Mapping of Cyclone Disaster Vulnerability using Geospatial Techniques and Analytical Hierarchy Process: Implications for Resilient Urban Planning in Coastal City of Southern Tamil Nadu

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Abstract

This study introduces a novel integrated approach for cyclone disaster vulnerability assessment in Thoothukudi Coastal City, Tamil Nadu uniquely combining Geographic Information Systems with Analytical Hierarchy Process methodology at neighbourhood scale. The research systematically analysed ten vulnerability parameters under five categories: meteorological (wind speed), coastal topography (distance from coast, elevation), geomorphological (aspect, drainage density), infrastructure-demographic (population density, building density, road network density) and environmental (land use/land cover, vegetation cover). Unlike previous regional assessments, this study developed a comprehensive neighbourhood-level vulnerability framework specifically calibrated for coastal urban planning applications.

The innovation lies in the integration of both physical exposure and socio-economic sensitivity parameters through expert-driven AHP analysis which established refined parameter weightages with wind speed (30%), coastal proximity (12%) and elevation (12%) emerging as dominant factors. The vulnerability mapping revealed that only 25.80% of the municipality falls under high to very high vulnerability zones predominantly in eastern coastal areas while 64.37% exhibits moderate vulnerability.

The research uniquely translates vulnerability science into actionable urban planning interventions including vulnerability-based zoning regulations, enhanced building standards in high-risk zones, strategic infrastructure placement and climate-responsive green infrastructure development. This study represents the comprehensive cyclone vulnerability assessment for Thoothukudi coastal city that bridges the gap between disaster science and practical urban planning by providing a replicable methodology for other coastal urban centres facing similar hazards.

Keywords: Cyclone Disaster vulnerability, Smart urban planning, Coastal hazards, Resilience, Risk assessment.

Introduction

Disasters have become increasingly prevalent worldwide with hydro-meteorological events accounting for over 70% of all natural disasters in recent decades[3]. Cyclones represent one of the most devastating natural hazards affecting coastal regions globally causing catastrophic impacts through intense winds, storm surges and torrential rainfall[28]. The annual economic losses attributed to tropical cyclones worldwide exceed 26 billion USD with the Asia-Pacific region bearing approximately 80% of this burden[22]. Between 1970 and 2019, cyclones claimed over 779000 lives globally and affected more than 400 million people[16]. International efforts to address cyclone related risks have intensified under Sendai Framework for Disaster Risk Reduction prioritizing vulnerability assessment[18]. In India, the eastern coastline along the Bay of Bengal serves as a frequent corridor for tropical cyclones with country experiencing an average of 5-6 cyclonic events annually[9].

Annual cyclonic events in India generate economic losses exceeding 2.5 billion USD with significant spatial variability in vulnerability patterns[5]. Tamil Nadu has witnessed several devastating cyclonic events in recent decades including Cyclone Vardah (2016), Cyclone Gaja (2018) and Cyclone Nivar (2020) which collectively caused infrastructure damage exceeding INR 30000 crores and affected millions of residents across the state's coastal districts[4]. The vulnerability of urban areas to cyclonic hazards has considerably increased in recent decades driven by the dual forces of rapid urbanization and climate change [31]. Urban populations in cyclone-prone coastal regions are expanding at unprecedented rates with an estimated 60% of the world's population expected to reside in cities by 2030[25]. This urban expansion often occurs lacking consideration of disaster risk resulting in development within high-hazard zones and the increase of substandard housing that cannot withstand extreme weather events[27].

In the coastal States of India including Tamil Nadu, the urban growth rates exceed 3% annually which significantly outpace the development of resilient infrastructure[12]. The climate change projections indicate a potential increase in

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cyclone intensity by 2-11% and storm surge heights by 0.4-0.6 meters by 2050 particularly affecting low-lying coastal urban centres [17]. To address the challenges posed by accelerating urbanization and worsening climate hazards, disaster-resilient urban strategies is crucial[8]. Traditional urban development models frequently neglect resilience in favour of economic gains leading to infrastructure and building designs vulnerable to cyclones[19]. Effectively integrating cyclone vulnerability assessments into urban planning, can protect lives, livelihoods and critical infrastructure in cities facing heightened exposure [21].

Geographic Information Systems (GIS) and advanced Spatial Analysis Techniques have emerged as powerful tools for cyclone vulnerability assessment enabling the integration of diverse datasets to identify high-risk zones with unprecedented precision[20]. Conventional vulnerability mapping approaches often suffer from limited spatial resolution. Insufficient integration of multi-dimensional risk factors compromises their utility for targeted urban interventions[30]. Geospatial technologies enable the quantitative and qualitative analysis of complex vulnerability patterns across physical, socio-economic and infrastructural factors by interpreting critical spatial heterogeneity that are unobserved[1].

The effectiveness of the Analytical Hierarchy Process (AHP) in disaster risk assessment is enhanced through its integration with GIS providing powerful methodological framework for assigning weights to diverse vulnerability indicators based on their relative importance[14]. This integrated approach enables planners to systematically prioritize intervention areas based on scientifically derived vulnerability indices rather than relying on intuitive judgments [13]. Recent applications of GIS-AHP methodologies have demonstrated significant improvements in cyclone vulnerability assessment accuracy, with studies reporting enhanced predictive capacity compared to traditional approaches[6,7,10,13,15]. Research gaps exist in adapting these technologies to India's rapidly developing coastal urban regions particularly regarding local knowledge and informal settlements[11].

Recent studies have demonstrated the efficacy of integrating Geographic Information Systems (GIS) with Analytical Hierarchy Process (AHP) methodologies for comprehensive cyclone vulnerability assessment [6,7]. This approach enables the systematic weighting of multiple vulnerability indicators typically categorized into physical, social and mitigation dimensions producing spatially explicit risk maps with enhanced precision and utility for decision-makers [10]. Research conducted in coastal regions of India has identified significant spatial variations in cyclone vulnerability with physical factors such as elevation, proximity to coastline and slope interacting with social parameters including population density, infrastructure accessibility and socioeconomic conditions[23]. The studies in Tamil Nadu have revealed that while certain coastal areas exhibit high physical and social vulnerability, the integration of mitigation capacity significantly alters overall risk profiles[29]. The study demonstrated by combining Fuzzy AHP with Multi-Criteria Decision Making (MCDM) techniques enhances the precision of vulnerability assessments achieving Area Under Curve (AUC) values exceeding 0.80 for various hazard types[26]. The application of these methodologies has proven instrumental in identifying priority intervention zones, optimizing resource allocation and informing adaptation strategies[2].

The recent innovations incorporating machine learning algorithms with traditional GIS-AHP approaches have accelerated vulnerability assessment through analytical processes maintaining rapidly urbanizing coastal regions facing increased cyclone frequency[14,24]. Based on methodological advancements of previous studies this research develops an innovative cyclone disaster vulnerability assessment framework for Thoothukudi Municipal Corporation using integrated Geospatial-AHP methodology at neighbourhood scale.

The study analyses vulnerability factors across five categories: Meteorological, Coastal Topography, Geomorphological, Infrastructure-Demographic and Environmental. Unlike previous regional assessments, this research uniquely calibrates parameters for urban planning applications through expert consultation, pioneering the integration of physical exposure with socio-economic sensitivity indicators. The study generates high-resolution vulnerability maps identifying priority intervention zones and bridges the gap between disaster science and practical planning by developing zone-specific resilience strategies that support evidence-based decision-making for enhancing cyclone resilience in coastal urban centres.

Material and Methods

Study Area: Thoothukudi Coastal city lies along the southeastern Tamil Nadu coastline, facing the Gulf of Mannar between latitudes 8° 39' - 8° 51' N and longitudes 78° 57' - 78° 12' E extending over 136.15 km² (Fig. 1). The study area experiences Köppen classification Aw climate (tropical savannah) with peak thermal conditions during May-June where temperatures often reach 39°C, while the annual thermal range spans 23-39°C. Thoothukudi's cyclone vulnerability stems from its direct exposure to Bay of Bengal weather systems with historical impacts from cyclones like Gaja (2018) and Ockhi (2017) causing significant damage to coastal infrastructure. The region's low-lying terrain averaging merely 4m above sea level offers minimal natural protection against storm surges.

Annual precipitation of approximately 660mm concentrates during the northeast monsoon months (October-December) coinciding with peak cyclonic activity. Vulnerability is further heightened by the presence of critical port facilities, chemical industries, thermal power plants and salt production zones located in exposed coastal areas.

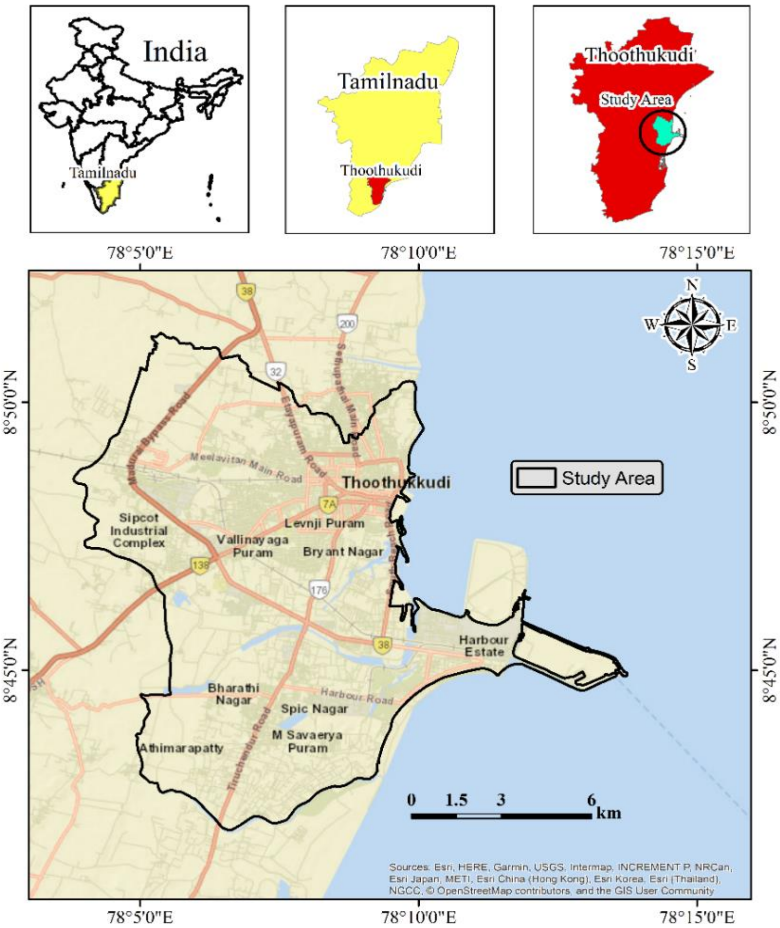

Fig. 1: Location map of the study area

The city's dense urban development pattern with approximately 320000 residents distributed across four zones and 60 wards places significant population clusters in cyclone susceptible zones particularly in eastern wards adjacent to the coastline.

Data Source

This study utilized multiple geospatial datasets representing the various factors contributing to cyclone vulnerability in Thoothukudi Coastal city. Meteorological data on wind speed patterns was acquired from the Global Wind Atlas at 250m spatial resolution providing essential information on potential cyclonic wind impacts. Coastal topographic parameters included distance from coastline derived by creating buffer zones from Survey of India (SOI) administrative shapefile and elevation data extracted from 30m resolution Shuttle Radar Topography Mission (SRTM) Digital Elevation Model. Geomorphological factors such as aspect and drainage density were calculated from the SRTM DEM using spatial analyst tools.

Infrastructure and demographic indicators comprised of population density obtained from SOI census data, building density extracted from Google Open Buildings 2.5 dataset accessed through Google Earth Engine (GEE) and road network density generated from Open Street Maps (OSM) vector data. Environmental parameters included Land Use/Land Cover (LULC) classification and vegetation cover indices derived from Landsat-8 satellite imagery with 30m resolution. All remote sensing data underwent rigorous pre-processing including atmospheric correction, geometric rectification and resampling to establish a consistent 30m resolution across analytical layers. Datasets were selected based on their spatial resolution adequacy for neighbourhood scale vulnerability assessment, temporal relevance to current urban conditions and their demonstrated effectiveness in previous cyclone vulnerability studies.

AHP-Based Multi-Criteria Analysis: The Analytical Hierarchy Process (AHP) was implemented to determine the relative importance of ten cyclone vulnerability parameters through pairwise comparisons. Expert evaluations were conducted using Saaty's 1-9 scale where criteria were systematically compared based on their contribution to overall vulnerability. Analysis of the pairwise comparison matrix revealed Wind Speed as the most significant factor with a precise weightage of 30% reflecting its direct impact on structural damage during cyclonic events. Distance to coast and elevation followed with 12% each highlighting the importance of proximity to shoreline and terrain height in determining surge vulnerability. Drainage density and Buildup density received 10% weightage, each acknowledging their influence on flood retention and exposure of physical assets.

Table 1
Cyclone Vulnerability Parameters with Area Distribution, Rankings and Weightage

Parameter	Class	Area	Percent	Rank	Rating	Weightage
Wind Speed (km/hr)	Light Breeze (14.76 - 19.00)	26.38	19.38	1	Very Low	30
	Gentle Breeze (19.00 - 23.00)	28.53	20.95	2	Low	
	Moderate Breeze (23.00 - 28.00)	27.91	20.5	3	Moderate	
	Fresh Breeze (28.00 - 33.00)	26.62	19.55	4	High	
	Strong Breeze (33.00 - 37.44)	26.70	19.61	5	Very High	
Distance from Coast (km)	Critical Coastal Zone (0 - 1)	22.92	16.84	5	Very High	12
	High Risk Coastal Belt (1 - 2.5)	20.86	15.32	4	High	
	Moderate Buffer Zone (2.5 - 5)	37.42	27.48	3	Moderate	
	Low Risk Inland Zone (5 - 10)	54.65	40.14	2	Low	
	Safe Inland Zone (>10)	0.30	0.22	1	Very Low	
Elevation (m)	Critical Zone (<3)	38.24	28.09	5	Very High	12
	Danger Zone (3 - 5)	24.81	18.22	4	High	
	Buffer Zone (5 - 10)	47.71	35.04	3	Moderate	
	Safe Zone (10 - 15)	16.36	12.01	2	Low	
	Protected Zone (>15)	9.03	6.63	1	Very Low	
Aspect (degree)	Flat (-1)	16.82	12.35	1	Low	5
	North (0-22.5)	16.66	12.23	4	High	
	Northeast (22.5-67.5)	16.09	11.82	5	Very High	
	East (67.5-112.5)	15.86	11.65	5	Very High	
	Southeast (112.5-157.5)	15.40	11.31	5	Very High	
	South (157.5-202.5)	14.90	10.95	4	High	
	Southwest (202.5-247.5)	14.65	10.76	3	Moderate	
	West (247.5-292.5)	14.32	10.52	2	Low	
	Northwest (292.5-337.5)	5.83	4.28	3	Moderate	
	North (337.5-360)	5.61	4.12	4	High	
Drainage Density (m/km²)	Minimal Channel (0 - 95)	26.70	19.61	5	Very High	10
	Sparse Channel (95 - 190)	27.20	19.98	4	High	
	Intermediate Channel (190 - 285)	28.04	20.59	3	Moderate	
	Dense Channel (285 - 380)	26.97	19.81	2	Low	
	Critical Drainage (>380)	27.24	20.01	1	Very Low	
Population Density (ppl/km²)	Sparse Population (21 - 5250)	24.87	18.27	1	Very Low	5
	Low Density Zone (5250 - 10500)	27.36	20.10	2	Low	
	Moderate Density Zone (10500 - 15750)	30.44	22.37	3	Moderate	
	High Risk Zone (15750 - 21000)	26.99	19.83	4	High	
	Critical Population Zone (>21000)	26.45	19.43	5	Very High	
Building Density (buildings/km²)	Rural/Open Area (0 - 1180)	23.38	17.17	1	Very Low	10
	Sparse Urban Area (1180 - 2370)	28.70	21.08	2	Low	
	Medium Urban Area (2370 - 3560)	35.31	25.94	3	Moderate	
	Dense Urban Area (3560 - 47560)	36.75	26.99	4	High	
	Critical Density Area (>4750)	11.99	8.81	5	Very High	
Road Network Density (m/km²)	Very Low Road Density (0 - 612)	26.65	19.57	5	Very High	5
	Low Road Density (612 - 1223)	27.69	20.34	4	High	
	Moderate Road Density (1223 - 1835)	28.17	20.69	3	Moderate	
	High Road Density (1835 - 2446)	27.16	19.95	2	Low	
	Very High Road Density (>2446)	26.48	19.45	1	Very Low	
Land use Land Cover	Salt Pan	23.27	17.09	5	Very High	6
	Cultivated Land	28.74	21.11	2	Low	
	Barren/Uncultivated Land	35.83	26.32	4	High	
	Settlement Area	21.68	15.93	3	Moderate	

	Trees/Shrub Area	22.15	16.27	1	Very Low	
	Water Body	4.47	3.28	3	Moderate	
Vegetation Factor	Wetland Zone (-0.33 - -0.15)	16.49	12.11	4	High	5
	Barren Zone (-0.15 - 0.00)	27.73	20.36	5	Very High	
	Scrubland Zone (0.00 - 0.20)	39.1	28.72	3	Moderate	
	Farmland Zone (0.20 - 0.40)	36.38	26.72	2	Low	
	Dense Vegetation Zone (0.40 - 0.53)	16.45	12.08	1	Very Low	

Land Use/Land Cover contributed 6% while Aspect, Road Density and Population Density received 5% each and vegetation cover was assigned 5% summarized in table 1. The Consistency Index (CI) was calculated as 0.142, yielding a Consistency Ratio (CR) of 0.095, below the 0.10 threshold, confirming acceptable judgment consistency among experts.

Cyclone Vulnerability Index: The cyclone vulnerability mapping was accomplished through weighted overlay analysis in ArcGIS integrating all ten standardized parameters according to their AHP-derived weights. Each parameter was reclassified to a uniform vulnerability scale (1-5), where 5 represented maximum vulnerability. The cyclone vulnerability index (CVI) was calculated using the formula:

$$CVI = \sum_{i-1}^{n} (wi * ri)$$

where CVI = Cyclone Vulnerability Index, wi = Weight of the parameter (from AHP analysis), ri = Reclassified rank value (1-5) of the ith parameter and n = Total number of parameters (10).

Results and Discussion

Spatial Distribution of Cyclone Influential Factors: The spatial analysis of ten cyclone influential factors across Thoothukudi Coastal city revealed significant geographical variations in vulnerability parameters with each factor exhibiting distinct distribution patterns that collectively determine the overall cyclone risk of the region.

Meteorological Factor: Wind speed is the primary meteorological factor with the highest weightage (30%) in vulnerability assessment exhibiting a clear west-to-east gradient across the study area (Fig. 2a). The spatial distribution reveals eastern coastal areas in particularly Harbour estate, Threspuram and Muthiapuram areas experiencing strong breeze conditions (33.00-37.44 km/hr, 19.61% of area), representing very high vulnerability zones that would face catastrophic impacts during cyclones when wind speeds could amplify to destructive levels exceeding 120 km/hr [24]. Moving westward side, a distinct zone of fresh breeze (28.00-33.00 km/hr, 19.55%) encompasses areas like eastern portions of Bryant Nagar representing high vulnerability zones. The central section features moderate breeze conditions (23.00-28.00 km/hr, 20.5%) including Muthammal Colony, while gentle breeze zones (19.00-23.00 km/hr, 20.95%) cover west-central areas. The western sectors including Korampallam, Mullakkadu and Athimarapatti villages experience light breeze conditions (14.76-19.00 km/hr, 19.38%), representing the least vulnerable areas though still susceptible during major cyclonic events[26]. This gradient pattern significantly influences overall vulnerability, with heightened risk concentrated in eastern coastal neighbourhoods directly exposed to the Gulf of Mannar.

Coastal Topographic Factor: The coastal topographic analysis revealed critical spatial patterns in two key vulnerability parameters each carrying a 12% weightage in the overall assessment (Fig. 2b). Distance from coast displays a clear concentric gradient pattern with 16.84% of the study area falling within the critical coastal zone (0-1 km) predominantly in Harbor estate, Threspuram and eastern coastal villages. These areas face immediate devastation during cyclonic storm surges and would experience rapid inundation[2]. The high-risk coastal belt (1-2.5 km, 15.32%) encompassing parts of Muthiapuram and Bryant Nagar regions remain highly susceptible to surge effects. The moderate buffer zone (2.5-5 km, 27.48%) formed through central portions includes Mullakkadu and western Bryant Nagar areas. Western sections including Sankaraperi and Korampallam villages fall within the low-risk inland zone (5-10 km, 40.14%) while negligible portions (0.22%) exceed 10 km from the coast.

Elevation reveals 28.09% of the study area lying within the critical zone (<3m) predominantly concentrated in Harbor estate, Threspuram and southeastern coastal stretches forming a significant central depression extending inland through Caldwell colony (Fig. 2c). These areas face threat during cyclones as storm surges of even 2-3 meters would cause catastrophic inundation[13]. The danger zone (3-5m, 18.22%) encompasses transition areas in central-eastern portions including parts of Bryant nagar and Mullakkadu areas remaining highly vulnerable to more severe cyclonic events.

The buffer zone (5-10m, 35.04%) constitutes the largest elevation class forming the dominant terrain through central portions including Muthammal colony and western Bryant nagar providing moderate protection against all but the most extreme surge events[6]. The western and northwestern sections exhibit the greatest resilience with safe zones (10-15m, 12.01%) and protected zones (>15m, 6.63%) concentrated around Sankaraperi and portions of

Korampallam village. This elevation distribution creates a fundamental vulnerability gradient with critical risk concentrated in eastern and southeastern part that progressively diminishes westward fundamentally shaping study areas overall cyclone risk[23].

Geomorphological Factors: The aspect revealed complex slope orientation patterns across the study area with significant implications for cyclone vulnerability (Fig. 2d). Northeast, east and southeast-facing slopes (collectively covering 34.78% of the area) received the highest vulnerability ratings due to their direct exposure to prevailing cyclonic winds from the Bay of Bengal[15]. These orientations scattered throughout the region but particularly evident in coastal areas facing maximum wind force and precipitation impact during cyclonic events[10].

The substantial flat terrain area (12.35%) is concentrated in central portions including Caldwell colony and Bryant nagar providing minimal deflection of cyclonic winds[26]. North and south-facing slopes (27.30% combined) maintain high vulnerability ratings but with slightly reduced wind exposure compared to easterly aspects. The western and northwestern aspects (14.80% combined) receive the lowest vulnerability ratings due to their sheltered orientation relative to typical cyclone path[17].

Drainage density revealed that areas with minimal channel density (0-95 m/km²) covering 19.61% of the study area face very high vulnerability to cyclone-induced flooding due to limited water evacuation capacity[6] (Fig. 2e). These poorly drained areas appear in patches along the periphery particularly in portions of Harbor estate and several western zones. Sparse channel networks (95-190 m/km²) encompass 19.98% of the area with high vulnerability ratings. The intermediate drainage class (190-285 m/km²) constitutes the largest category with 20.59% creating moderate vulnerability zones primarily in transition areas.

The dense channel networks (285-380 m/km²) and critical drainage areas (>380 m/km²) together cover 39.82% demonstrating enhanced drainage capacity with correspondingly lower vulnerability ratings[24]. The complex drainage pattern reveals localized flooding hotspots particularly where minimal channel density coincides with low-lying terrain in parts of Caldwell colony, Thermal nagar and coastal zones[7].

Infrastructure and Demographic Factors: The infrastructure and demographic analysis revealed critical vulnerability patterns through population density, building density and road network density collectively accounting for 20% of the total vulnerability assessment. Population density analysis identified that 39.26% of Thoothukudi falls under high to very high vulnerability categories with critical population zones (>21000 people/km², 19.43% of area) concentrated in northern Sankaraperi, northeastern Threspuram and parts of Muthiapuram (Fig. 2f). These densely populated areas face heightened vulnerability due to evacuation challenges and greater potential for human impact during cyclones[13,29]. The moderate density zone (10500-15750 people/km²) constitutes the largest category at 22.37% predominantly in central areas including Bryant nagar and eastern Harbor estate.

Sparse population zones (18.27%) concentrated in southern Thermal nagar, Mullakkadu and western patches face significantly reduced human vulnerability but may also receive lower priority during emergency response efforts[2]. Building density carries 10% weightage reveals that 35.8% of the study area falls under high to very high structural vulnerability categories (Fig. 3a). Dense urban areas (3560-4750 buildings/km², 26.99%) form a significant zone through central Thoothukudi, while critical density zones (>4750 buildings/km², 8.81%) appear as scattered areas notably in portions of Threspuram and Muthiapuram localities. These areas face increased damage potential during cyclones due to building density and associated debris hazards[12,17].

Western and southwestern portions predominantly comprise of rural/open and sparse urban areas (38.25% combined) offer reduced structural vulnerability but potentially lacking proper construction standards[15]. Road network density reveals that 39.91% of the study area faces high to very high evacuation challenges (Fig. 3b). Areas with very low road density (0-612 m/km², 19.57%) predominate in northern Sankaraperi village and western parts creating evacuation paths during cyclonic events[13,29]. Central portions including Bryant nagar and Caldwell colony exhibit moderate to high road density facilitating more efficient emergency response[29]. The inverse vulnerability relationship highlights that areas with better connectivity (approximately 39.40% of municipality) possess enhanced resilience through improved evacuation potential and emergency service access during cyclonic events[26].

Environmental Factors: The environmental analysis through Land Use/Land Cover (LULC) and vegetation indices revealed critical natural protective factors against cyclonic impacts. LULC assessment weighted 6% identified that 43.41% of the study area falls under high to very high vulnerability categories (Fig. 3c). Salt pans (17.09%) received the highest vulnerability rating due to their exposed nature and proximity to coastal zones concentrated in eastern Harbor estate, southern Mullakkadu and southeastern coastal stretches[6,7,17]. These areas provide no natural resistance to cyclonic winds and are highly susceptible to storm surge inundation[23].

Barren/uncultivated land (26.32%) similarly exhibits high vulnerability and dominates the western portions around Sankaraperi and northern regions. Settlement areas (15.93%) concentrated in Threspuram, parts of Muthiapuram and central Bryant Nagar localities receive moderate vulnerability ratings due to the dual nature of built environments offering some wind resistance while being susceptible to structural damage[2]. The most resilient trees/shrub areas (16.27%) and cultivated land (21.11%) provide natural cyclone protection primarily in western and southwestern portions[12]. Vegetation analysis through NDVI contributes 5% to the vulnerability assessment revealing that 32.47% of the region falls under high to very high vulnerability categories (Fig. 3d).

Barren zones (-0.15 to 0.00 NDVI, 20.36%) with very high vulnerability ratings are predominantly located in northern Sankaraperi village, parts of Muthiapuram and scattered through central zones. Wetland zones (-0.33 to -0.15 NDVI, 12.11%) with high vulnerability are concentrated in eastern coastal areas and southern Mullakkadu. The predominant scrubland zone (0.00 to 0.20 NDVI, 28.72%) creates moderate vulnerability conditions throughout central portions[10]. Areas with substantial natural cyclone protection through dense vegetation (0.40 to 0.53 NDVI, 12.08%) are limited primarily to southwestern Athimarapatti, Muthiapuram and isolated patches in central zones offering critical natural wind breaks and reduced erosion potential during cyclonic events[13].

Determinants of Cyclone Risk: The multi-criteria analysis revealed the complex interplay of determinants shaping cyclone vulnerability across Thoothukudi Municipal Corporation. Wind speed emerged as the dominant factor (30% weightage) establishing an east-west vulnerability gradient with eastern coastal zones experiencing strong breeze conditions (33.00-37.44 km/hr) that would intensify dramatically during cyclonic events[13,26]. This meteorological determinant directly influences structural damage potential and human safety during cyclones[15]. Coastal topographic parameters (24% combined weightage) function as fundamental physical determinants with 28.09% of the study area lying below 3m elevation and 32.16% located within 2.5km of the coastline.

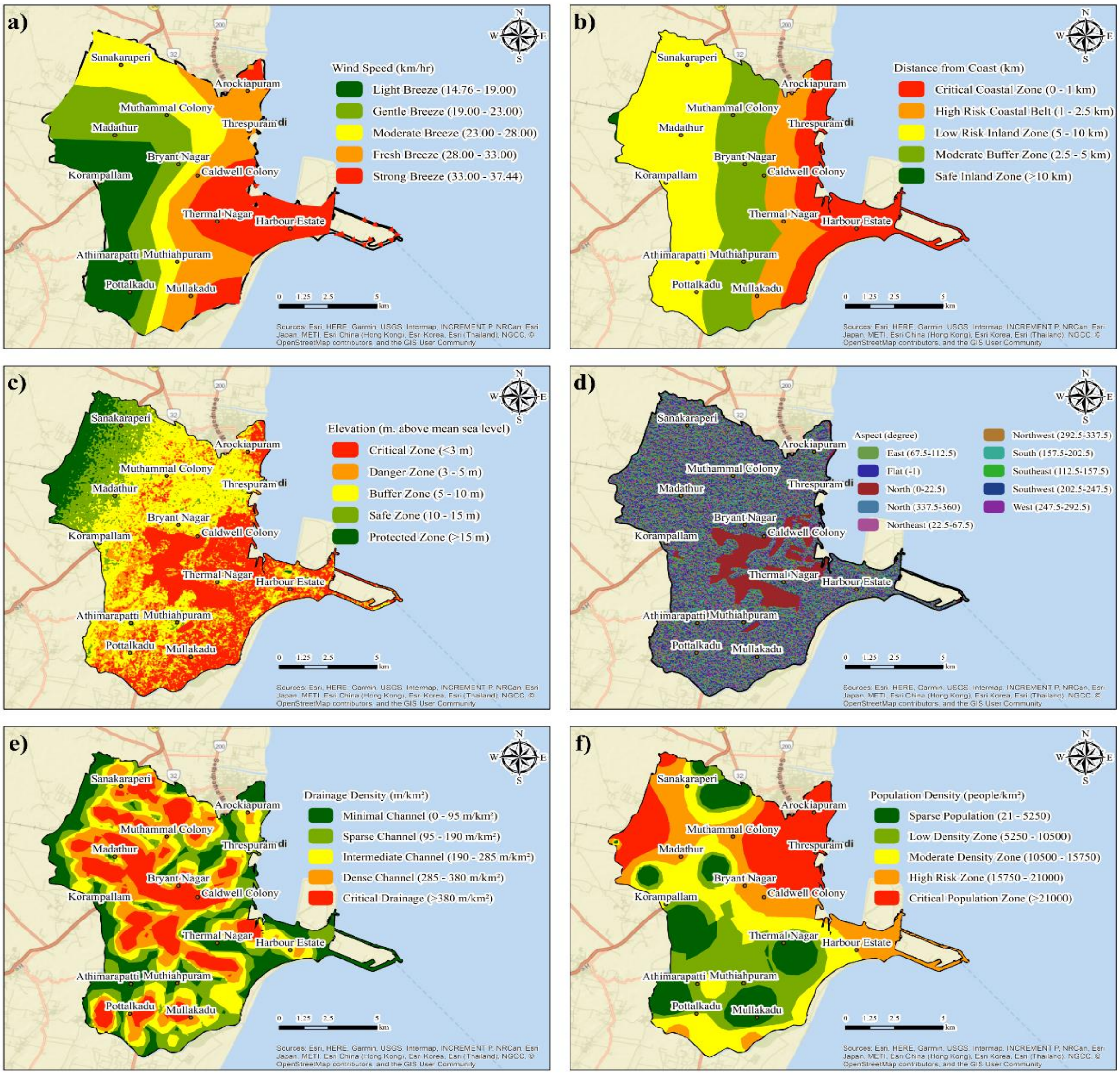

Fig. 2: Spatial distribution of key cyclone vulnerability parameters: (a) Wind speed zones, (b) Coastal proximity classification, (c) Elevation zones, (d) Aspect orientation, (e) Drainage density patterns and (f) Population density distribution across the study area.

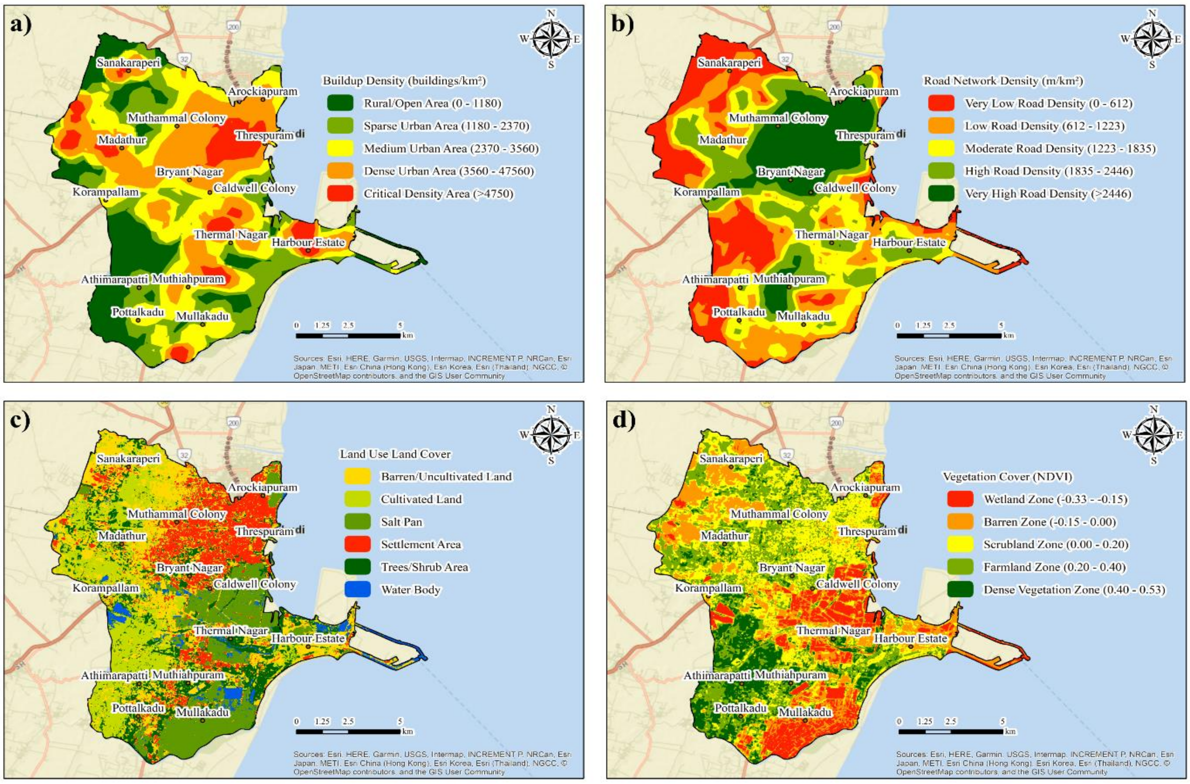

Fig. 3: Spatial distribution of: (a) Building density, (b) Road network density, (c) Land use/land cover and (d) Vegetation cover (NDVI) in the study area.

Table 2
Distribution of Cyclone Vulnerability Classes in the Study Area

S.N.	Class	Area (km²)	Percent
1	Lowly Vulnerable	13.39	9.83
2	Moderately Vulnerable	87.64	64.37
3	Highly Vulnerable	34.65	25.45
4	Very Highly Vulnerable	0.48	0.35

These factors establish baseline susceptibility to storm surge inundation and coastal flooding creating zones of compound vulnerability where low elevation coincides with coastal proximity particularly in Harbor estate, Threspuram and portions of Caldwell colony[24,29]. Geomorphological factors (15%) modify vulnerability through terrain characteristics, with east-facing slopes (34.78%) increasing direct exposure to cyclonic winds from the Bay of Bengal. Drainage capacity introduces hydrological vulnerability with 39.59% of the region having minimal to sparse drainage networks that would struggle to manage cyclone-induced precipitation[6,10]. Infrastructure and demographic determinants (20% combined) introduce critical social dimensions to vulnerability assessment.

Areas with high population density (39.26%) combined with dense building concentrations (35.8%) face amplified humanitarian impacts, while limited road networks (39.91% with low/very low density) constrain evacuation potential during cyclonic events[22]. Environmental factors (11%) reflect natural protective capacity with only 28.35% of the municipality containing substantial vegetation cover that could mitigate wind impacts[26]. Salt pans (17.09%) and barren lands (26.32%) offer minimal resistance to cyclonic forces.

Cyclone Vulnerability Index: The integrated cyclone vulnerability index reveals distinct spatial patterns across Thoothukudi Municipal Corporation (Fig. 4). Moderately vulnerable areas dominate the landscape encompassing 64.37% (87.64 km²) of the region primarily in central and northwestern portions including Muthammal colony, Muthiapuram and western Bryant nagar. Highly vulnerable zones constitute 25.45% (34.65 km²) concentrated predominantly in eastern coastal areas including Harbor estate, Threspuram and the southeastern coastline where multiple high-risk factors converge. Western sections including portions of Korampallam, Athimarapatti Muthiapuram and isolated patches in central zones exhibit low vulnerability (9.83%, 13.39 km²). Very highly vulnerable areas represent a minimal but critical 0.35% (0.48 km²) appearing as isolated hotspots in eastern coastal sections where extreme risk factors coincide shown in table 2.

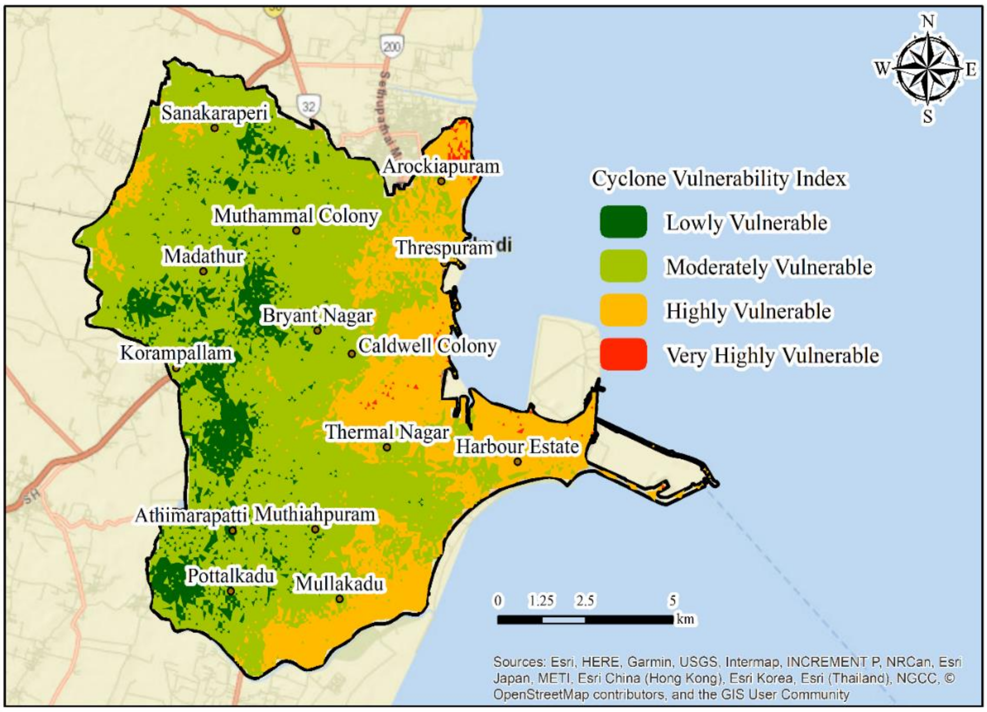

Fig. 4: Cyclone vulnerability index map of the study area showing the spatial distribution of vulnerability classes

The vulnerability distribution reflects the cumulative influence of weighted factors with the east-west gradient largely driven by wind speed patterns, coastal proximity and elevation[6,13]. Eastern coastal areas face compound vulnerability through strong winds, low elevation and direct coastal exposure creating the continuous band of high vulnerability evident in Harbor Estate and Threspuram[7,23,29]. The moderate vulnerability zone dominating central zones reflects balanced risk region where certain favourable factors (improved drainage, higher elevation) offset unfavourable ones (medium population density, moderate building density).

Western sections benefit from reduced wind exposure, higher elevation and greater distance from the coast creating the most resilient zones[15,25,26]. These patterns underscore the need for zone-specific adaptation strategies with particular urgency for the highly vulnerable eastern sectors comprising of over one-quarter of the municipality.

Implications for Smart Urban Planning: The cyclone vulnerability mapping provides a scientific foundation for developing zone-specific smart urban planning strategies across Thoothukudi Municipal Corporation. For highly and very highly vulnerable eastern coastal areas (25.80%) development restrictions, elevated building designs and surge barriers should be prioritized while existing structures require retrofitting for cyclone resilience. The dominant moderately vulnerable zones (64.37%) would benefit from targeted drainage improvements, moderate building code enhancements and strategic placement of community shelters. Low vulnerability western sectors present opportunities for sustainable development with standard resilience measures. This spatial differentiation enables resource optimization by directing intensive interventions to critical zones while implementing cost-effective measures elsewhere.

Smart planning applications include: (1) digital vulnerability-based zoning regulations integrated with municipal GIS systems (2) automated building permit systems requiring enhanced structural standards in high-risk zones (3) IoT-enabled early warning systems with location-specific protocols (4) sensor networks for real-time drainage monitoring in flood-prone areas and (5) climate-responsive green infrastructure prioritization in strategic buffer zones. The multi-criteria approach supports precision planning interventions allowing Thoothukudi to transform vulnerability data into implementable resilience strategies across infrastructure development, environmental management and regulatory frameworks.

Conclusion

This study developed a novel cyclone disaster vulnerability assessment framework for Thoothukudi Municipal Corporation uniquely integrating Geographic Information Systems with Analytical Hierarchy Process methodologies at neighbourhood scale. The research analysed ten vulnerability parameters across five categories bridging the gap between disaster science and practical urban planning applications. Results revealed that 25.80% of the municipality falls under high to very high vulnerability zones predominantly in eastern coastal areas where multiple risk factors converge, while 64.37% exhibits moderate vulnerability and 9.83% shows low vulnerability in western sections.

Wind speed emerged as the dominant vulnerability determinant (30% weightage), creating a fundamental east-west vulnerability gradient, while coastal topographic parameters established baseline physical susceptibility to storm surges. The innovative integration of both physical exposure and socio-economic sensitivity indicators highlighted critical vulnerability dimensions in densely populated coastal zones with limited evacuation potential. This comprehensive neighbourhood-level assessment for Thoothukudi provides an evidence-based foundation for targeted interventions including zone-specific building codes, strategic infrastructure placement and vulnerability-based development regulations.

The methodology offers a replicable framework for other coastal urban centres facing similar hazards. Future research should incorporate climate change projections to model vulnerability scenarios under intensified cyclonic conditions and should explore integrated vulnerability-opportunity mapping to maximize resilience-building initiatives.

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