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Integrated GIS-Based Framework for Assessing Climate Change, Ocean Sustainability, and Coastal Resilience Using Multi Hazard in Indian Coast : Case of Tamil Nadu Coastline.

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Integrated GIS-Based Framework for Assessing Climate Change, Ocean Sustainability, and Coastal Resilience Using Multi Hazard in Indian Coast : Case of Tamil Nadu Coastline.

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KEYWORDS : Coastal Resilience, GIS-MCDA, Climate Change, Coastal Vulnerability

ABSTRACT :

India's coasts are getting increasingly prone to sea-level rise, storm surges, coastal erosion, and cyclone. In order to identify the extent of climate hazards and coastal resilience along the 1076 km of coastline of Tamil Nadu, this work aims at developing an integrated GIS- MCDA approach. In this study, the integrated variables were developed using remote sensing indices, climate hazard data, terrain features and socio-economic parameters with a five-levels of Coastal Resilience Index (CRI). Highly vulnerability of the flood and sea level rise for the Cauvery Delt (namely Nagapattinam, Thiruvarur, Mayiladuthurai) and the high exposure of cyclone for Chennai- Cuddalore belt was identified and the degradation of mangroves by fracturing leads to the less natural coastal defense was highlighted. The framework is designed to aid in adaptive zoning, ecosystem-based adaptation and coastal management as per SDGs 11, 13 and 14.

1 INTRODUCTION :

Climate change has emerged as one of the most significant drivers of coastal environmental change in India. Rising sea levels, increasing sea surface temperatures, marine heatwaves, changing monsoon patterns, intensifying tropical cyclones, coastal flooding, shoreline erosion, and saline water intrusion are increasingly threatening both ecological systems and human settlements . The Indian Ocean has warmed faster than many other tropical oceans during recent decades, contributing to increased cyclone intensity, changing ocean circulation, and ecosystem degradation. India has a coastline of approximately 7,517 km, supporting nearly 250 million people and contributing significantly to national economic development through fisheries, ports, tourism, coastal industries, and maritime trade . The coastline of Tamil Nadu is about 1,076 km from north of Pulicat to Kanyakumari. There are many habitats along the coast and associated communities. Coastal processes affecting the coast range from shoreline erosion, cyclones, coastal inundation and storm surges to a projected rise in sea levels, and important coastal and marine environments exist along the Tamil Nadu coast.

These coastal regions also contain ecologically significant ecosystems, including mangrove forests, coral reefs, estuaries, salt marshes, seagrass meadows, and coastal wetlands, which provide essential ecosystem services such as shoreline stabilization, biodiversity conservation, carbon sequestration, fisheries productivity, and natural protection against coastal hazards. Ocean sustainability has consequently become a critical component of climate adaptation and sustainable coastal development .Healthy marine and coastal ecosystems perform indispensable ecological functions by regulating carbon cycles, supporting biodiversity, sustaining fisheries, improving water quality, and protecting coastlines against storm surges and wave action .

Blue carbon ecosystems, particularly mangroves, seagrasses, and salt marshes, have received increasing attention because of their exceptional capacity for long-term carbon storage while

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simultaneously enhancing coastal resilience.Coastal resilience has evolved from a disaster management concept to a comprehensive socio-ecological framework encompassing the capacity of interconnected human and natural systems to anticipate, absorb, adapt to, and recover from climate-induced disturbances. Rather than focusing solely on reducing vulnerability, resilience emphasizes maintaining ecosystem functions, institutional effectiveness, community adaptive capacity, and sustainable economic development under changing climatic conditions .

Geographic Information Systems (GIS), remote sensing, spatial modelling, and multi-criteria decision analysis have substantially improved the assessment of coastal environments by enabling detailed analyses of shoreline dynamics, land-use change, coastal vulnerability, ecosystem degradation, and climate hazards. The integration of multi-source geospatial datasets including satellite observations, Digital Elevation Models (DEMs), shoreline change analysis, land-use/land-cover information, socio-economic indicators, and environmental variables provides robust evidence for identifying vulnerable coastal areas and supporting adaptation planning. Furthermore, multi hazard assessment frameworks facilitate the simultaneous evaluation of flooding, erosion, cyclones, sea-level rise, saline intrusion, and ecosystem degradation, offering a more comprehensive understanding of cumulative coastal risks than single-hazard approaches . A statewide GIS-based coastal vulnerability study also demonstrated the high sensitivity of Tamil Nadu's coastal and marine environments to climate-induced hazards and socio-economic impacts.

There is an urgent need to develop an integrated GIS-based framework that combines multi-hazard assessment**,** ocean sustainability indicators**,** socio-ecological resilience**,** and spatial planning to support sustainable coastal development in India. Geographic Information Systems (GIS), remote sensing, machine learning, Digital Shoreline Analysis System (DSAS), and multi-criteria decision analysis (MCDA) provides unprecedented opportunities to integrate diverse environmental and socio-economic datasets into holistic resilience assessments. Multi-hazard geospatial frameworks can simultaneously evaluate sea-level rise, shoreline erosion, cyclone exposure, flood susceptibility, land-use dynamics, ecosystem degradation, infrastructure vulnerability, and community adaptive capacity, thereby supporting evidence-based coastal planning.

By integrating climate change indicators, ecosystem health, socio-economic characteristics, governance capacity, and geospatial analysis, such a framework can identify priority intervention areas, evaluate resilience patterns, and provide scientific guidance for adaptive coastal planning. The proposed framework will contribute to strengthening climate resilience while supporting the objectives of Sustainable Development Goals (SDGs) 11 (Sustainable Cities and Communities), 13 (Climate Action), and 14 (Life Below Water)**,** as well as India's coastal management and climate adaptation policies .

This study proposes an Integrated GIS-Based Framework for Assessing Climate Change, Ocean Sustainability, and Coastal Resilience Using Multi-Hazard and Socio-Ecological Indicators to support sustainable coastal planning in India. By integrating climate, environmental, ecological, socio-economic, governance, and geospatial datasets into a unified analytical framework, the study aims to identify resilience hotspots, evaluate cumulative climate risks, and provide scientifically robust decision-support tools for adaptive coastal management and sustainable development.

OBJECTIVE & AIM :

The specific goals of the study are to create a spatial database of, for example, climate, remote sensing, physical, ecological, environmental, and socioeconomic data in the study region that is relevant to assessing and communicating the status of coastal resilience along the Tamil Nadu coastline; to examine key coastal and climate hazards like cyclone threat, flooding, coastal inundation, sea level rise, shoreline retreat, rainfall variation, and terrain vulnerability; and to develop a Multi-Hazard Index by standardising and integrating spatial hazard indicators. Additionally, to determine and compare spatial variations in population, infrastructure,

economic assets, demographic information, livelihood reliance, and other socioeconomic parameters to identify variations in exposure and sensitivity; to assess ecological resilience and ocean sustainability based on indicators like mangroves, wetlands, NDVI, NDWI, coral reefs, protected areas, and water environmental variables; and to determine adaptive capacity based on socioeconomic, institutional, coping, livelihood, and core service indicators. The information from these eight dimensions will then be combined using GIS-based MCDA to create a Coastal Resilience Index (CRI), with the outputs used to determine spatial resilience patterns, identify coastal hotspots, and find high priority intervention zones. The robustness of the index will be tested, and results will be spatially translated for application in coastal planning, conservation, and adaptation.

This study attempts to develop an integrated GIS based index and framework for the assessment of coastal resilience along the Tamil Nadu coast by systematically integrating climate change hazards, ocean sustainability, ecological, exposure of human community, social sensitivity and adaptive capacity of Tamil Nadu coast. The study aims to spatially explore the linkages among multi-hazard exposure, ecological resilience and human vulnerability through the integration of remote sensing, GIS-based spatial analysis and Multi-Criteria Decision Analysis (MCDA). The index would help to spatially explore the variations in the resilience and would serve as a decision support for ecosystem based adaptation (EbA), resilient land-use planning, infrastructure planning, protecting natural ecosystems and sustainable coastal management.

2nLITERATURE STUDY :

2.1 Climate Change and Emerging Coastal Vulnerabilities

Climate change has emerged as one of the most significant drivers of environmental transformation in coastal regions, threatening ecological integrity, economic development, and human settlements. Rising sea levels, increasing sea surface temperatures, extreme precipitation, cyclones, storm surges, coastal flooding, shoreline erosion, saltwater intrusion, and ocean acidification have intensified the vulnerability of coastal ecosystems worldwide. India, with more than 11,000 km of coastline and over 250 million people living within 50 km of the coast, is particularly vulnerable to these interconnected climate hazards. Recent studies emphasize that these hazards rarely occur independently; instead, they interact across physical, ecological, and socio-economic systems, creating cascading risks that require integrated assessment rather than single hazard planning .

2.2 Climate Change and Ocean Sustainability: The Role of Blue Ecosystems

The relationship between climate change and ocean sustainability has become increasingly important in coastal planning because healthy marine ecosystems enhance climate adaptation and disaster resilience . demonstrated that mangroves, seagrass meadows, coral reefs, and salt marshes function as critical blue carbon ecosystems, providing carbon sequestration, shoreline stabilization, fisheries productivity, biodiversity conservation, and natural protection against coastal hazards. The degradation of these ecosystems reduces ecosystem services while simultaneously accelerating climate change through carbon release described coastal zones as complex social-ecological systems where atmospheric, terrestrial, and oceanic processes interact continuously, arguing that sustainable coastal management

requires integrating ecological conservation with human development rather than treating them separately. Mangroves protect coastlines Exposure to coast hazards can potentially be greatly decreased with the help of coastal ecosystems; it was found that mangroves of Pichavaram and Muthupet in Tamil Nadu showed lower exposure to coast risks even as future rise in sea-levels poses threat to mangrove area.

2.3 GIS, Remote Sensing and MCDA for Integrated Coastal Assessment

Recent research increasingly supports the use of Geographic Information Systems (GIS), Remote Sensing (RS), and Multi-Criteria Decision Analysis (MCDA) for climate adaptation planning. These technologies enable spatial integration of environmental, socio-economic, and hazard-related datasets to identify vulnerable areas and prioritize adaptation measures. Marzouk and Azab (2024) developed an integrated GIS–AHP framework combining remote sensing, spatial analysis, and multi-criteria evaluation to identify climate-sensitive coastal zones and recommend adaptation strategies. Their work demonstrated that integrating multiple spatial indicators provides more reliable decision support than conventional vulnerability assessments based on individual variables .

2.4 Geospatial Assessment of Coastal Vulnerability in India

Within India, several studies have successfully applied geospatial techniques to evaluate coastal vulnerability. Ramamurthy et al. (2025) assessed the resilience of coastal communities in Thiruvananthapuram using the Digital Shoreline Analysis System (DSAS), weighted overlay analysis, and geospatial vulnerability mapping. The study integrated shoreline erosion, flooding, storm tides, socio-economic vulnerability, and infrastructure exposure to generate a Composite Vulnerability Map that supports spatial planning and climate adaptation. Similarly, Benhur et al. (2024) evaluated shoreline dynamics in Puducherry using Sentinel-2 imagery and DSAS, reporting an average shoreline accretion rate of **2.92 m/year** following hybrid beach restoration . GIS based coastal vulnerability studies can pinpoint vulnerable coastal areas by correlating and combining physical parameters such as elevation, slope, geomorphology, shoreline change, sea level rise etc. This can be done by researchers, such as on coastal areas along the Tamil Nadu coast. The fusion of GIS and AHP can take rainfall, topography, drainage, and land use parameters into account to present the spatial distribution of flood hazard for coastal areas. For vulnerable coastal areas in Tamil Nadu, these frameworks can help in the design of flood mitigation and adaptation strategies at district level for the specific regions.

2.5 Socio-Ecological Dimensions of Coastal Resilience

The concept of coastal resilience has evolved from disaster response toward comprehensive socio-ecological resilience. adopted a Socio-Ecological Systems (SES) framework in Andhra Pradesh using Fuzzy Cognitive Mapping (FCM) to investigate interactions among governance, ecosystems, and communities. The study identified saltwater intrusion, ecosystem degradation, governance effectiveness, and stakeholder participation as critical determinants of resilience, emphasizing that resilience emerges from dynamic interactions among environmental, institutional, and social components rather than from engineering interventions alone . The combination of ecological and social-economic resilience can circumvent the shortcomings of traditional physical vulnerability indices, presenting a more thorough picture of coastal resilience considering compound hazards .Demographic,

socioeconomic, and structural factors also shape physical risks, emphasizing the human dimension of spatial coastal risk evaluation. Moving beyond traditional risk assessments of vulnerability using disparate indicators-socio-economic, ecologic, climatic, hydrological, geologic and maritime-a recent study has devised a Spatially Explicit Socio-Ecological Resilience (SERI) index .

2.6 Policy and Institutional Gaps in Indian Coastal Climate Adaptation

More recent policy-oriented research has shifted toward integrated climate governance. The 2026 issue brief *Strengthening Coastal Resilience in India* argues that most existing adaptation policies remain fragmented because they assess cyclones, flooding, sea-level rise, erosion, and storm surges independently. The report recommends adopting a multi-hazard governance framework that recognizes cascading interactions among hazards, socio-economic vulnerability, and ecosystem degradation to improve long-term adaptation planning . A systematic review of Indian coastal climate policies likewise found that cyclones, sea-level rise, floods, and rainfall extremes account for more than 60% of documented coastal climate risks, yet policy implementation remains fragmented across institutions and sectors, limiting effective adaptation .

Recent international reviews further reinforce the importance of GIS-based integrated planning. A 2026 systematic review concluded that GIS is evolving beyond mapping into a decision-support platform that integrates land sea interactions, climate scenarios, vulnerability assessment, and adaptive governance for coastal spatial planning .

2.7 GIS as a Decision Support Framework for Coastal Planning

Climate change is intensifying the frequency and severity of coastal hazards, including sea level rise, storm surges, coastal erosion, flooding, and ocean warming, posing significant threats to coastal ecosystems and human settlements. As one of the world's most climate-vulnerable nations, India's extensive coastline faces increasing environmental, socio-economic, and infrastructural risks that challenge sustainable coastal development. Although numerous studies have assessed individual coastal hazards, limited research has integrated climate change, ocean sustainability, and coastal resilience within a comprehensive geospatial framework. Advances in Geographic Information Systems (GIS), Remote Sensing (RS), and multi-hazard assessment provide powerful tools for evaluating spatial vulnerability and supporting evidence-based coastal planning. Therefore, this study proposes an integrated GIS-based framework to assess climate change impacts, ocean sustainability, and coastal resilience using a multi-hazard approach to support sustainable coastal planning and climate adaptation in India.

RESEARCH GAP :

- How can climate change impacts, ocean sustainability indicators, and coastal resilience be integrated into a single GIS-based spatial framework for sustainable coastal planning in India ?
- Can a multi-hazard geospatial framework provide more reliable and comprehensive assessments of coastal resilience than conventional single-hazard approaches, particularly under future climate change scenarios ?
- How can dynamic interactions among shoreline change, sea-level rise, coastal ecosystems, land use, and human settlements be incorporated into a single spatial assessment model to improve long-term coastal resilience planning ?

3 MATERIALS AND METHODS

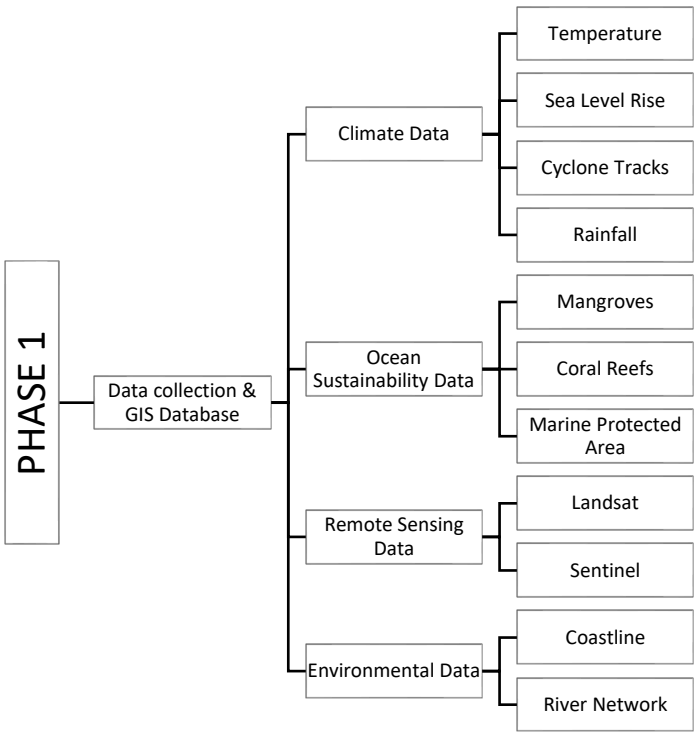
3.1 METODOLOGY FRAMEWORK

3.1.2 Phase 1 Methodology Framework

Phase 1 Methodology Framework From the figure 1 establishes an integrated GIS based coastal database to critically assess existing conditions, historical trends, and future vulnerabilities. The database integrates climate-change variables, including temperature, sea level rise, rainfall, and cyclone tracks, to identify spatial and temporal patterns of climate driven coastal. Ocean sustainability indicators, such as mangrove ecosystems, coral reefs, and coastal protected areas, are incorporated to assess the ecological assets that underpin coastal resilience and to identify areas requiring conservation and restoration. Multi temporal remote sensing datasets, particularly Landsat and Sentinel imagery, provide consistent spatial evidence for detecting changes in land cover, coastal ecosystems, shoreline dynamics, and human-induced pressures. In parallel, environmental datasets such as coastline and river networks are integrated to understand coastal hydrodynamics, freshwater marine linkages, and potential pathways of flood and sediment movement. This merged datasets allow us to carry out a multidimensional screening of climate hazards, coastal ecosystems, aquatic and human pressures that will serve as a framework to support future coastal risks' vulnerability analysis, prioritisation of impacts, and coastal resilience efforts.

3.1.2 Phase 2 Methodological Framework

Figure 1 Phase 1 Methodological Framework - Data Collection & GIS Database



In Phase 2 from the figure 2, the standardized GIS database created in Phase 1 was processed and utilized to obtain spatially-based indictors for climate change, ocean sustainability and multi-hazard assessment. For the Climate Change Assessment, processing of temperature, rainfall, sea-level rise and coastal flood datasets was achieved through spatial interpolation, temporal analysis, raster reclassification and overlay. LST from satellite image was determined to examine the thermal distribution over the coastal region. For the Ocean Sustainability Assessment, derivations of NDVI, NDWI and LULC from remote sensing and environment data were done. Coastal wetlands, water quality and marine ecosystems were then classified, normalized and spatially assessed to provide information about ecosystem condition and environmental sustainability. The individual hazard layers, including coastal flood hazard, shoreline erosion hazard, cyclone hazard and coastal inundation hazard were created using terrain, shoreline, cyclone, sea level and hydrology data in the Multi-Hazard Assessment. Each indicator was standardized onto a common spatial dimension and reclassified into an index based on severity or susceptibility level. Various techniques like overlay, weighted overlay, spatial analysis and MCDA were utilized to obtain combined results of climate, environment and coastal hazard. Various map outputs, including climate change assessment maps, ocean sustainability maps, hazard maps and integrated multi-hazard assessment map, were produced providing required spatial information of coastal hazard required for coastal vulnerability and resilience assessment in phase 3.

3.1.3 Phase 3 Methodology framework

Phase 3 from figure 3 will focus on preparing, standardizing, and integrating socio-economic and spatial data to evaluate coastal vulnerability and exposure. In the case of exposure, population, infrastructure, and economic data will be spatially prepared. This step will include georeferencing, data cleansing, aggregation, and clipping to the study extent.Infrastructure data will be classified by hazard

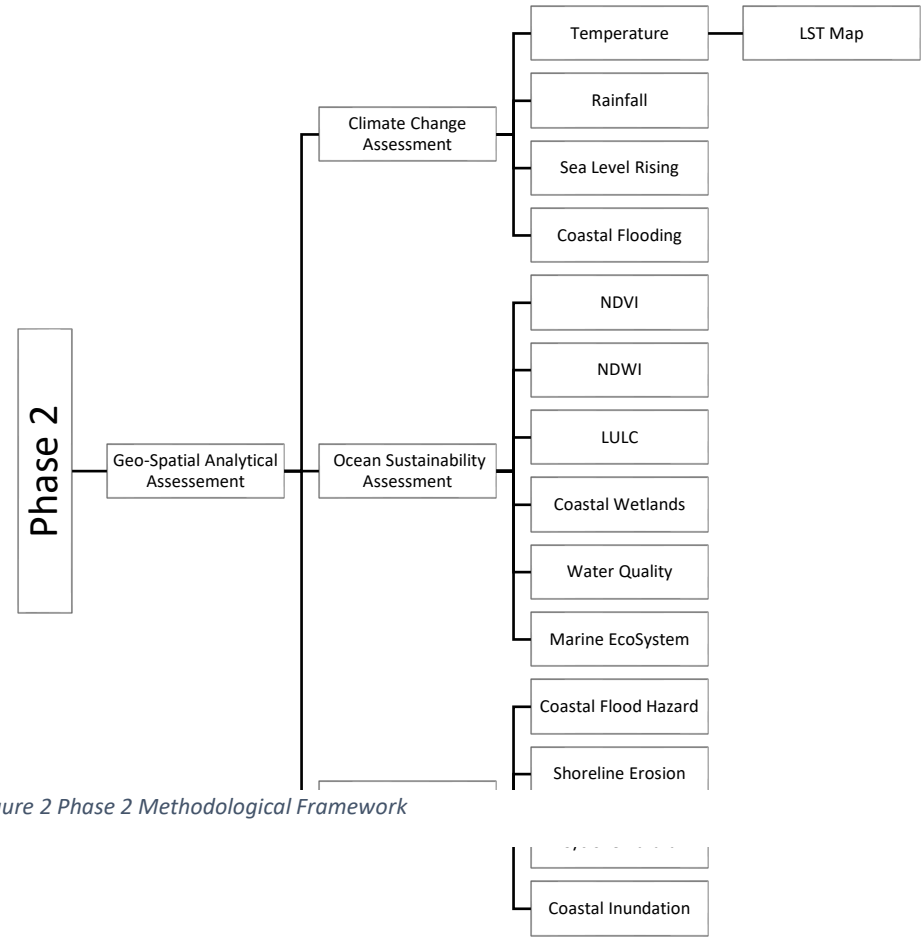
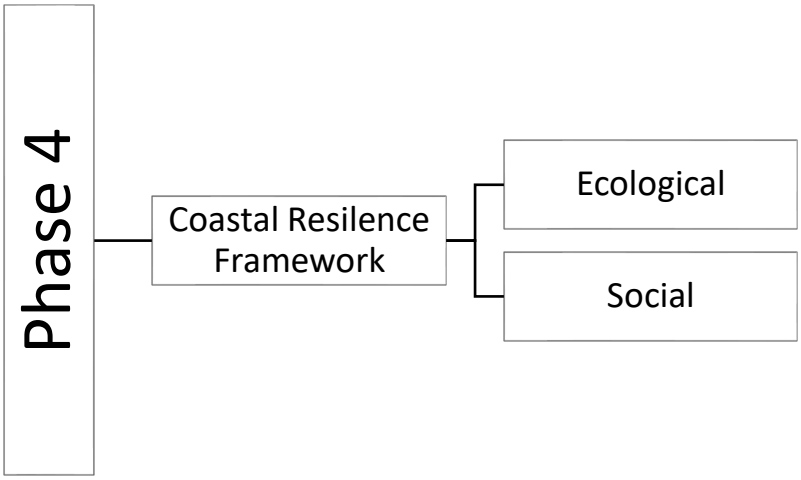


Figure 2 Phase 2 Methodological Framework

type, location, density and critical facility importance, and built asset value. Economic data would be



represented spatially through parameters, such as employment, economic activity, dependence livelihood, asset distribution within each coastal area. Social sensitivity, economic sensitivity. For vulnerability social sensitivity factors, such as population characteristics, demographic composition, dependents ratio, literacy level, livelihood, etc and economic sensitivity factors (dependency livelihood, income, employment, asset); indicators would be standardized, variables with different units will be converted into consistent data units or standardized values ranging from 0-1 or 1-5 scale and spatial overlaid with the multi-hazard index calculated from phase 2 to identify vulnerable population, infrastructure and economic activities within coast hazard area.

MCDA model will be used to create separate indices of exposure and vulnerability based on weighted indices, followed by integration of indices with hazard data to form risk zones.

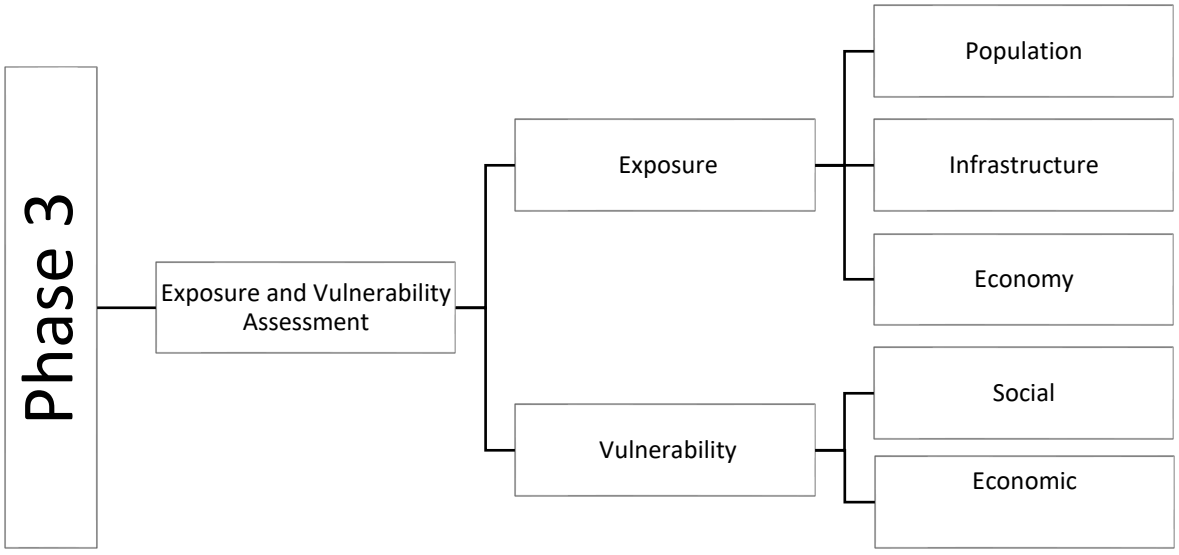


Figure 3 Phase 3 Methodological Framework - Exposure & Vulnerability Index

3.1.4 Phase 4 Methodology framework

Phase 4 Methodology from the figure 4 dealing with Normalization, Weighting and Aggregation. In this phase, the indicators selected for both ecological and social components are standardized, weighted, normalized and aggregated to form the Coastal Resilience Index (CRI). Ecological (Mangroves, Coral Reefs, Wetlands, NDVI, NDWI, water quality) and social indicators (demography, livelihood, economy, coping, adaptation) are cleaned, projected to a common resolution and then standardized Suitable weights aredetermined, again using MCDA, expert consensus or literature review.

4 INDICATOR SUPPORTIVE MATRIX

Finally, the indicators are aggregated for both Ecological and Social components into Ecologic and Social Resilience Sub-indices as Shown in the Table 1, the last is combined to form the CRI, then

reclassified in 5 categories of resilience, to highlight areas which needs prioritized adaptation actions for enhancing resilience

Table 1 Indication Selection Matrix

Dimension	Indicator	Specific analytical area	Why selected for your research	Supporting research
Climate change	**Temperature / LST**	Thermal climate	Captures spatial thermal stress and climate variability that may influence coastal environmental conditions and human exposure.	
	Rainfall	Hydro-climatic stress	High rainfall can increase runoff, waterlogging and flood susceptibility, particularly when combined with low slope/elevation and drainage limitations.	
	Sea-level rise	Future coastal hazard	Represents a major long-term climate-driven pressure and allows future inundation exposure to be spatially identified.	
Multi-hazard	**Coastal flooding**	Hydro-meteorological hazard	Converts rainfall, terrain and hydrological conditions into a spatial flood-hazard layer.	
	Cyclone exposure	Extreme-weather hazard	Historical cyclone tracks identify spatial differences in recurrent cyclone exposure along the coast.	
	Shoreline erosion	Coastal geomorphological hazard	Represents long-term shoreline instability and complements instantaneous hazards such as cyclone and flooding.	
	Coastal inundation	Direct coastal hazard	Identifies areas potentially affected by coastal water penetration and allows SLR/hydrological effects to be spatially integrated.	
Terrain	**Slope**	Topographic susceptibility	Controls runoff, drainage and water accumulation; low-gradient coastal areas are particularly relevant to inundation and waterlogging.	
Coastal exposure	**Distance/proximity to coastline**	Coastal exposure gradient	Provides a spatial proxy for decreasing direct influence of coastal hazards inland.	
Land system	**LULC**	Anthropogenic/environmental transformation	Distinguishes built-up, agricultural, vegetation and water surfaces and captures human modification of coastal systems.	
Ecological	**NDVI**	Vegetation condition	Provides spatial information on vegetation abundance/condition and ecological buffering capacity.	
	Mangroves	Natural coastal defence	Mangroves provide ecosystem services and can act as natural buffers against waves, erosion and storm impacts.	
	Coral reefs	Marine ecosystem	Represents marine ecological capital and ecosystem-based coastal protection.	
	Coastal wetlands	Wetland ecosystem	Represents natural ecological and hydrological assets that contribute to coastal-system functioning.	
	Water quality	Aquatic environmental condition	Adds environmental quality to the resilience assessment rather than measuring only physical hazards.	

Exposure	**Population**	Human exposure	Identifies people potentially exposed to physical hazards.	
	Infrastructure	Built-asset exposure	Identifies critical physical assets potentially affected by coastal hazards.	
	Economic activity/assets	Economic exposure	Represents the economic consequences associated with hazard exposure.	
Social sensitivity	**Demography**	Population sensitivity	Captures differences in population characteristics that influence sensitivity to hazards.	
	Dependency ratio	Population sensitivity	Identifies populations potentially more dependent on household/community support during disasters.	
	Literacy	Adaptive capacity	Can represent access to information and potential capacity for disaster awareness and response.	
Economic sensitivity	**Livelihood**	Livelihood dependence	Identifies dependence on coastal resources and activities that may be disrupted by hazards.	
	Income	Household economic capacity	Represents economic capacity to absorb and recover from hazard impacts.	
	Employment	Economic dependence	Indicates potential disruption of employment and economic activity after hazard events.	
Economic exposure	**Asset distribution**	Material exposure	Identifies concentration of economic assets within hazard-prone locations.	
Resilience capacity	**Coping capacity**	Short-term response	Represents the ability of communities/systems to respond to existing hazards.	
	Adaptation capacity	Long-term adjustment	Represents the ability to adjust to changing climate and future hazards.	
Institutional	**Governance**	Institutional capacity	Represents the ability of institutions to coordinate and implement adaptation measures.	

The selection of indicators from the table 1 was guided by well-developed theories and empirical studies in the field of coastal vulnerability and resilience, and designed to demonstrate the dimensions of hazard, exposure, sensitivity, ecological condition and adaptive capacity as interacting components. Traditional coastal vulnerability studies have focused on physical and geophysical variables such as sea-level rise, shoreline change, elevation, slope, geomorphology and inundation [Citations], although newer frameworks in coastal vulnerability have called for the integration of hydroclimate, ecological and socioeconomic factors. Examples of traditional and newer coastal vulnerability assessments of Tamil Nadu include sea-level rise, shoreline change, LULC, elevation and inundation [Citations], while cyclone risk assessments in the state have incorporated population, LULC, NDVI and distance to coast [Citations].

Table 2 Indicator direction table

Indicator	Relationship with hazard	Relationship with resilience
SLR	+	−
Cyclone frequency	+	−
Flood susceptibility	+	−
Erosion rate	+	−

Coastal distance	−	+
Slope	Context dependent	Context dependent
NDVI	−	+
Mangrove density	−	+
Wetland extent	−	+
NDWI	Context dependent	+
Population density	+	−
Infrastructure density	+	−
Literacy	−	+
Income	−	+
Livelihood diversity	−	+
Governance capacity	−	+

Most recently, research in the field of socio-environmental and socio-ecological resilience has demonstrated the need to jointly characterize climatic, ecological, socioeconomic and institutional conditions rather than isolating any particular system. [Citations] Therefore, this study presents indicators in six groupings, representing climate change, multi-hazard, ecological sustainability, exposure, social-economic vulnerability and resilience-capacity dimensions. Climate change impacts assessed include rainfall, LST and sea-level rise; hazards include flooding, cyclone exposure, shoreline change and inundation; spatial controls on hazard distribution include slope, terrain, river proximity and network; ecological health dimensions include NDVI, NDWI, mangroves, wetlands, coral reefs, water quality and protected areas; as shown in Table 2 whereas the vulnerabilities encompass the human facets of population, infrastructure, economic activity, demographics and livelihoods. Resilience capacities include preparation, coping, adaptation and governance. This multidimensional conceptualization of coastal resilience aligns with studies in socio-ecological and socio-ecological resilience, which have shown that resilience depends on interactions among ecological, human and physical systems and is therefore best characterized using several indicators.

5 GEO – SPATIAL ANALYSIS

5.1 Climate & Nature resources mapping :

5.1.1 Coastline map of Tamil Nadu :

Study Area : Tamil Nadu Coastline, Tamil Nadu

From figure 5 We can see the Tamil Nadu's 1,076 km coastline nearly 15% of India's mainland coast stretching over 14 districts from Pulicat lake in the north to the tip at Kanyakumari, goes from being sand dominated, (Coramandel Coast) and being composed of shallower, narrow Palk strait and the island dominated, island archipelago, island dominated Gulf of Mannar, with the shores turning into rocky, jagged surfaces. It also contributes almost 15% of India's maritime income in terms of export values to the trade between 3 major ports, 17 minor ports of international importance such as those handling international trade like Chennai, Kamarajar (Ennore), V O C (Tuticorin) which cater to the demands of commercial shipping, and thermal power related freight movement, extensive salt and fish farming (Tuticorin is the Salt Capital and is also major fish farming center of south Tamil naduand, supports more than a million livelihoods in related occupations and fisheries). However there are some most ecologically varied marine eco systems in the coast of south Asia along its stretch. Some of these including the mangrove forests such as Pichavaram and Muthupet, brackish water lake, Pulicat, where it borders the two states of the country in which, there is a huge dugong and sea grass eco system and the Gulf of Mannar marine bio-reserve, which has some of the best grown corals, seagrass meadows and are home to endangered dugongs. The riverine waters originating from Kaveri, Palar and Ponnaiyar merge at the Bay of Bengal, along this stretch of coast adding immensely to these rich estuarine systems and livelihoods of over one million people. Risks posed by climate change such as increasing storms generated by the northeast monsoon winds and high waves and subsequent sea level rise have increased with severe erosion in almost 40 percent of its coastal length prompting the state to actively move towards coastal zone management.

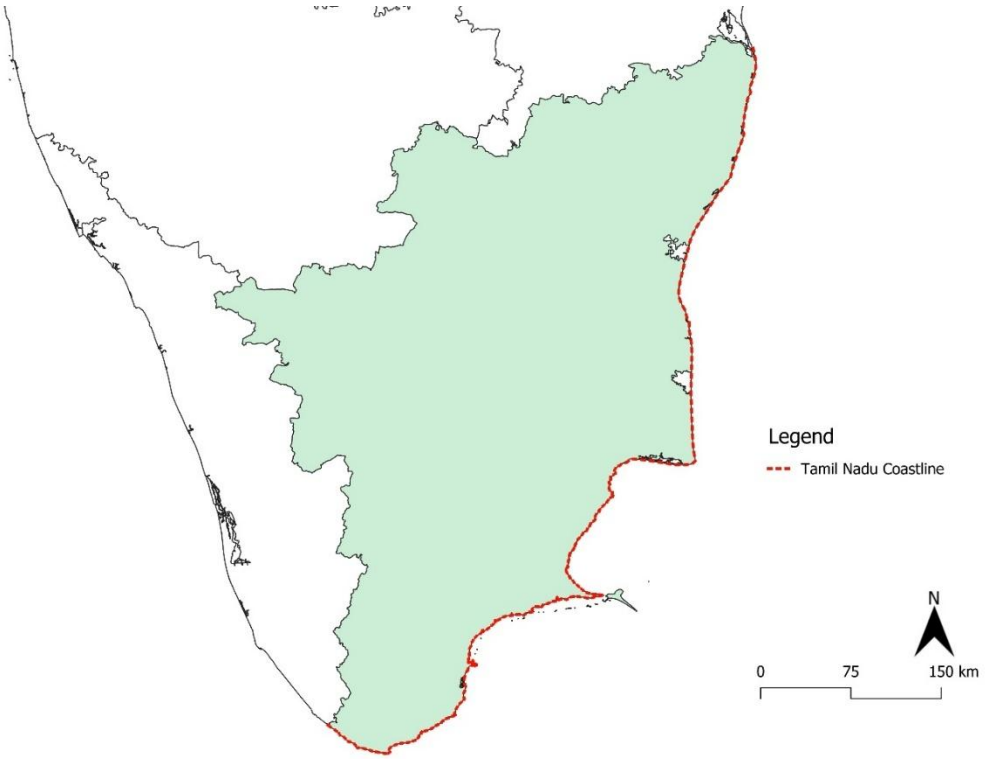


Figure 5 Study area Map : Tamil Nadu Coastline (Author,2026)

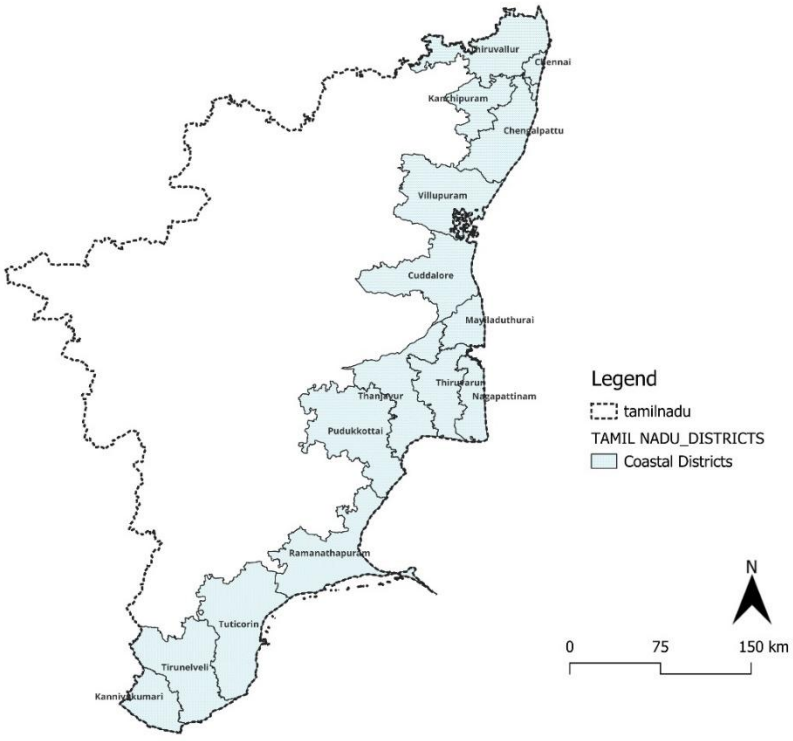
5.1.2 Coastal Districts of Tamil Nadu :

The provided cartographic model from figure 6 shows the spatial allocation of the 14 coastal administrative districts of Tamil Nadu representing a broad marine coastline in the eastern part and at the southern extremity. An analysis of maritime exposure from space across the emphasized zone indicates tremendous diversity. Whilst northern and center regions (including Chennai, Chengalpattu, Cuddalore) possess linear stretch of coastline with little variation, The south, central delta and the extremities are structurally a very fragmented, intricate and tortuous shape, districts like Tanjavur, Thiruvaroor has limited contact with coast with little margin of coastal influence against total area (53:7). Other parts of south like Ramanathapuram, Nagapattinam again forms a complex irregular coastline protruding well into the Palk Bay and Gulf of Mannar. From the southern point in Kanniyakumari onwards up to the northern extremities such spatial differentiation in coastal impact, has to give it due importance in micro scale ICZM((Integrated Coastal Zone Management) policy framing.

5.1.3 Coastal Area Buffers :

Provides three buffers along the study coast at described in the figure 7 as 1km, 5km and 10km distance to produce spatial stratification with gradients of coastal influence. The 1km buffer demarcates the immediate coast with greatest expected vulnerability to coastal hazard impacts like storm surge, coastal flooding, erosion and sea-level rise, the 5km buffer reflects intermediate coastal influence and the 10km buffer gives broad spatial scale. Buffer geometry reflects irregular shoreline geometry and thus a wider coverage around curves or headlands, with the greatest extent being the 10km buffer,

Figure 4 Tamil NaduCoastal Districts Map (Author,2026)



indicating how impacts may extend far from the coast inland. These 3 zones map the spatial area used to assess spatial integration for the indicators.

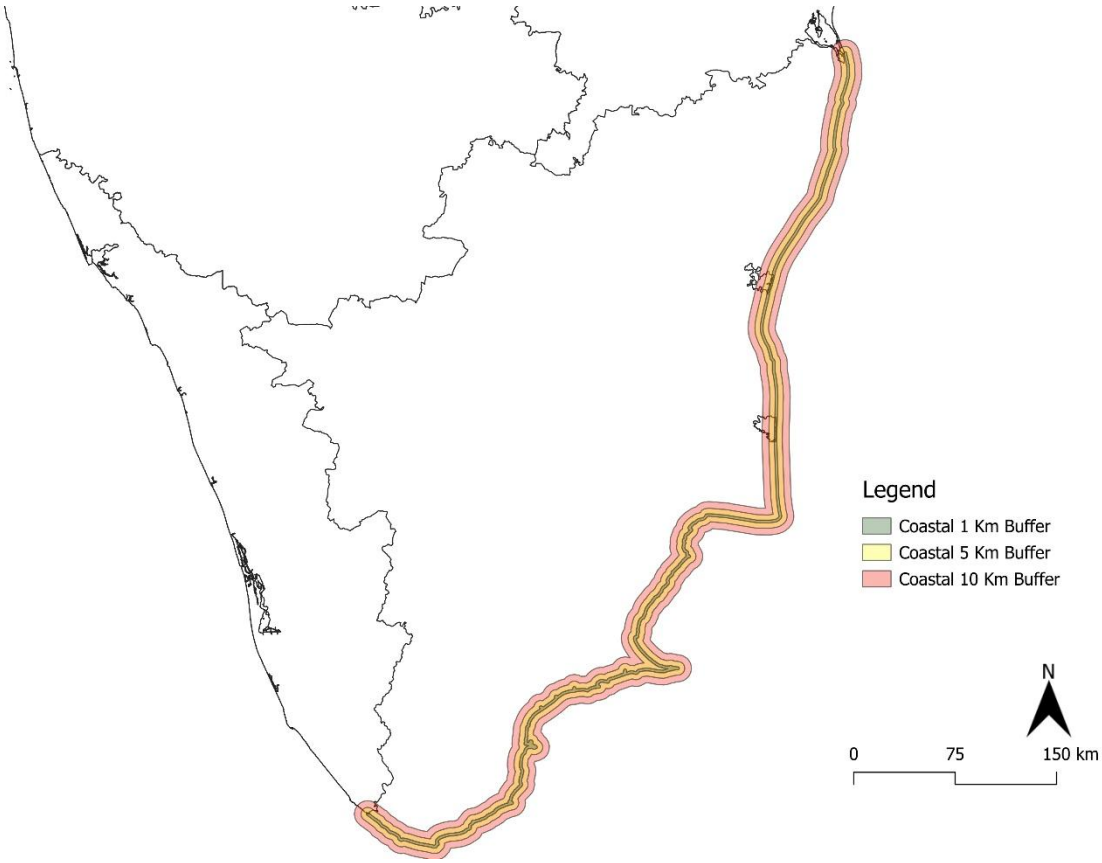


Figure 7 Coastal Area Buffers Respectively 1 Km, 5 Km, 10 Km (Author,2026)

5.1.4 Rainfall Intensity Data :

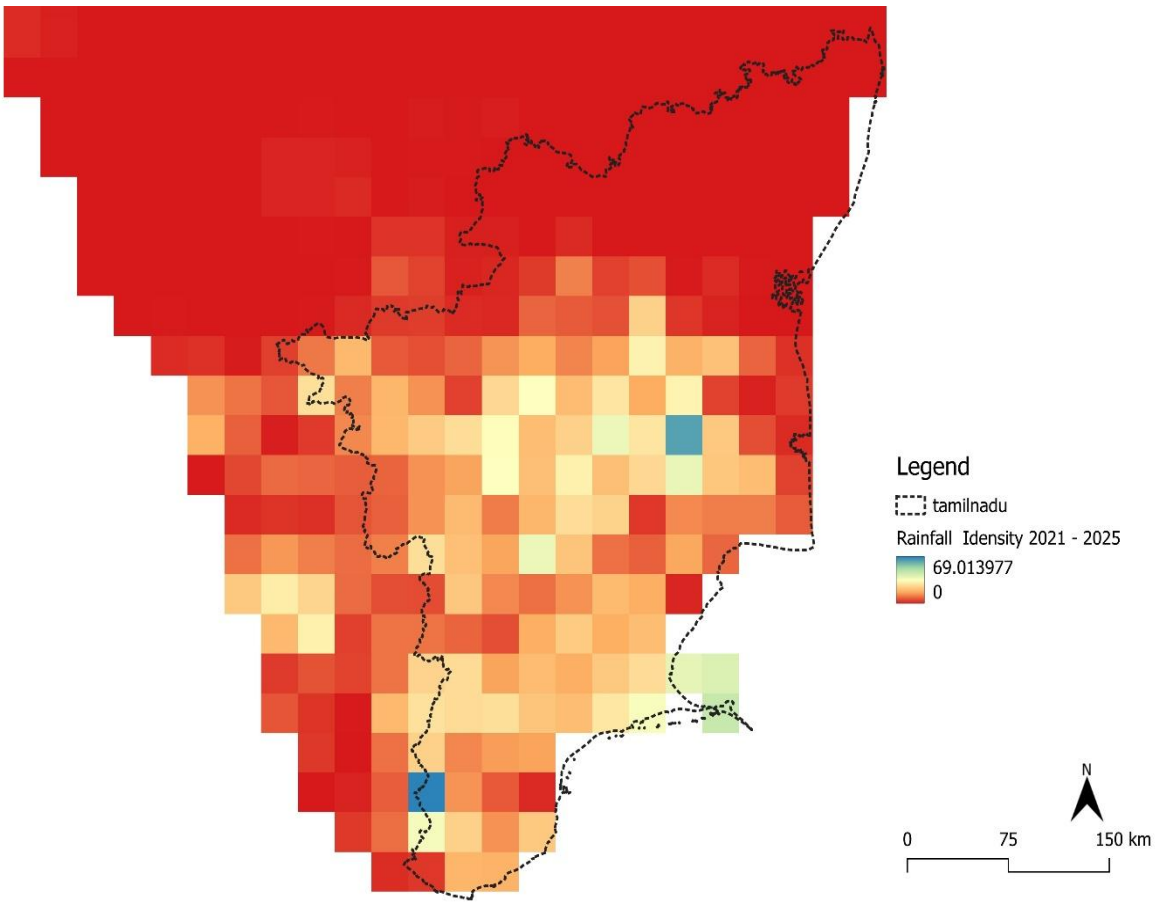


Figure 8 Rainfall Intensity Map Of Tamil Nadu (Author,2026)

Rainfall (mm) Total Tamil Nadu Spatial variation from the figure 8 The rainfall across Tamil Nadu depicts significant variation across the geographic area, with the values of raster layer vary from a minimum of 0 mm to a maximum of 69.01 mm. There are no records of rain in a number of areas in the state. The mean rainfall is 9.87 mm, whereas the median value is 4.81 mm revealing a positively skewed distribution of high rainfall zones with a number of areas concentrated areas that receive heavy rainfall. The standard deviation of rainfall value is 11.89 mm which highlights spatial variation in total rainfall Received amounts over Tamil Nadu. Nearly 25 per cent of mapped cells recorded a total of rain in value between 0 and 4.81 mm (lower quartile), while upper quartile is around 17.63 mm. Approximately 95 per cent of pixels received less than 31.77 mm (95th percentile).The large difference between mean and median rainfall value indicates the presence of spatially concentrated higher values over Tamil Nadu rather than uniform distribution. These results have important implication in our assessment and analysis, since areas receiving high rainfall may become prone to flooding as it affects surface runoff, waterlogged areas when combined with factors of low elevation, high density and poor drainage.

5.1.5 LULC – Tamil Nadu 2025 :

In the 2025 LULC map from the figure 9 for Tamil Nadu, the land use/cover pattern is highly heterogeneous with dominant cropland and barren land, followed by vegetation and forest area. While built up land and water body comprises relatively minor proportion of land cover/use. Cropland and barren areas, are widely distributed covering large part of the central, eastern, and southern regions of the state, attesting to a predominantly agrarian and low intensity land se pattern.

Vegetation and forest, are primarily located in western and southern parts of the region, especially covering a large tract along the western Ghats, influenced by terrain characteristics and ecological settings. Built up lands, though fragment and more and more continuous over space form increasingly

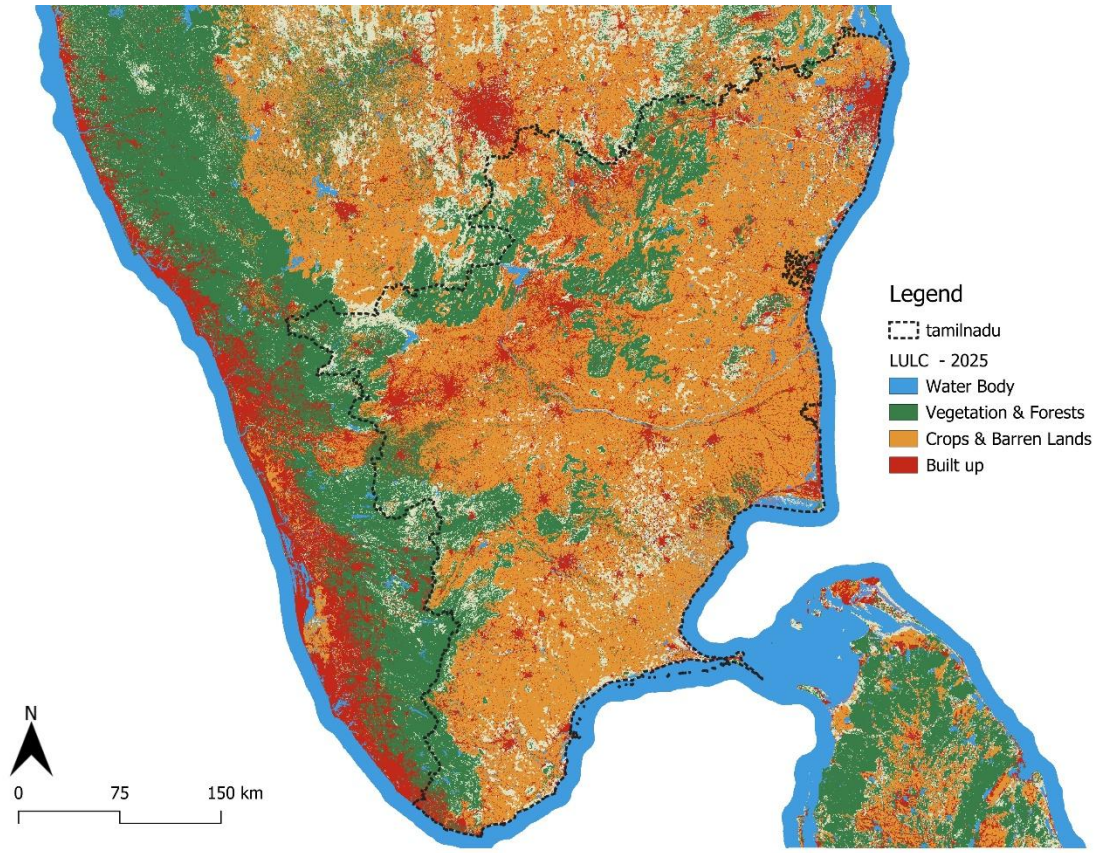


Figure 9 LULC 2026 Map Of Tamil Nadu (Author,2026)

larger enclave within agricultural, landscape particularly within major town and city along coastal

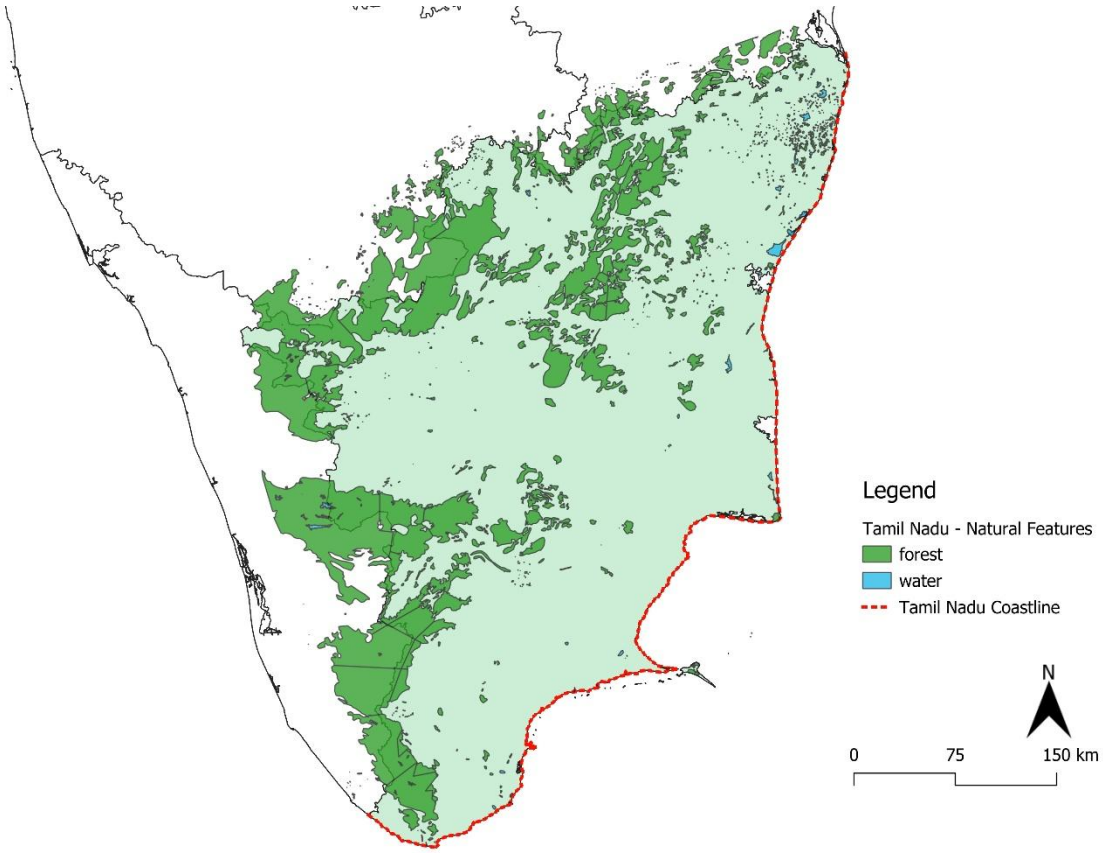


Figure 10 Natural Feature Map - Tamil Nadu (Author,2026)

region. Water bodies form a relatively insignificant part though spatially significant, are associated mainly along large water bodies such as rivers, reservoirs and lakes and a coastal water belt. Thus the LULC pattern reflects a typical agrarian ecological- urban gradient and is characterized by expansion of built up lands within and adjacent to existing Agricultural Landscapes; and the land interface. For Coastal resilience the spatial pattern of built-up land, agricultural and natural vegetative cover is important, since land transformation from natural to impervious built-up land surfaces, enhances flood potential and increases fragility of ecology, in while vegetation cover and water bodies may provide buffering and resilience.

5.1.6 Natural Features of Tamil Nadu :

5.1.6.1 Forest cover

Natural features of Tamil Nadu From the figure 10 , we observe that forest cover is heavily clustered in the west and south parts of Tamil Nadu, in and around the Western Ghats region, whereas water features are dispersed as small and discrete units. This spatial arrangement shows a strong accumulation of forest in the high elevated western and southern regions, and a relative dominance of non forest cover in the eastern and central areas of the state. These spatial clusters of forests create an eco-corridor in the west and the south, where these forests stretch somewhat contiguously in the westernmost zones of Western Ghats, and become highly fragmented further inwards. On the other hand, water features occupy a small spatial area and appear in discrete patches that are surface water features.

• Forests provide various ecosystem services including runoff regulation, soil erosion control, provision of habitat to flora and fauna and a buffer for climate variability and extreme weather events

• Inland water bodies contribute to regulating local hydrology and support ecosystem functions, providing flood-storage and other services.

5.1.6.2 Water Body

The distribution of water bodies from the figure 10 in Tamil Nadu is fairly fragmented and non-uniform with major water body densities concentrated in the east and centre, with a few dispersed across the interior. Water bodies seem less dense in the interiors to the west of forest areas whereas, few water bodies are found close to coast refer the figure 10. Their distribution is characteristic of surface water features in a network system comprised by the Rivers, Reservoirs, Lake and Tanks.

As far as coastal resilience is concerned, these are functional in storage of water, attenuation of floods, groundwater recharge and for drainage connectivity, but, water bodies near coastal heavily built up area may serve as channels for ingress of flood water into the land under severe rainfall, storms and coastal inundation. Thus it is necessary to study its relationship with other elements like drainage, built up areas and coastline to use for multi- hazard & coastal resilience assessment subsequently.

5.6.3 Mangroves :

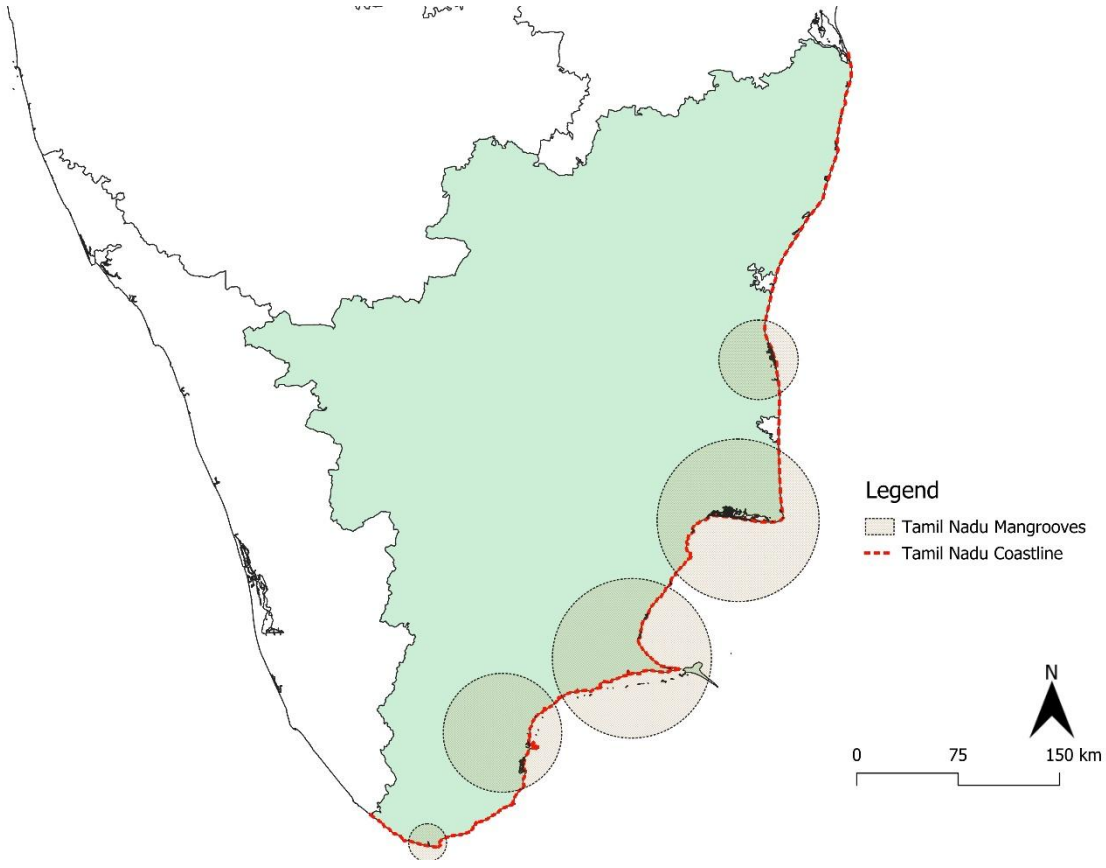


Figure 11 Mangroves Location in Map - Tamil Nadu (Author,2026)

The map reveals that from figure 11 mangroves are patchily distributed in discrete patches on specific parts of the TN coast rather than in contiguous strips across the entire coastline. Large aggregations are typically found near estuaries, deltas and sheltered coasts due to appropriate mix of freshwater inflow, tidal exchange and sediment deposition. The distributed mangrove areas are in the form of smaller and larger patches on the map, with conspicuous large concentrations in the mid and south of the TN coast, with thin and sporadic coverage in north and south-west coast.

Since distribution is thus fragmented, it is likely that these mangrove areas represent key but spatially constrained natural coastal buffers. From coastal resilience standpoint, the value of mangroves comes from their ability to dissipate wave energy, absorb storm surge threat and limit shoreline erosion and coastal inundation while facilitating high ecological and physical functions like providing coastal protection and supporting marine biodiversity and sediment trapping capacity. Accordingly, any spatial overlay analysis including mangroves, human habitations, low-lying areas and hazards (multi-hazard exposure zone), ought to be undertaken in the next stage (coastal vulnerability/resilience assessment) with focus on including these areas as ecologically significant adaptation (ESA) and natural resilience (NRA) zones.

5.2 Hazard and Vulnerability & Exposure Mapping :

5.2.1 Cyclone Track Map

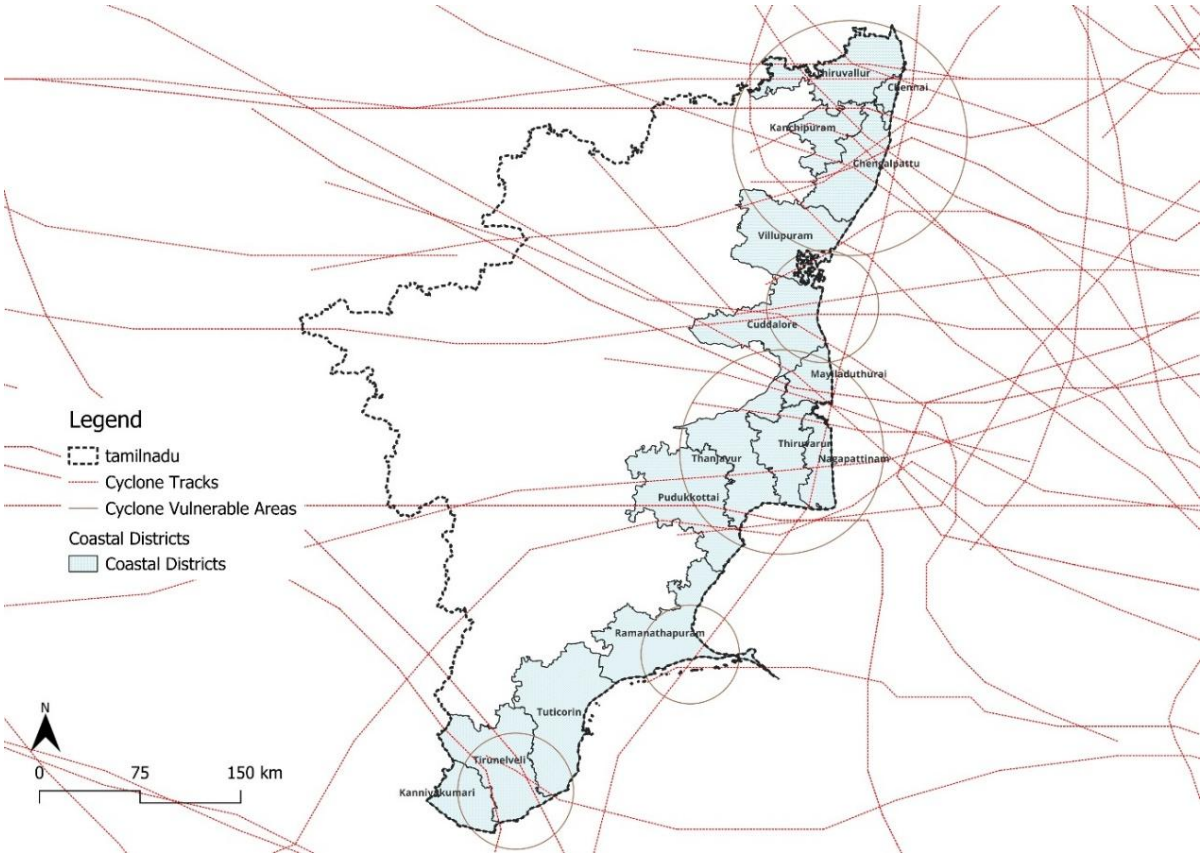


Figure 11 Cyclone Track Map of Tamil Nadu (Author,2026)

The analysis highlights significant geospatial concentration of cyclones to the east of Tamil Nadu coast, which has the most exposure in northern and central coastal region of the State. The map area covers 14 coastal districts of Tamil Nadu, right from Chennai in the north to Kanniyakumari in the south. It could be observed that the cyclone track network had considerably more tracks along Chennai-Chengalpattu-Kancheepuram-Villupuram-Cuddalore-Mayiladuthurai-Nagapattinam line (NE coast), denoting a high potential of the historical cyclones in these areas. The cyclone susceptible areas marked by different sizes of concentric circles represent areas with high exposure to cyclones centered near five major coastal sector: the region along Chennai Metropolitan Coast (CMC), Cuddalore region, the region along the coast of Nagapattinam-Thiruvarur districts, region along the Ramanathapuram district coast and the Kanniyakumari region. The intersection zone of cyclone tracks with the cyclone vulnerable zones are concentrated particularly along the Chennai-Cuddalore corridor.

5.2.2 Terrain Roughness Map

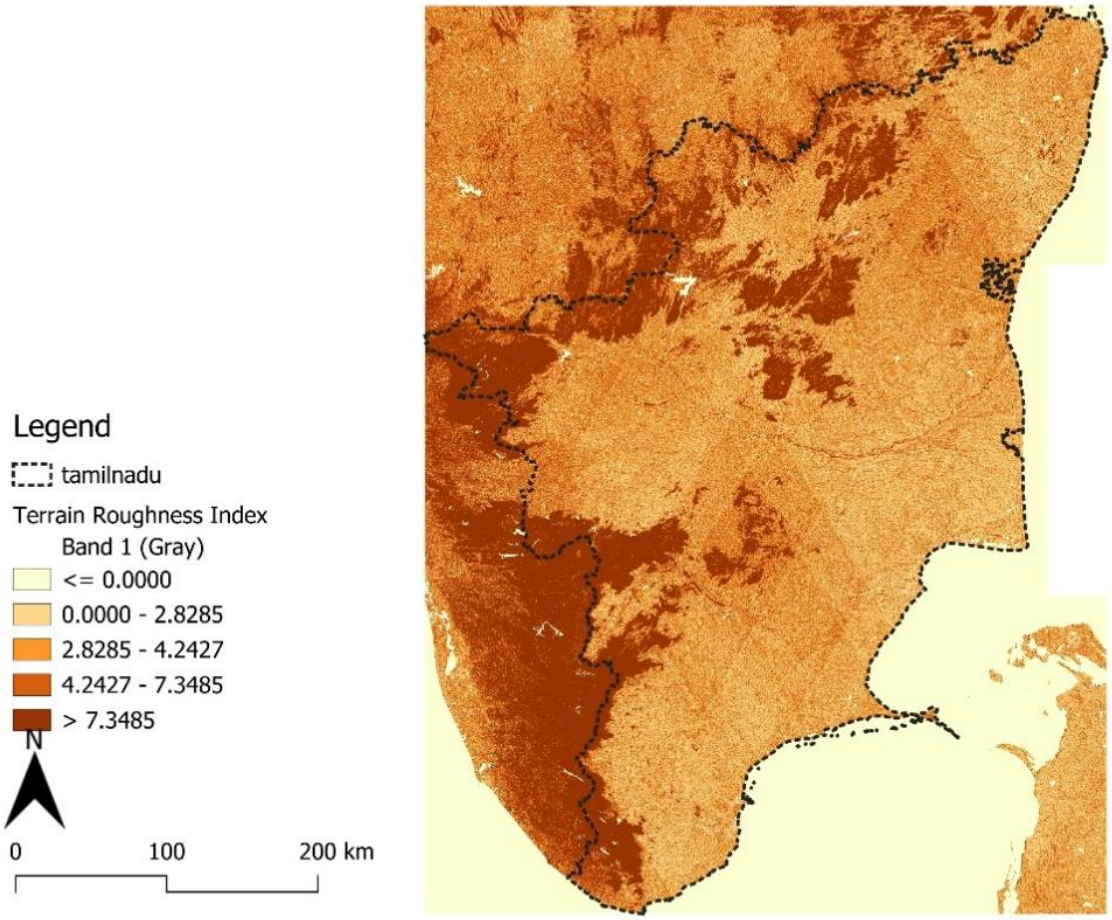


Figure 12 Terrain Roughness Map - Tamil Nadu (Author,2026)

The case of the state of Tamil Nadu the TRI map from the figure 12 presents a significant heterogeneity of topographic surface features throughout the space (Figure 6), the values ranging from 0 up to >7.35. Low and moderate classes of roughness (0-4.24) constitute most of the area with high geographic prevalence (mainly central, eastern and coastal plains), showing a smooth and lightly undulated topography. , low TRI values, between 0 and 2.83, are widely spread over the central and eastern regions of the state, while high TRI values, between 2.83 and 4.24, are located in the transition between low areas and more mixed landscapes.

More relevant high TRI values, 4.24-7.35, are located mainly in western and northwestern Tamil Nadu, predominantly over rugged lands correlated with the relief of the Western Ghats and surrounding uplands. Finally, high to maximum TRI values, >7.35, are mainly registered on the highly rugged western mountain relief. In contrast, western and coastal territories, mainly include low TRI values as they are mainly flat regions. Generally, a west-east relief gradient is observed in relation to roughness where values increase over the highlands and decrease towards the coastal plains. The unevenness at the coastal region is significant from the point of view of hazard and resilience assessment because smooth and plain surfaces Favor the inland propagation of coastal risks, while high relief represents an obstacle.

5.2.3 Slope Map

The slope based vulnerability of Tamil Nadu from figure 13 the is found to have strong spatial gradation from gently undulating eastern and coastal plains towards the elevated western and south-western part of the state. The map classifies the terrain into five categories of vulnerability i.e. Very Low, Low, Moderate, High and Very High category of vulnerability. Large part of central, northern and eastern Tamil Nadu is represented as Very Low and Low vulnerability category, characterising predominantly gentle slopes and gentle terrain. Moderate vulnerability category is seen as a wide transitional belt in central Tamil Nadu whereas High and Very High vulnerability classes are predominantly located at the eastern coastal margin, coastal region of southern and south-eastern part of the state and parts of the western hill. The presence of highest vulnerable class on gentle sloping coastal terrain indicates more susceptibility to water logging, coastal inundation and poor drainage. Coupled with sea level rise and intense rainfall these areas can become very vulnerable. However in the steeper western parts more variation in terms of slope value can be expected and different types of hazard can occur, such as rapid surface runoff and soil erosion. Slope vulnerability is spatially varying, with vast area covered by low slopes providing potential areas of increased vulnerability for coastal inundation and waterlogging; and steeper areas may be more susceptible to hazards related to rapid surface runoff and erosion. This classified map based on terrain slope therefore will serve as an appropriate topographic input for integration with sea level rise, flooding and coastal multi-hazard vulnerability into the coastal vulnerability and adaptation assessment.

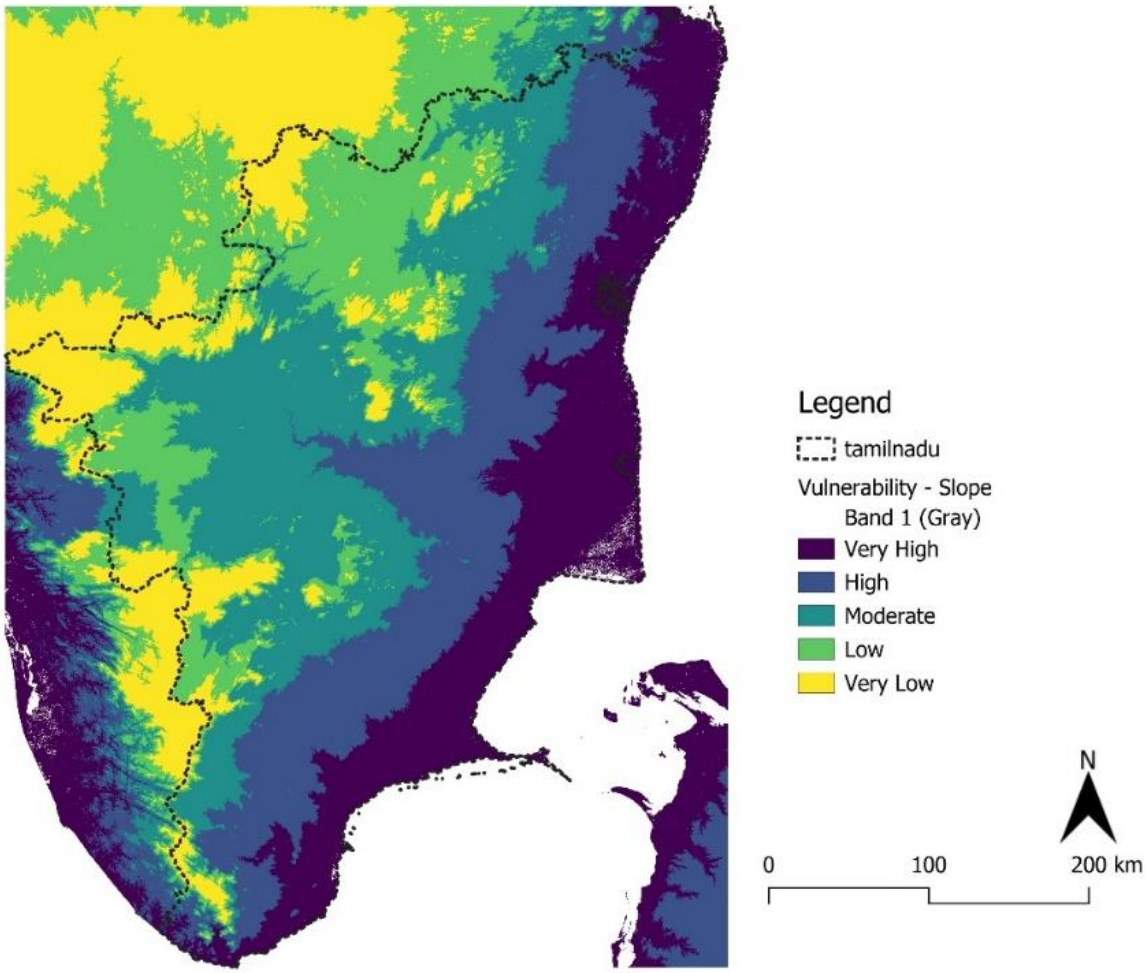


Figure 13 Slope - Vulnerability Map (Author,2026)

5.2.4 See Level Rise Vulnerability Map

The SLR analysis from figure 14 reveals that the areas identified as potentially inundated during a specified SLR event are mainly concentrated along the coast of Tamil Nadu and with limited spread over inland parts. The inundation is most pronounced and widespread along the Cauvery delta and the adjoining coastal zone, with significant concentrations near Nagapattinam, Thiruvarur, Mayiladuthurai and in parts of Pudukkottai which identifies the low-lying coastal and delta region as vulnerable to SLR impact. There are relatively small and scattered patches of inundation near the Chennai-Chengalpattu and Cuddalore coasts and along the southern coastal belt near Thoothukudi which confirms smaller scale inundation in pockets of low elevation exposed to sea-level rise. The relatively concentrated and contiguous area of inundation near Nagapattinam-Thiruvarur-Mayiladuthurai on the coast identified the Cauvery delta as a hot spot exposure area to SLR due to large low-lying expanse of land and proximity to the coast, while western and inner parts of the state did not show significant inundation areas. Spatial pattern analysis clearly shows the uneven distribution and localized nature of risk to sea level rise. Higher exposure is linked to factors like proximity to the coast, lower elevation

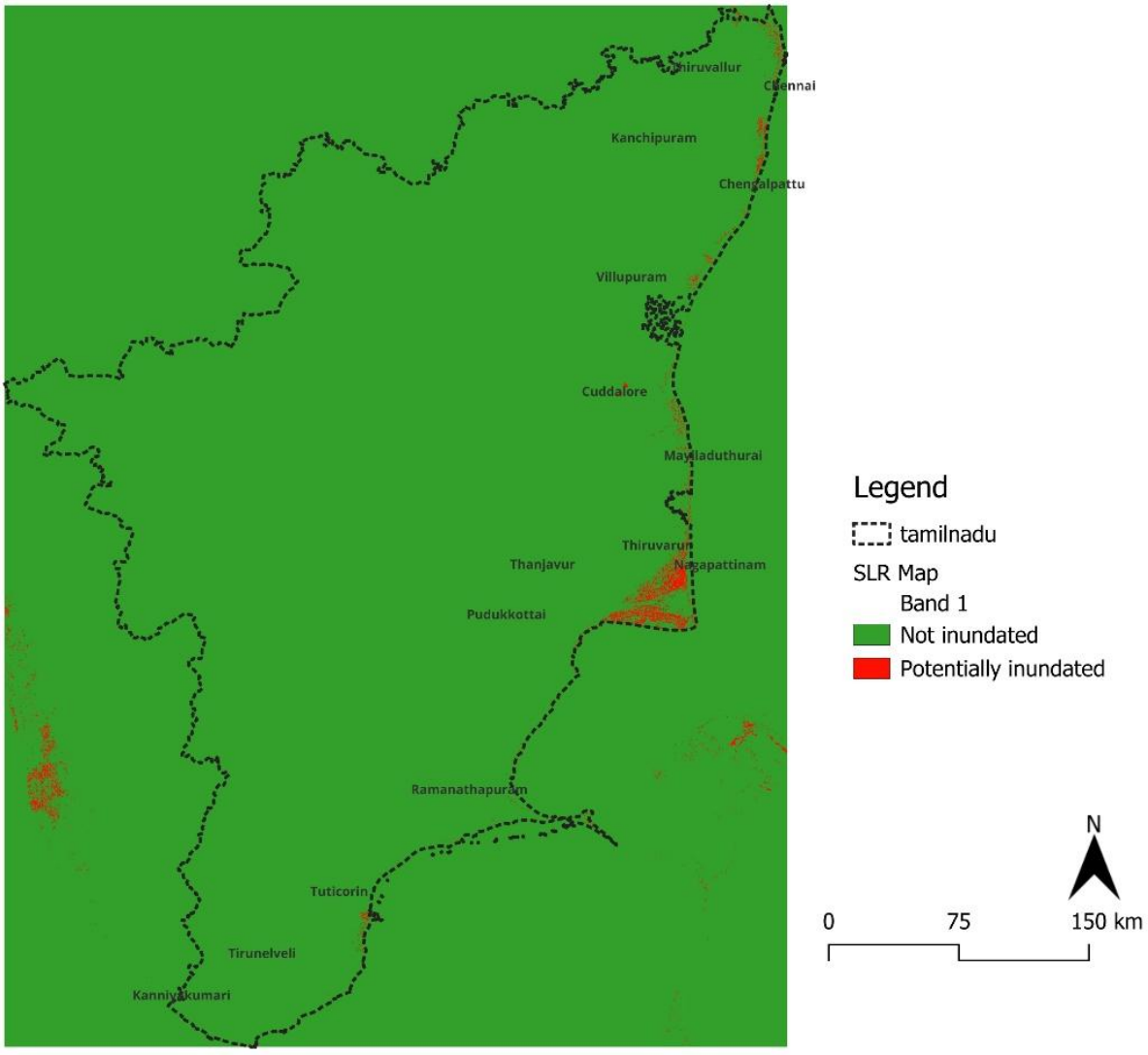


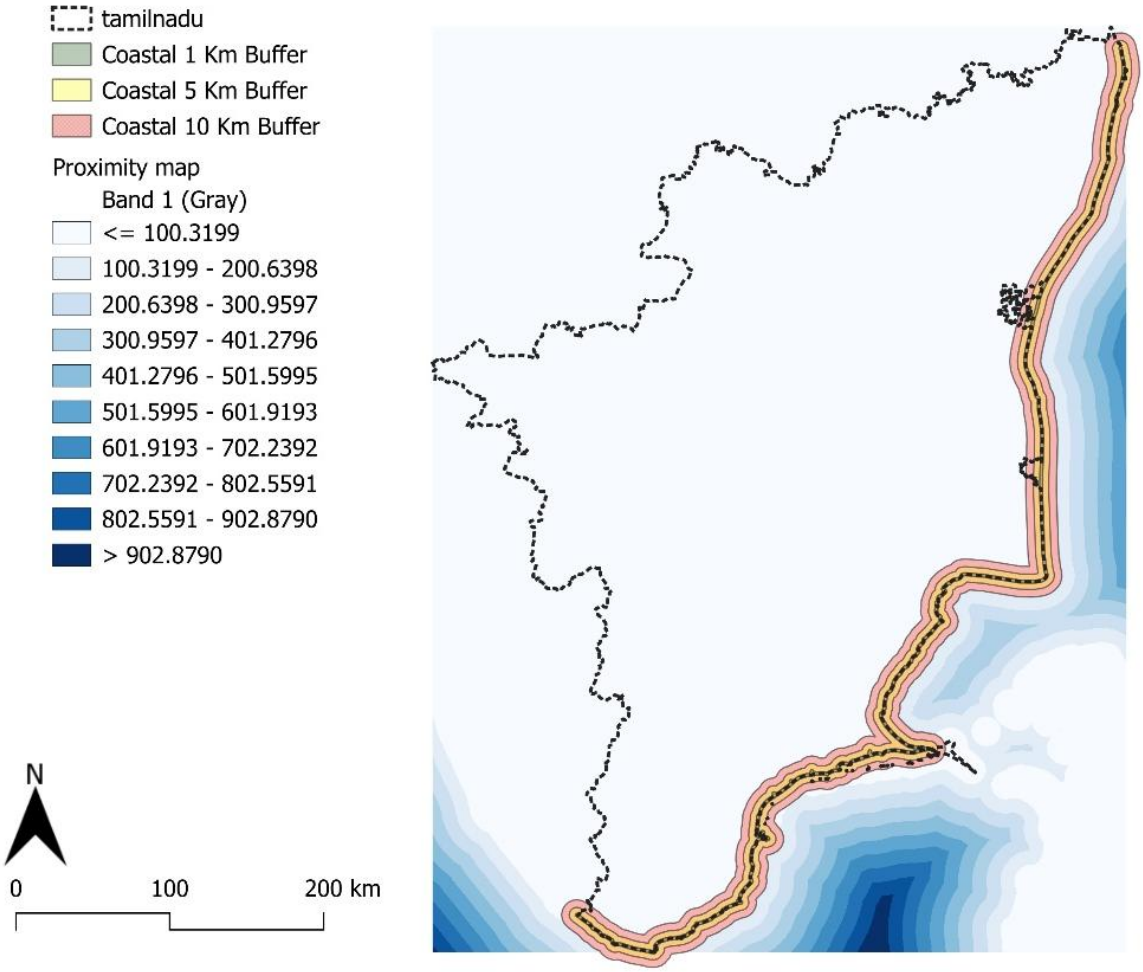
Figure 14 Sea level Rise Vulnerability Map

and presence of river deltas, and it provides a critical baseline for subsequent analysis on population, and economic activities and to frame strategies for adaptation to SLR especially in the hotspot areas along the coast of Tamil Nadu.

5.2.5 Proximity assessment – Vulnerability

The coastal proximity analysis from the figure 15 clearly shows a spatial gradient in distance from the Tamil Nadu coast with the1k m, 5k m, and 10k m coastal buffers the limiting zones of direct coastal influence with increasing proximity distances. The distance raster varies from nearly 100.32 to over 902.88 units, with decreasing values being closest to shore and increasing toward inland and offshore points. The 1km buffer zone constitutes the zone of highest proximity, and consequently likely highest degree of risk associated with coastal hazards such as sea-level rise, storms surges, inundation and erosion.

The 5km buffer zone delineates a more generalized zone of coastal influence with expanded potential for exposure to associated secondary hazards, and the10km buffer zone defines the widest zone of coast influence, potentially relevant in coastal vulnerability and resilience planning. Geographically, the narrow strip along the coastline clearly has a value corresponding to lowest proximity values while the distance values increase going away from shore, which conforms with an



expected inverse relationship between distance and coast proximity. Thus, this analysis can serve to delineate different zones of coastal exposure risk (highest, moderate and relatively low) which can later be linked to the slope, ruggedness of the land terrain and sea-level rise, land cover and population layers for assessment of coastal vulnerability and resilience. More specifically, these three proximity zones may be used to evaluate hazards based on distance from the shore.

6 DISCUSSION

The results indicate that the spatial overlap of gently slopes, localized hydrometeorological extreme and structural social-ecological vulnerability shape the risk distribution along Tamil Nadu coast. The inverse spatial correlation between elevation and vulnerability emphasizes how steep slopes within low coastal plains substantially reduced the hydraulic resistance for the onslaught of sea-level rise, surge inundation etc., thereby increasing hazard exposures. The structure vulnerability is enhanced along some areas, such as in Cauvery delta, in regions with low topographical slope combined with the rainfall variability, where deluge prone flood accumulation areas exist. In reality, clear over-concentration of spatial distribution of cyclonic tracks to NE coast of TN (Chennai to Nagapattinam) confirm that hazard exposures are non uniform and adaptation strategies need to focus on a micro level instead of planning an administrative level.It's an evidence-based adaptation on the basis of ecosystem perspective. There is clear gap between natural coastal defines and the present habitat pattern in the area. Dense cover in the Western Ghats helps regulating Inland hydrologic response whereas, habitats with a capacity to attenuate ocean wave energy only exist in isolated estuaries; coastal cover only survives as small patches. Ongoing rapid land use change at near shore proximity 5 km form the natural protective cover to impermeable constructed area lead to increased surface run off. This study moves away from the conventional single hazard evaluation by creating an integrated framework based on the fusion ofclimate hazards and ocean sustainable values and vulnerability parameters within a GIS-MCDA framework.

Table 3 Literature And research Gap Matrix

Supported Literature	Study Area	Main Focus	Hazards / Variables Considered	Method / Technique	Ecological Dimension	Socio-economic Dimension	Research Gap	Contribution to this Study
)	Global / Coastal ecosystems	Coastal ecosystems and climate adaptation	Coastal vegetation, carbon, ecosystem functions	Ecological assessment	High	Low	Mainly ecosystem-focused; limited spatial multi-hazard assessment	Integrates ecological resilience with physical hazards and social vulnerability
	Tropical Indian Ocean	Ocean warming and ecosystem degradation	SST, marine productivity, ocean warming	Climate/ocean analysis	High	Low	Focuses mainly on ocean-climate processes rather than coastal spatial vulnerability	Links climate indicators with terrestrial coastal hazards and resilience
	Ecosystem services	Ecosystem resilience	Ecosystem services and resilience	Resilience framework	High	Moderate	Conceptual rather than spatially explicit coastal risk assessment	Converts ecological resilience concepts into spatial GIS indicators
	Tamil Nadu Coast	Coastal vulnerability	Physical, environmental and socio economic variables	GIS-based vulnerability assessment	Moderate	Moderate - High	Vulnerability-oriented; limited integration of ocean sustainability and resilience	Extends vulnerability assessment toward integrated resilience + sustainability

	Coastal zones	Climate adaptation	Climate/environmental indicators	GIS–AHP / MCDA	Moderate	Moderate	Strong multicriteria approach but limited integration of multiple coastal hazards and socio-ecological resilience	Uses integrated GIS-MCDA for multi-hazard and socio-ecological resilience
	Thiruvananthapuram, Kerala	Coastal community resilience	Erosion, flooding, storm tides, infrastructure, socio-economic variables	DSAS + weighted overlay	Moderate	High	Regional/local scale; does not comprehensively integrate ocean sustainability indicators	Applies a broader state-scale framework integrating ecological, physical and social dimensions
	Tamil Nadu coastal watersheds	Shoreline change	Erosion and accretion	Remote sensing / shoreline analysis	Moderate	Low	Primarily shoreline dynamics; does not assess cumulative multi-hazard resilience	Incorporates shoreline-related risk within a multi-hazard framework
	Andhra Pradesh	Socio-ecological resilience	Governance, ecosystem, community interactions	Socio-Ecological Systems + FCM	High	High	Strong conceptual social-ecological interaction but limited GIS-based spatial hazard integration	Spatially integrates socio-ecological dimensions with hazard and environmental indicators
	Coastal regions	Socio-ecological resilience	Socio-economic, ecological, climatic and physical indicators	SERI / resilience index	High	High	Resilience index approach does not fully integrate Tamil Nadu-specific multi-hazard spatial planning	Develops a Tamil Nadu-specific GIS-MCDA Coastal Resilience Index
	India	Coastal resilience governance	Cyclones, floods, SLR, erosion, storm surge	Multi-hazard governance framework	Moderate	High	Policy-oriented; limited spatial GIS implementation	Translates multi-hazard governance concepts into spatial decision support
	International	GIS for coastal spatial planning	Climate scenarios, vulnerability, land-sea interaction	GIS decision-support framework	Moderate	Moderate	Conceptual/systematic review rather than empirical Tamil Nadu application	Provides an empirical GIS-MCDA implementation for Tamil Nadu

	Tamil Nadu Coast – 14 coastal districts	Integrated Coastal Resilience & Sustainable Coastal Planning	Climate change, rainfall, LST, SLR, flooding, cyclone, erosion, slope, terrain, proximity, LULC, NDVI, NDWI, mangroves, wetlands, water quality, population, infrastructure, economy and social vulnerability	GIS + Remote Sensing + MCDA + Multi-hazard Overlay + CRI	High	High	-	Integrates climate hazards, ocean sustainability, ecological resilience, exposure and socio-economic vulnerability into one spatial decision-support framework

The Table 3 Literature And research Gap Matrix demonstrate the comparative analysis show that There exists a methodological lacuna in previous studies of coastal system most of these have concentrated more or less independently on single hazard or physical or ecological vulnerability or socio economic elements and failed to examine their interactions in a single geographical reference system (space). The current research move ahead the above disparate analysis methodology and combine together multi hazard; climate parameters, ocean sustainability, ecological capital and socio economical risk via GIS – MCDA for building GIS based CRI. Thus, we would provide stronger foundation to delineate combined risk hotspots, places for ESAs, disaster resistant infrastructure and progressive coastal planning in the state of Tamil Nadu.

6.1 Overlay Analysis

Four most relevant geo-physical factors rain fall, slope, terrain, and accessibility in to five levels of value intervals (Band 1) were combined, creating overlay map for Tamil Nadu. Lowest overlay value (≤480.5134, dark red) covers considerable portion of plain lands & East coast regions of Tamil Nadu indicating the most of area with spatial uniformity across the plain areas. As moving from East to West & towards north & north western portions of plains regions overlay value begins to raise moderately and represents secondary level of overlay values (Band 2; 480.5134 - 1006.9232, light orange).Highest values and then the value range increase more significantly on & along the border lines regions & along interior ranges of Western & Eastern Ghats, and represented high to top value bands 3,4,5 i.e. In white to dark grey colours [1006.9232-1533.3331(Band 3), 1533.3331 -2059.7429 (Band4), >2059.7429 (Band 5) respectively]. The statistically spatial distribution indicate there exist strong positively correlated spatial relationship between high overlaid values and highest altitude high slope region, inversely low overlaid values distributed in high area across the Eastern coast plain region and western part of interior plain regions.

Spatial pattern of multi-criteria decision making overlay model shows marked spatial geographic stratification regulated by terrain processes. Topographic effect shows dominant position and broadest geographic range for primary band (480.5134) covering the large shape reduce overall composites. However,

north-westerly shift, with gradually increasing index value in secondary range (≤480.5134 to 1006.9232) becomes extremely prominent while rapidly emerging into third and fourth ranges (1006.9232 to greater than 2059.7429).Eastern coastal tracts and inland plains of Tamil Nadu, which implies a high spatial consistency as terrain slope, proximity and

Ghats. High concentration of highest composite values in particular (greater than 2059.7429) in

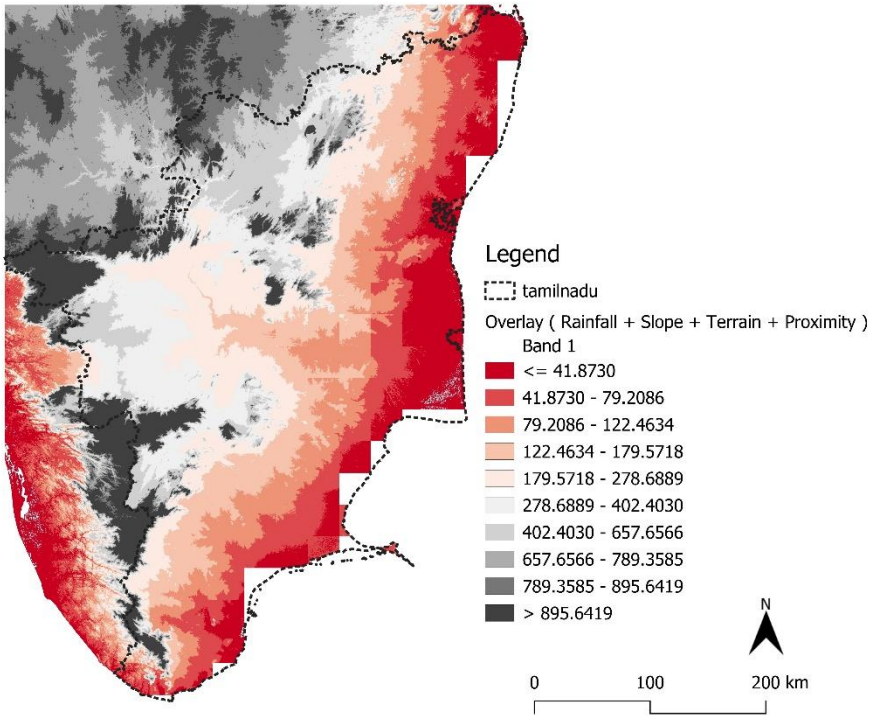


Figure 17 Overlay Rainfall + Slope + Terrain + Proximity (Author,2026)

particular localized stream head and high relief areas shows high weighting

and areas receiving heavy precipitation along both ranges of Western Ghats and Eastern Ghats. High concentration of highest composite values in particular (greater than 2059.7429) in particular localized stream head and high relief areas shows high weighting value from slope and heavy rainfall,

6.1.1 Decision supporting Hazard & Coastal Resilience Framework

The multi-criteria composite overlay map shown in the figure 17 integrates both the physical environmental indicators (rainfall, slope, terrain, aspect, distance) with marine risk factors (cyclone tracks, vulnerabilities) and marine ecological buffers (mangroves), into ten discrete statistical index bands ranging from 41.8730 to > 895.6419. In terms of geographical distribution low and least value index bands (41.8730 - 79.2086, bold and medium red) show comprehensive and universal presence all over eastern coastal plain and low lying interior regions of Tamil Nadu, which reflect spatial homogeneity of high extent over flat landscapes of low elevations. Coastal low value belts are directly interwoven by extensive network of historical cyclone paths and large concentric cyclone vulnerability sectors mostly along Chennai-Cuddalore region and Cauvery delta region However, mangrove habitats, in these highly exposed coastal regions have mapped as isolated and discrete patches along river mouths indicating limited defensive capacity against maritime adversities.Further inland into the western and north western regions, composite index values gradually increase through intermediate value bands (122.4634 - 402.4030, light peach to cream) before reach sharp increase in terms of higher value bands (657.6566 to > 895.6419$, dark grey and black). These high index values concentrate

within the extreme terrain (slopes and rugged mountainous) of western ghats. From general statistical spatial representation, there is a clear inverse relationship of low value of physical components along the coast and high exposure of multi-hazardous agents in one side and high value of physical components in interior on the other side corresponding with high elevation landforms that are topographically shielded.

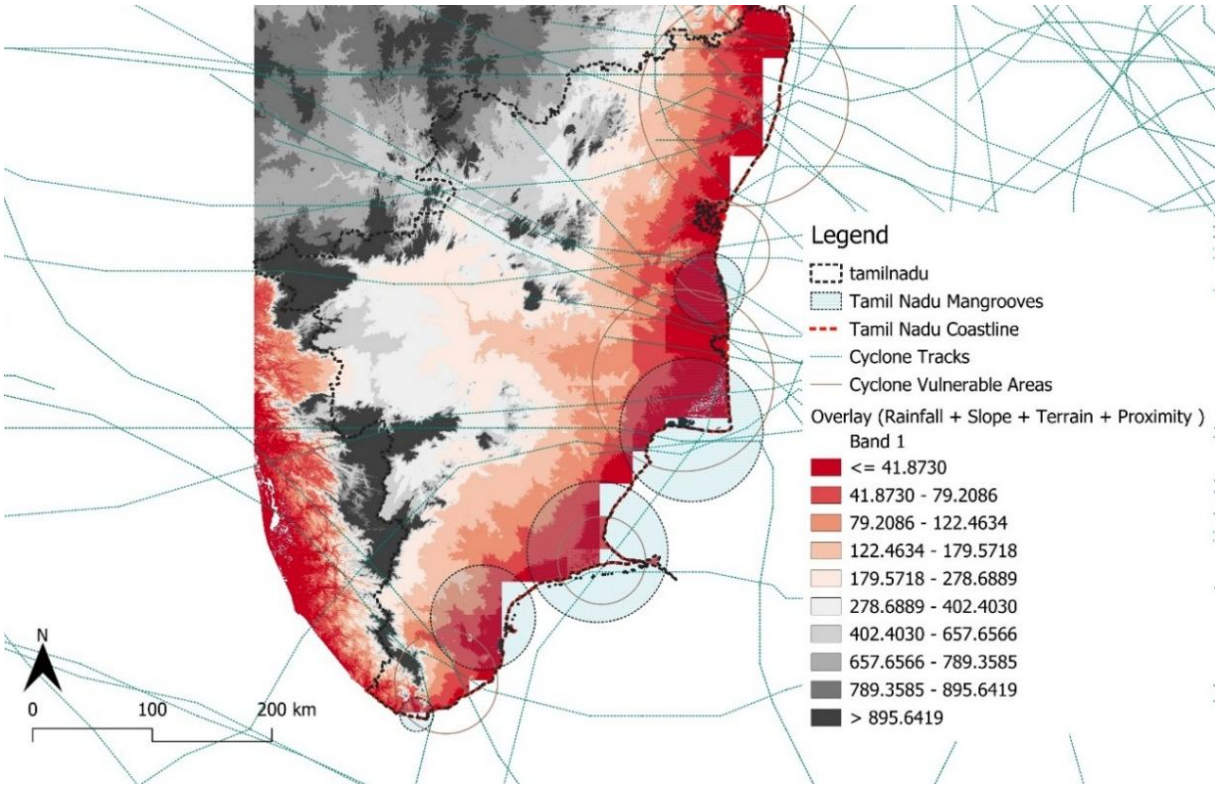


Figure 18 Overall Coastal Resilience & Hazard Map - Tamil Nadu (Author,2026)

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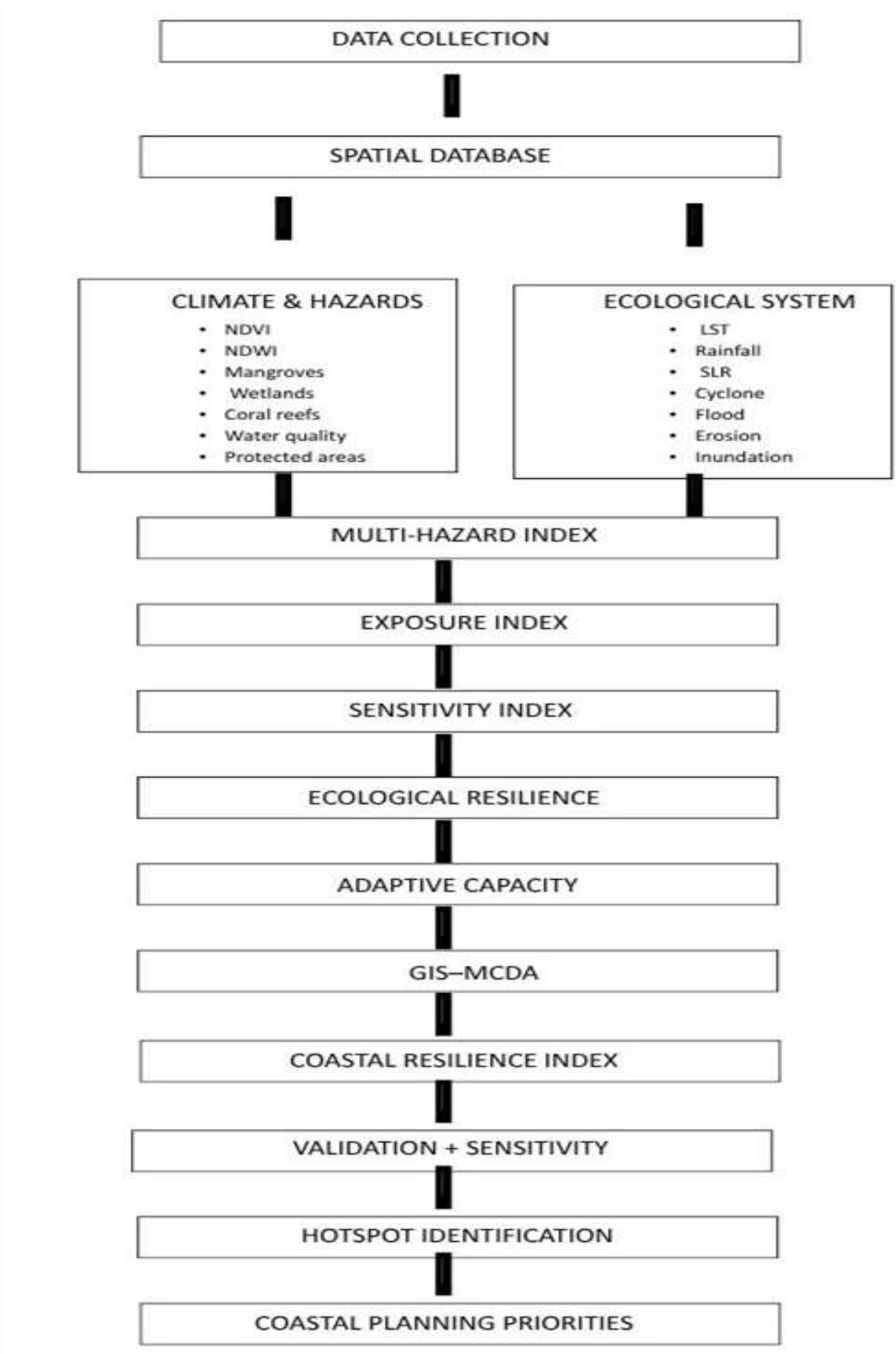


Figure 19 Overall Methodology Framework

7 LIMITAION OF THE RESEARCH :

This research has several limitations which are related to data availability, spatial and temporal resolution, indicator choice, and assumptions of the MCDM methodology. The various climate, ecological, socioeconomic, and remote sensing datasets used in this study may have different spatial and temporal resolutions, which can lead to inconsistencies, and discrepancies if combined in a GIS-based overlay analysis. The assessment also reflects the conditions during the period of observations only, and may not be capable of revealing long-term variations of shoreline change, sea-level, cyclone behaviour, ecological conditions, or socioeconomic status.

While the selection of indicators is carefully based upon systematic literature review, these inevitably provide an oversimplification of complex dimensions, eg. Institutional capacity, socio-economic situation, community knowledge, community social networks, or local coping capacity, which are inherently difficult to quantify and spatialize. In addition, the use of weightings within GIS-MCDA may introduce an element of subjectivity to the final Coastal Resilience Index. The condition of correlated indicators such as population and population density, vegetation and NDVI, or wetlands and NDWI, can also influence the index if not adequately explored. The weighted-overlay approach may not fully incorporate the non-linear, coupled interactions of compound hazards (e.g., cyclone, storm surge, heavy rainfall, river inundation, rising sea level, coastal erosion), or the scale mismatch of socioeconomic and environmental data may influence the Spatial Resolution of results. Furthermore, while remote sensing indicators serve as useful proxies of ecological conditions, they are unable to measure actual ecosystem health, functionality, biodiversity, connectivity, or ecological services. The 1 km, 5 km, and 10 km buffers delineate a generalized zone of influence, rather than physically model the zonation of hazards. Hence, the analysis cannot be presented as a precise assessment of community or site resilience, but should be treated as a spatial decision-making, and comparative, analysis of coastal resilience.

8 FUTURE RESEARCH & ASPECTS :

Further research can expand on this framework to include a dynamic predictive and process oriented coastal resilience assessment. Future work can employ CMIP6 climate projections and different climate scenarios in modelling temperature, rainfall, extreme events, cyclone behaviour and sea-level rise. Integrating high-resolution digital elevation models, tidal condition, bathymetry, storm-surge properties, wave conditions and projected sea-level rise with hydrodynamic modelling can produce more reliable coastal inundation and flooding simulation. Compound and cascading hazards can be explored in greater depth in terms of interactions between cyclone, storm surge, rainfall, river-flooding, erosion and sea-level rise. Multi-temporal Landsat and Sentinel datasets can be used to track and monitor shoreline change, mangrove change, vegetation condition, built-up change, surface temperature and coastal water condition over time to build the framework into a dynamic coastal resilience monitoring system. Inclusion of household and participatory GIS survey, local knowledge, livelihood data, institutional capacity and local coping strategies can add to the representation of social vulnerability and adaptive capacity. Next-generation MCDA and uncertainty analysis can also be employed to investigate how the indicator selection, normalization method and indicator weight can impact the calculated Coastal Resilience Index. Machine-learning approaches may be used to develop hazard susceptibility models, non-linear relationship analysis and future risk prediction. Ecosystem services assessment, ecosystem-based adaptation alternatives, nature-based solutions, ecosystem restoration, managed retreat, coastal infrastructure strengthening and coasta development can be assessed through scenario-based approaches in terms of their cost, benefit and risk.

The application of the framework as a GIS- or web-based coastal decision-support system for planners and coastal authorities can be pilot tested for transferability to other Indian coastlines under different environmental, societal and governance regimes.

9 CONCLUSION :

The integrated GIS-MCDA framework from the figure 19 that we developed can be scaled to support assessment of both multi-hazard exposure and social-ecological resilience for climates exposed to risk along coastlines. Applied to the 14 districts of coastal Tamil Nadu, our model helps in explicitly identifying the most hazard-vulnerable hot spots and comparing the vulnerability to inundation of the relatively flat delta districts with northern, more developed areas-which display significant hazard to cyclones. Synthesizing, with reference to ecologically identified vulnerability parameters into one framework and integrating human social vulnerability in terms of indices, contributes towards a more forward looking tool (Coastal Resilience Index – CRI) for the planners to support single-hazard evaluation to adaptive zoning. Further enhancements of the framework should involve incorporating time series hydrodynamic models, coping capacities of local inhabitants and more precise micro-climate modelling to aid adaptive zoning; as a result these spatial baseline datasets can aid in sustainable Coastal Zone Management with regard to ecological resource and individual life's supportability.

We presented an approach that unified multi source geospatial datasets, remote sensing, and Multi Criteria Decision Analysis (MCDA) to generate a socio-ecological resilience map for the Tamil Nadu coast as shown in the figure 189 & figure 19 As spatial observations show coastal risk being uneven, the interplay between terrain elevation and hazards revealed a spatial dependence between areas of risk and low elevation; thus lower-lying coastal lowland areas namely the Cauvery Delta and other north coastal districts were more susceptible to sea level rise, storm surges and extreme monsoon precipitation. In addition, the highly fragmented spatial distribution of mangroves, a primary form of natural shoreline protection, clearly highlights the need for an ecosystem-based approach for rehabilitation in the buffer zones directly at the shoreline 5 Km. With the deployment of a stratified Coastal Resilience Index (CRI), the application translates spatial information into local adaptation actions to enable enhanced coastal resilience in the long-term.

10 Overall research Outcome :

In overall research methodology as shown in the figure 19 Tamil Nadu, coastal vulnerability has been found to be spatially varied with Cauvery delta (Nagapattinam, Thiruvarur and Mayiladuthurai) and the Chennai-Cuddalore belt identified as the highly prone multi-hazard hotspots owing to its collective impact of low elevation, sea level rise, flood, cyclonic impact and ecology degradation. Application of coupled GIS-MCDA over 1076 km of coastline covering 14 coastal districts in Tamil Nadu proves that integrated approach to physical, climate, ecological and socioeconomic drivers can develop a solid framework for identifying compound-risk hot spots and developing a case for eco-based adaptation and resilient coastal planning.

It would be the Adoptive Framework to adopt a any city or District Or State or Country, Its Provides a Intergraded Coastal Resilience Index to Face the Extreme and unexpected climate changes and weather. It would be the skeleton for Coastal Resilience and it help for future research to provide the adequate precaution to face the Nature disasters

CRediT authorship contribution statement

Jeyasuriya Durai : Writing Original Draft, Conceptualization. Akshaya Radhakrishnan - Review & editing. Zorba R - Review & editing.

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Declaration of competing interest

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Data availability

Data will be made available on request.

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