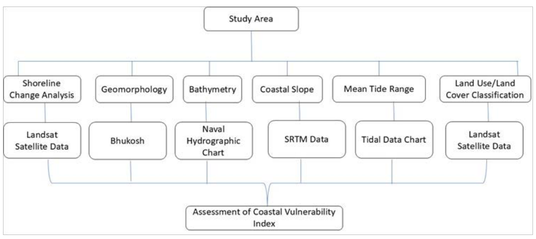

Figure 2 Methodology for CVI

Results

An evaluative metric, the Coastal Vulnerability Index, has been developed to assess the shoreline's susceptibility to evolving environmental conditions (Spinu et al., 2025; Vadivel et al., 2025). The CVI systematically ranks the following factors based on their physical contributions to the coastline: Geomorphology, Regional coastal slope, Bathymetry, Land Use and Land Cover, Rates of shoreline change, and the mean tidal range (Joevivek et al., 2013). The rankings for each parameter were combined to compute an index value that encompasses the entire study area. This methodology integrates the inherent vulnerabilities of the coastal frameworks to fluctuations with their intrinsic capability to adapt to transforming ecological conditions, thereby producing a quantitative, albeit relative, assessment of the shoreline's inherent susceptibility to the repercussions of the coastal dynamic ecosystem.

Coastal Vulnerability Ranking

The empirical values of the variables are assigned a vulnerability ranking based on specified value ranges.

The geomorphological variables denote the relative extent of features modified and resistant to erosion across various landforms (Arokiyadoss et al., 2025). The geomorphological vulnerability index values are categorized into five distinct classes: Very Low, Low, Moderate, High, and Very High. Within the study area, notable geomorphic features include Beach, Beach Ridge, Channel Bar, Deltaic Plain, Creek Network, Lagoon, Mangrove Swamp, Paleo Distributary, Salt Pan, Swale, Tidal Flat, Tidal Inlet, Waterbodies, and River (Figure 3), all of which are assigned a high-risk ranking.

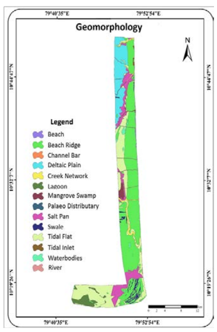

Figure 3 Geomorphology

The land use/land cover variables represent the relative proportions of different landforms, including Alluvial Plains, Saltpans, Settlements, Vegetation, and Waterbodies (Figure 4). Landforms prone to anthropogenic risks increase vulnerability (N. A. et al., 2025). There are five levels for the Land Use and Land Cover vulnerability index values: Very Low, Low, Moderate, High, and Very High. Due to high erosion rates, most areas are at high risk, particularly in the villages of Nagapattinam, Vedekkupoigainallur, Therkupoigainallur, Velankani, Pushpavanam, and Periyakuthagai.

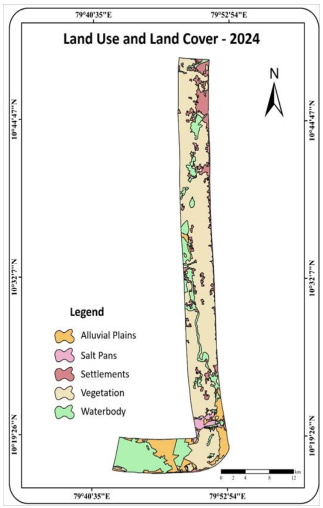

Figure 4 Land Use and Land Cover

The nearshore coastal bathymetry is determined by the fate of waves approaching the coast. Coastal and nearshore regions with a mild slope are generally considered less vulnerable, whereasareas with a steep slope are deemed extremely sensitive(Anfuso et al., 2021; Monteys et al., 2015). A coastline with a slope of 0.1˚ to 0.2˚ is classified as low-risk, medium risk with a slope of 0.2˚ to 0.5˚, and the coastal slope of between 0.5˚ and 0.9˚ is classified as high-risk. The study region is classified as low risk due to its entire slope ranging from 0.1˚ to 0.2˚ (Figure 5).

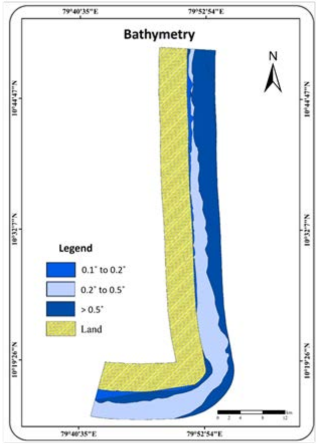

Figure 5 Bathymetry

The low-sloping coastal zones are believed to recede more quickly than steeper regions (Kantamaneni et al., 2022; Theocharidis et al., 2024). The regional coastal slope helps discern the relative weakness of immersion and the possible velocity of shoreline withdrawal. The coastline with a slope of 0˚- 3˚ has a low risk rating, 3˚- 6˚ has a medium risk rating, 6˚-10˚ has a high risk rating and the coastal region with an elevation of more than 10˚ has been ranked asa very high risk. The coastal slope is measured perpendicular to the shoreline to a specific distance seaward and a certain distance landward. In the study region, the risk class for coastal region elevation is considered to be low (Figure 6).

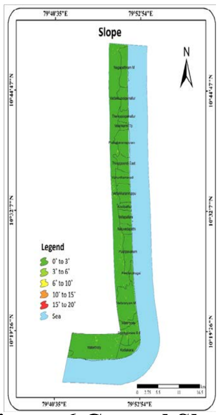

Figure 6 Coastal Slope

It turns out that the tide range of a smaller region won't change much over a year. Since the tide value for the entire coastline is less than or equal to 1.56 m, the whole coast is classified into the same vulnerability class based on the computed tide range for 2024 (Tide-Forecast.com, n.d.).

The study area's shoreline change rate was calculated over 30 years. The region has extremely high erosion rates, exceeding 1 to 2 meters per year. Rates of deposition exceeding 1.0 to 2.0 m/yr are classified as low-risk. The areas considered to be at high risk are Periyakuthagai, Vedakkupoigainallur, Therkupoigainallur, and Nagapattinam, whereas Naluvedapathi, a part of Kodiakarai, and Vellapallam are at low risk (Figure 7).

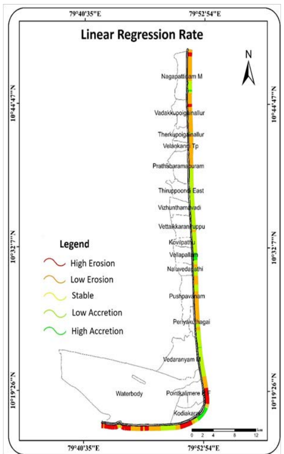

Figure 7 Shoreline Change Rate

The Coastal Vulnerability Index (CVI) for the coastal villages along stretches of the Nagapattinam coastis classified and categorized into five risk categories based on the CVI ranking as Very Low, Low, Medium, High, and Very High, based on their vulnerability to the six relative risk variables. The CVI valuesin the study region ranged from 8.13 to 17.19. Among the 16 coastal villages, Pointkalimere R.F. and Kodiakaraifall under the very high-risk category (Figure 8). The coastlines of Vettaikkaraniruppu and Kovilpathu villages are categorized as Moderate risk. In contrast,the remaining 12 coastal villages, namely Nagapattinam, Vadakkupoigainallur, Therkupoigainallur, Velankanni, Prathabaramapuram, Thiruppoondi, Vizhunthamavadi, Vellapalam, Nalavedapathi, Pushpavanam, Periyakuthagai and Vedaranyam, are classified as having a high vulnerability rate (Table 1).

Table 1 Coastal Vulnerability Index of Nagapattinam District

Village Name	CVI Values	Risk Factor
Nagapattinam	12.23	High risk
Vadakkupoigainallur	12.74	High risk
Therkupoigainallur	10.03	High risk
Velankanni	10.02	High risk
Prathabaramapuram	12.12	High risk
Thiruppoondi	10.87	High risk
Vizhunthamavadi	10.28	High risk
Vettaikkaraniruppu	9.17	Moderate risk
Kovilpathu	8.13	Moderate risk
Vellapalam	12.91	High risk
Nalavedapathi	11.76	High risk
Pushpavanam	10.30	High risk
Periyakuthagai	12.61	High risk
Vedaranyam	11.61	High risk
Kodiakarai	17.19	Very High-risk
Pointkalimere R.F	16.33	Very High-risk

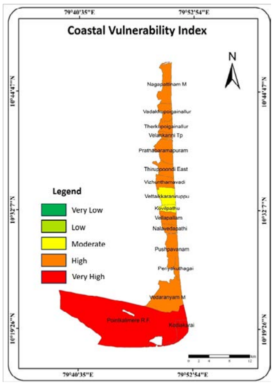

Figure 8 Coastal Vulnerability Index

Discussion

The Coastal Vulnerability Index analysis provides an integrated assessment of shoreline susceptibility along the Nagapattinam coast by synthesizing six key physical and anthropogenic variables. The results indicate that a substantial portion of the coastline falls into high-to-very high vulnerability categories, highlighting the combined influence of geomorphology, shoreline change rates, and land-use dynamics on coastal stability.

Geomorphology emerged as a dominant contributor to coastal vulnerability in the study area. Landforms such as beaches, tidal flats, lagoons, deltaic plains, and mangrove swamps were assigned high-risk rankings due to their unconsolidated nature and susceptibility to erosion. Wave action, storms, and sea level rise rapidly alter the morphology of these coasts due to their brittle and soft nature (Pereira et al., 2025; Rocha et al., 2023). These unstable, soft features that dominate the coast of Nagapattinam emphasize the inherent fragility of the coastal system and its limited resistance to dynamic marine processes.

Alterations in land use and land cover (LULC) patterns along the coast exacerbate vulnerability, particularly in areas experiencing intensive anthropogenic pressure (Dibba et al., 2025; Faria de Deus & Tenedório, 2021; Tharik et al., 2025). Settlements, salt pans, and modified alluvial plains were identified as high-risk zones due to increased shoreline destabilization. Anthropogenic activities that alter the coast, such as coastal development, vegetation removal, and alteration of natural drainage, significantly accelerate erosion and reduce coastal resilience (Osman, 2025; Roukounis & Tsihrintzis, 2022). Due to increased population density and unplanned development along the coast of the study area, high vulnerability is observed in the villages such as Nagapattinam, Velankani, and Pushpavanam.

Bathymetry and the regional coastal slope exhibited relatively low vulnerability across the study area, as the nearshore and coastal slopes fall within gentle ranges. Coasts with low gradient slopes are generally considered less vulnerable to wave energy concentration, as theymay experience faster landward shoreline retreat under sustained sea-level rise and storm conditions(Wells, 2021; Xu et al., 2026). Though these parameters indicate a low risk of coastal vulnerability, their long-term effects should not be ignored, especially in light of future climate change.

The mean tidal range showed minimal spatial variation along the Nagapattinam coastline, resulting in a uniform vulnerability classification for this parameter. This limited tidal flushing can enhance sediment residence time and amplify erosion during storm surges and extreme events (Du et al., 2023; Syvitski et al., 2009). This tidal range, along with flooding and storm-induced water levels, significantly influences the coastal shoreline and makes it vulnerable to change.

Shoreline change rate was identified as a critical indicator of coastal vulnerability, with erosion rates exceeding 1-2 m/yr in several villages. High erosional rates were observed along the coasts of Periyakuthagai, Vedekkupoigainallur, Therkupoigainallur, and Nagapattinam villages, indicating active shoreline retreat, along the southeast coast of India (Dwivedi et al., 2023; Prakasam C. and Aravinth, 2022; Sekar et al., 2024). In contrast, areas such as Naluvedapathi and a part of Kodiakarai exhibited lower vulnerability due to relatively stable or accreting shorelines, possibly influenced by sediment supply and the presence of mangroves, as well as reduced human intervention.

The integrated CVI values ranged from 8.13 to 17.19, classifying most coastal villages in the study area as having high and very high vulnerability. The identification of Pointkalimere Reserved Forest and Kodiakarai as very high-risk zones highlights that ecologically significant and protected regions remain highly susceptible due to their geomorphic setting and exposure to coastal processes (S et al., 2025).

Overall, the CVI-based assessment effectively captures the spatial variability of coastal vulnerability along the Nagapattinam coast and demonstrates the importance of integrating both natural and anthropogenic factors, with a need for site-specific coastal management strategies, including shoreline stabilization, controlled land-use planning, and ecosystem-based adaptation measures. The CVI framework can serve as a valuable decision-support tool for policymakers and coastal planners to prioritize vulnerable zones and implement sustainable coastal protection measures.

Suggestions and Recommendations

The Coastal Vulnerability Index (CVI) results indicate that high and very high-risk zones such as Nagapattinam, Vellapalam, Kodiakarai, and Pointkalimere require immediate and prioritized management interventions. Restoration of coastal ecosystems, particularly mangroves, is essential as they act as natural buffers against erosion and storm impacts. Strict enforcement of Coastal Regulation Zone (CRZ) guidelines is necessary to control unplanned urbanization, aquaculture, and sand mining activities. Structural measures such as seawalls and groynes may be implemented in erosion-prone areas with careful planning to avoid negative impacts. Continuous monitoring using Remote Sensing and Geographic Information Systems, along with DSAS, is crucial for tracking shoreline changes. Incorporating climate projections from the Intergovernmental Panel on Climate Change will improve long-term preparedness. Community awareness and participation should be strengthened to enhance resilience and disaster readiness. Sustainable livelihood practices must be promoted to reduce pressure on coastal ecosystems. An Integrated Coastal Zone Management approach is recommended to balance development and conservation. Additionally, future research should include socioeconomic factors and high-resolution data to improve vulnerability assessment accuracy.

Conclusion

The CVI analysis based on the six vulnerability parameters indicates that the southernmost regions, namely Pointkalimere and Kodiakarai, are under Very High vulnerability risk, with CVI values of 16.33 and 17.19. The villages of Vettaikkaraniruppu and Kovilpathu are classified as having moderate vulnerability, whereas all the other 12 coastal villages in the study area are categorized as having high vulnerability. Alterations in the indexing factors, such as Land Use and Land Cover, Geomorphology, and shoreline rate of change, strongly influence the CVI in the study area, resulting in a high-risk index.

The effectiveness of any Coastal Vulnerability Index (CVI) calculation is significantly influenced by the quality and variety of the data used, which, in turn, affects the vulnerability assessment. The current index could be improved by incorporating additional factors such as wave height, tidal range, and storm probability. Both natural processes, such as littoral drift, tidal movements, and nearshore bathymetry, and human activities, such as the construction of seawalls, groins, or breakwaters, alter the shoreline and affect the erosion and accretion dynamics of coastal areas. The shoreline change map generated from this study will serve as a valuable resource for coastal engineers and management authorities, aiding in the development of effective management strategies and regulations for coastal zones. Scientific research indicates that vegetation in coastal regions enhances slope stability, stabilizes sediments, and reduces wave energy reaching the shore, thereby safeguarding the coastline from erosion and serves as the natural defense mechanisms of coastal ecosystems.

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