Nanotechnology Perceptions
ISSN 1660-6795
www.nano-ntp.com

Synergizing Hazard Resilience And Renewable Energy Potential For Smart Coastal Development: A GIS-MCDA Approach In Thoothukudi, India

C. Antony Zacharias Grace*, John Prince Soundranayagam, A. Antony Alosanai Promilton***, V. Stephen Pitchaimani***, Ernest Amita Roy****

**Research Scholar, Reg No: 19212232132011, Research Department of Physics, V. O. Chidambaram College, Thoothukudi, Tamil Nadu, India. (Affiliated to Manonmaniam Sundaranar University, Tirunelveli). E-mail: graceraja83@gmail.com*
*** Research Department of Physics, V. O. Chidambaram College, Thoothukudi, Tamil Nadu, India. (Affiliated to Manonmaniam Sundaranar University, Tirunelveli) E-mail: johnprince06@gmail.com, amisartho@gmail.com*
****PG and Research Department of Geology, V. O. Chidambaram College, Thoothukudi, Tamil Nadu, India. (Affiliated to Manonmaniam Sundaranar University, Tirunelveli) E-mail: geopromilton@gmail.com, stephen.geo@voccollege.ac.in*

Coastal cities face escalating environmental challenges, demanding integrated planning that balances development with climate resilience. This study develops a comprehensive GIS framework for Thoothukudi, India, integrating multi-hazard vulnerability (flood, cyclone, urban heat island) with solar energy potential to delineate smart planning zones. Using the Analytical Hierarchy Process, flood vulnerability (51%) and cyclone vulnerability (38%) were weighted highest. Three indices such as compound vulnerability, development opportunity, and urban resilience were combined to establish five smart planning zones (no development to priority development). Results show 78.88% of the area has moderate vulnerability. Preferred development zones (34.63% of the area) are concentrated in the southwest, benefiting from favourable elevation and solar conditions. Restricted development zones cover 32.46%, primarily in the central urban core and coastal industrial areas. The framework identified strategic development corridors extending from high-resilience southwestern zones towards moderate-resilience areas, providing evidence-based guidance for sustainable expansion. This integrated methodology offers a transferable approach for coastal cities to implement climate-informed planning, addressing both disaster risk reduction and sustainable development. The resulting smart planning zones provide municipal authorities with actionable spatial guidance for adaptive management and renewable energy development while upholding environmental safety standards.

Keywords: Coastal Urban Planning, Multi-hazard Vulnerability, Smart Planning Zones, Renewable Energy Potential, Climate Resilience, Sustainable Development

1. INTRODUCTION

Coastal urban environments worldwide face unprecedented challenges as accelerating climate change intersects with rapid urbanization trends(Cissé, 2025). More than 680 million people currently inhabit low-elevation coastal zones, with this population projected to exceed one billion by 2050 (Bendoni et al., 2025; McMichael et al., 2020). These densely populated areas experience disproportionate exposure to multiple climate-related hazards including intensified tropical cyclones, increased flood frequencies and elevated temperatures due to both global warming and localized urban heat effects (Vinayachandran et al., 2022). Traditional urban planning approaches developed during periods of relatively stable climatic conditions prove increasingly inadequate for addressing the compound nature of contemporary environmental risks (Blakely, 2022; Mumtaz et al., 2025). Coastal cities in developing regions face particularly acute vulnerabilities where rapid population growth often outpaces infrastructure development and regulatory frameworks. The convergence of sea-level rise, extreme weather events and urban expansion creates complex risk landscapes that demand innovative planning methodologies (Mariano & Marino, 2022). Conventional single-hazard assessments fail to capture the synergistic effects of multiple environmental stressors leading to inadequate risk characterization and suboptimal planning decisions. The existing planning frameworks typically operate in reactive modes responding to disasters after they occur rather than proactively building resilience through evidence-based spatial planning (Adebayo, 2024). This reactive approach results in perpetual cycles of damage and reconstruction imposing substantial economic burdens on urban communities while failing to address underlying vulnerability drivers (Rezvani et al., 2023).

Multi-hazard vulnerability assessment has emerged as a critical component of contemporary urban planning offering systematic approaches to understanding and quantifying compound environmental risks (Drakes & Tate, 2022; Mohammadi et al., 2024). Geographic Information Systems and remote sensing technologies have revolutionized the spatial analysis capabilities available to urban planners enabling comprehensive evaluation of hazard exposure, sensitivity and adaptive capacity across urban landscapes (Abdalla & Abdalla, 2024; Rezvani et al., 2023). Smart city initiatives worldwide increasingly emphasize the integration of environmental risk considerations with sustainable development objectives recognizing that long-term urban prosperity depends fundamentally on environmental resilience (Mehmood et al., 2024). The United Nations Sustainable Development Goals explicitly call for making cities inclusive, safe, resilient and sustainable highlighting the global recognition of interconnected urban challenges (Barcellos-Paula et al., 2025). Recent advances in satellite Earth observation capabilities provide unprecedented opportunities for monitoring urban environmental conditions at fine spatial and temporal resolutions (Yu & Fang, 2023). Machine learning algorithms and big data analytics enhance the ability to process vast environmental datasets, enabling more sophisticated risk modelling approaches (Gomes et al., 2025). The translation of these technological capabilities into practical planning tools remains challenging particularly in resource-constrained developing urban contexts. Many existing multi-hazard assessment frameworks focus exclusively on risk characterization without adequately considering development opportunities that could enhance urban resilience while supporting economic growth (Mohammadi et al., 2024). This limitation often results in overly restrictive planning recommendations that may be politically and economically unfeasible in rapidly growing urban areas.

Tropical coastal cities face distinctive challenges that differentiate them from their temperate counterparts including higher baseline temperatures, intense monsoon system and greater exposure to tropical cyclones (Calvin et al., 2023). Tropical cities often possess significant renewable energy potential particularly for solar power generation due to abundant solar irradiation throughout the year (Ukoba et al., 2024). The integration of renewable energy considerations into urban planning processes remains limited despite growing recognition of energy security as a critical component of urban resilience (Kapucu et al., 2024). Coastal urban areas in India exemplify these challenges where cities like Chennai, Visakhapatnam and Kochi experience recurring flood events, cyclone impacts and increasing urban heat intensities. The development of industrial corridors along India's coastline has accelerated urbanization while simultaneously increasing environmental pressures and infrastructure vulnerabilities (Sharma & Khan, 2023). Traditional land use planning in these contexts often fails to account for the spatial variability of environmental risks or the potential for leveraging natural resources to enhance urban sustainability (Metternicht, 2018). Climate change projections indicate that coastal Indian cities will experience more frequent extreme weather events, higher temperatures and altered precipitation patterns over the coming decades (Subramanian et al., 2023). The National Action Plan on Climate Change emphasizes the need for climate-resilient urban development, yet practical methodologies for implementing such approaches at the city scale remain underdeveloped (Rezvani et al., 2023a). Existing planning practices typically address individual hazards in isolation, missing opportunities to develop integrated strategies that simultaneously reduce risks and enhance development potential.

The primary objective of this research is to develop an integrated GIS-based framework for delineating smart planning zones that simultaneously consider multi-hazard vulnerability and renewable energy development opportunities in coastal urban environments. Specific objectives include: (1) developing spatially explicit assessments of flood vulnerability, cyclone exposure, urban heat island intensity and solar energy potential using satellite remote sensing and GIS techniques, (2) creating compound vulnerability and development opportunity indices through multi-criteria decision analysis and (3) establishing a classification system for smart planning zones that balances risk reduction with sustainable development objectives. This framework aims to provide urban planners and policymakers with evidence-based tools for making informed decisions about land use allocation, infrastructure development, and disaster risk reduction strategies.

2. MATERIALS AND METHOD

This research employed a comprehensive GIS-based framework integrating multi-hazard vulnerability assessment with renewable energy potential mapping to develop evidence-based smart planning zones for coastal urban environments.

2.1 Study Area

Thoothukudi Municipal Corporation (8°45'N to 8°50'N and 78°08'E to 78°12'E) located in Tamil Nadu, India serves as the investigation area for this research. The study area encompasses 136.15 km² along the Gulf of Mannar coast and supports a population of approximately 237000 inhabitants. This coastal urban centre experiences a tropical semi-arid climate with distinct wet (October-December) and dry (January-September) seasons. Annual precipitation ranges from 570-750 mm with normal rainfall of 694 mm primarily concentrated during the northeast monsoon period. The region faces recurrent environmental challenges including coastal flooding during cyclonic events, urban heat stress during summer months (March-June) and periodic droughts. As a major port city and industrial hub, its key position serves as an example of rapidly developing coastal urban areas in the Indian Ocean region. The flat coastal topography with elevations ranging from sea level to 45 meters above mean sea level contributes to flood vulnerability while offering favourable conditions for solar energy applications is shown in **Figure 1**.

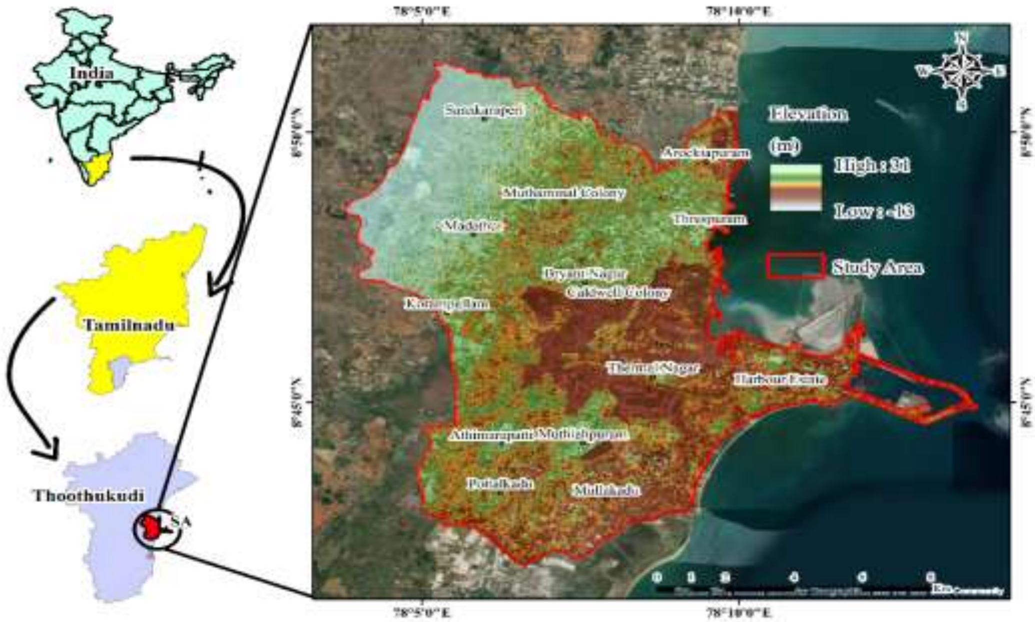

Figure 1. Digital elevation model of the study area.

2.2 Data Collection

Multi-source datasets were systematically acquired to support comprehensive environmental assessment and renewable energy evaluation. Landsat 8 Operational Land Imager and Thermal Infrared Sensor imagery provided the foundation for land surface analysis with cloud-free scenes selected during post-monsoon periods to ensure consistency. The Shuttle Radar Topography Mission 30-meter digital elevation model supplied topographic information for drainage analysis and slope calculations. Meteorological datasets from the India Meteorological Department included daily temperature, precipitation, humidity and wind speed records. Solar irradiation data derived from NASA's Surface Meteorology and Solar Energy database provided long-term average values across the study region. Census 2011 demographic data and Municipal Corporation infrastructure databases furnished population density and critical facility location information. Ground control points collected using differential GPS supported geometric correction and validation procedures.

3.3 Methodology

The analytical framework comprised four sequential phases is shown in Figure 2. Each component underwent systematic quantification using established geospatial techniques before integration through weighted overlay analysis.

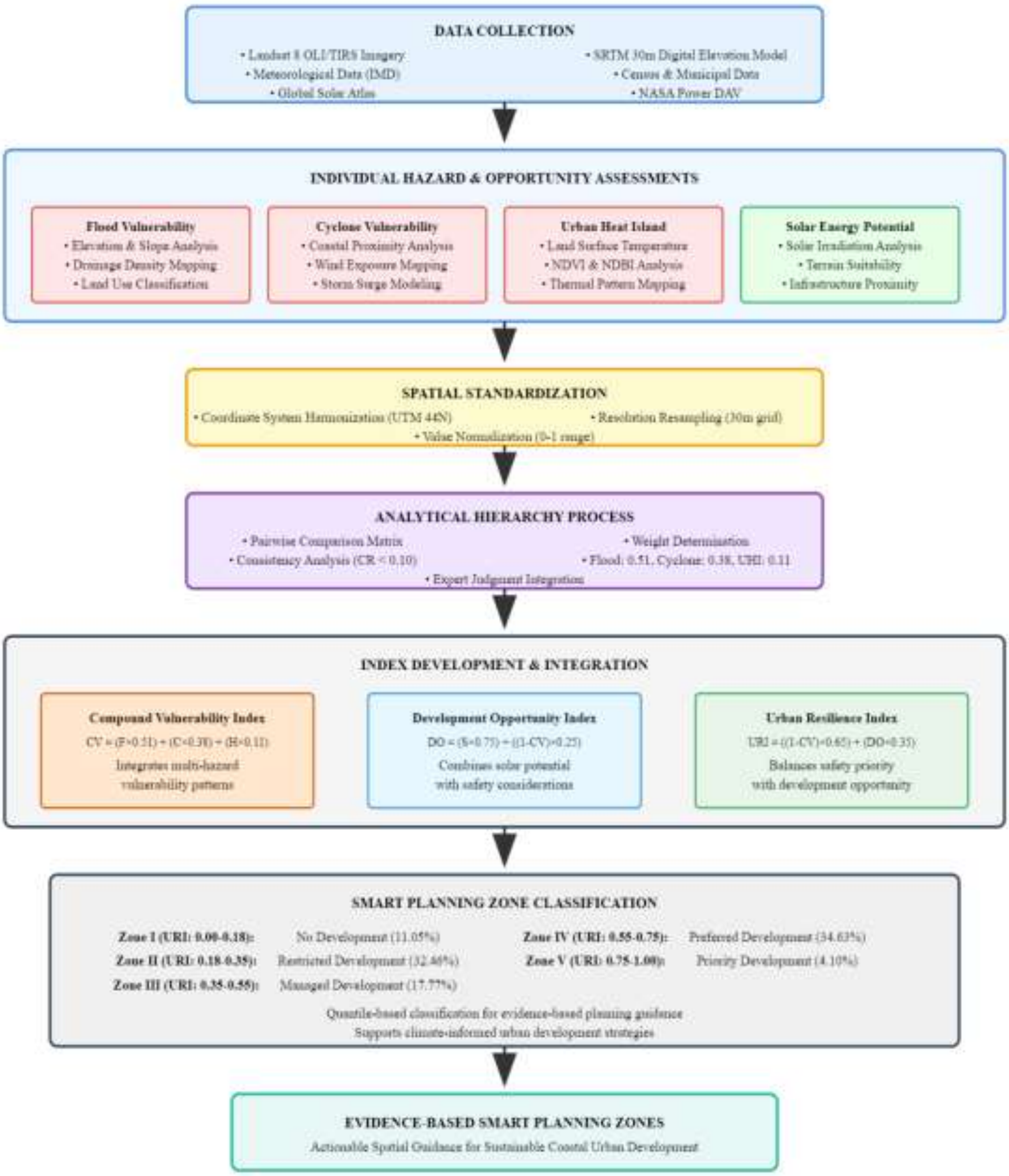

Figure 2. Methodology Flow chart of the Integrated Urban Smart Planning study.

3.3.1 Individual Assessment Framework

Individual assessments employed standardized multi-parameter approaches to quantify spatial vulnerability patterns across the study area.

3.3.1.1 Flood Vulnerability Evaluation

Flood vulnerability mapping utilized a hierarchical approach incorporating elevation characteristics, slope gradients, drainage density patterns, land use classifications, soil infiltration properties and precipitation intensity data. Digital elevation models were processed to extract topographic parameters, while drainage networks were delineated through flow direction and accumulation analysis. Land use land cover classification employed both Maximum Likelihood Classification and Support Vector Machine algorithms applied to multi-temporal satellite imagery to achieve optimal accuracy. The integration of these parameters through weighted overlay analysis produced spatially explicit flood vulnerability indices across the study area.

3.3.1.2 Cyclone Vulnerability Assessment

Cyclone vulnerability evaluation incorporated meteorological parameters including historical storm track frequencies and wind velocity patterns, topographical elements such as coastal proximity and elevation characteristics, geomorphological features encompassing shoreline configuration and land form types, infrastructure and demographic variables including population density and critical facility exposure and environmental protection factors such as mangrove coverage and natural barrier effectiveness. Each parameter was systematically weighted based on its relative contribution to overall cyclone vulnerability with spatial integration performed through multi-criteria overlay techniques to generate comprehensive vulnerability maps.

3.3.1.3 Urban Heat Island Intensity Mapping

Urban heat island intensity was quantified through land surface temperature retrieval from thermal infrared satellite imagery combined with spectral index analysis. Land surface temperature calculations utilized single-channel algorithms applied to Landsat thermal bands, while vegetation indices including Normalized Difference Vegetation Index and Soil Adjusted Vegetation Index were computed alongside built-up indices such as Normalized Difference Built-up Index. Correlation analysis between land surface temperature and various spectral indices enabled quantification of relationships between urban land cover types and thermal patterns facilitating the identification and classification of heat island zones.

3.3.1.4 Solar Energy Potential Assessment

Solar energy suitability evaluation integrated photovoltaic performance parameters including solar irradiation intensity and sunshine duration, climatic factors encompassing temperature and humidity patterns, topographic considerations such as slope orientation and terrain characteristics, environmental constraints including land use compatibility and protected area restrictions and accessibility factors covering proximity to electrical grid infrastructure and transportation networks. Multi-criteria analysis techniques were employed to synthesize these diverse parameters into composite suitability indices identifying optimal locations for solar energy development.

3.3.1.5 Spatial Data Standardization Framework

All individual assessment outputs underwent systematic standardization to ensure compatibility for integrated analysis (Table 1). Coordinate system harmonization projected all datasets to WGS 1984 UTM Zone 44N, while spatial resampling established uniform 30-meter resolution across all layers. Extent normalization ensured consistent coverage boundaries and value range standardization was achieved through min-max normalization techniques.

Table 1: Standardization Parameters Applied to Individual Assessment Layers

Assessment	Range	Standardized Range	Resampling Method	Data Type
Flood Susceptibility	2.0 - 5.0	0.0 - 1.0	Bilinear	Continuous
Cyclone Vulnerability	2.0 - 5.0	0.0 - 1.0	Nearest Neighbour	Thematic
UHI Intensity	1.0 - 4.0	0.0 - 1.0	Bilinear	Continuous
Solar Potential	1.0 - 5.0	0.0 - 1.0	Bilinear	Continuous

3.3.2 Analytical Hierarchy Process Implementation

Weight determination for multi-criteria integration employed the Analytical Hierarchy Process methodology. Pairwise comparison matrices were constructed using Saaty (1980)based on expert judgment and literature review considering the relative importance of each assessment component for coastal urban planning decisions (**Table 2 and 3**).

Table 2 AHP Pairwise Comparison Matrix for Compound Vulnerability Components

Criteria	Flood	Cyclone	UHI
Flood	1.00	0.50	4.00
Cyclone	2.00	1.00	5.00
UHI	0.25	0.20	1.00

Table 3 Derived AHP Weights for Compound Vulnerability Index

Vulnerability Component	AHP Weight	Percentage Influence
Cyclone Vulnerability	0.38	38%
Flood Vulnerability	0.51	51%
UHI Intensity	0.11	11%

3.3.3 Index Development and Integration

Standardized hazard and opportunity assessments were synthesized through mathematical integration using AHP-derived weights to create composite indices for planning guidance. Three hierarchical indices were developed serving specific planning objectives within the comprehensive framework.

3.3.3.1 Compound Vulnerability Index Development

The compound vulnerability index synthesized multiple hazard assessments into a unified vulnerability metric. This integration prioritized primary hazard factors while incorporating environmental stress components to provide comprehensive vulnerability characterization.

$$\mathrm{CVindex} = (\mathrm{Fnorm} \times \mathrm{Wf}) + (\mathrm{Cnorm} \times \mathrm{Wc}) + (\mathrm{Hnorm} \times \mathrm{Wh})$$

Where, CVindex is Compound Vulnerability Index (0-1), Fnorm is Normalized Flood Vulnerability, Cnorm is Normalized Cyclone Vulnerability, Hnorm is Normalized Heat Island Intensity, Wf, Wc, Wh are AHP-derived weights.

3.3.3.2 Development Opportunity Index Construction

Sustainable development potential incorporated solar energy suitability with safety considerations. Weight allocation prioritizes renewable energy potential (75%) over low-risk areas (25%)

$$\mathrm{DOindex} = (\mathrm{Snorm} \times 0.75) + \big((1 - \mathrm{CVnormalized}) \times 0.25\big)$$

Where, DOindex is Development Opportunity Index, Snorm is Normalized Solar Energy Potential and CVnormalized is Normalized Compound Vulnerability.

3.3.3.3 Urban Resilience Index Calculation

Comprehensive planning guidance integrated vulnerability reduction with development enhancement. Weight distribution emphasizes safety (65%) while incorporating opportunity (35%).

$$\mathrm{URI} = ((1 - \mathrm{CVnormalized}) \times 0.65) + (\mathrm{DOindex} \times 0.35)$$

Where, URI is Urban Resilience Index (0-1), CVnormalized is Normalized Compound Vulnerability and DOindex is Development Opportunity Index.

3.3.4 Smart Planning Zone Determination

Smart planning zones were delineated through statistical classification of the urban resilience index establishing five distinct categories for planning guidance (Table 4). Zone boundaries were determined using natural breaks classification to optimize within-group homogeneity and between-group heterogeneity.

Table 4 Smart Planning Zone Determination Criteria

Zone Class	URI Threshold	Development Category	Spatial Strategy
Zone I	0.0 - 2.0	No Development	Disaster preparedness focus
Zone II	2.0 - 4.0	Restricted Development	High Risk Management
Zone III	4.0 - 6.0	Managed Development	Climate-Adaptive Infrastructure
Zone IV	6.0 - 8.0	Preferred Development	Sustainable Growth
Zone III	8.0 - 10.0	Priority Development	Smart City Core

3. Results

3.1 Individual Assessment Outcomes

The individual assessment framework successfully quantified spatial vulnerability and opportunity patterns. Flood vulnerability assessment (Figure 3a) revealed that 52.08% of the area (70.9 sq.km) falls within high to very high susceptibility categories, with moderate vulnerability covering 31.91% (43.44 sq.km) and low vulnerability areas representing only 16.02% (21.81 sq.km), indicating significant flood exposure concentrated in low-lying coastal zones and areas with inadequate drainage infrastructure (Burayu et al., 2023; Kader et al., 2024; Saranya et al., 2024). Cyclone vulnerability (Figure 3b) analysis demonstrated that 64.37% of the study area (87.64 sq.km) exhibits moderate vulnerability, while 25.80% (35.13 sq.km) shows high to very high vulnerability levels, with the most severe impacts concentrated along the immediate coastal zone reflecting storm surge susceptibility and wind exposure (S. Das & Ghosh, 2024; T. Das et al., 2024; Hasan et al., 2024). Urban heat island intensity (Figure 3c) mapping identified that 63.07% of the area (85.9 sq.km) experiences moderate thermal stress, with 19.38% (26.39 sq.km) classified as strong to very strong heat island zones, primarily corresponding to dense built-up areas and industrial complexes, while 17.56% (23.92 sq.km) remains as thermal cold spots (Ezimand et al., 2024; Kasniza Jumari et al., 2023; Zhao et al., 2024). Solar energy potential (Figure 3d) assessment revealed highly favourable conditions with 60.43% of the study area (82.28 sq.km) demonstrating good to excellent solar potential indicating substantial renewable energy development opportunities, while areas with low to moderate potential comprise 39.57% (53.87 sq.km) demonstrating the region’s significant capacity for sustainable energy generation (Faqe Ibrahim et al., 2024; Imam et al., 2024; Kasniza Jumari et al., 2023).

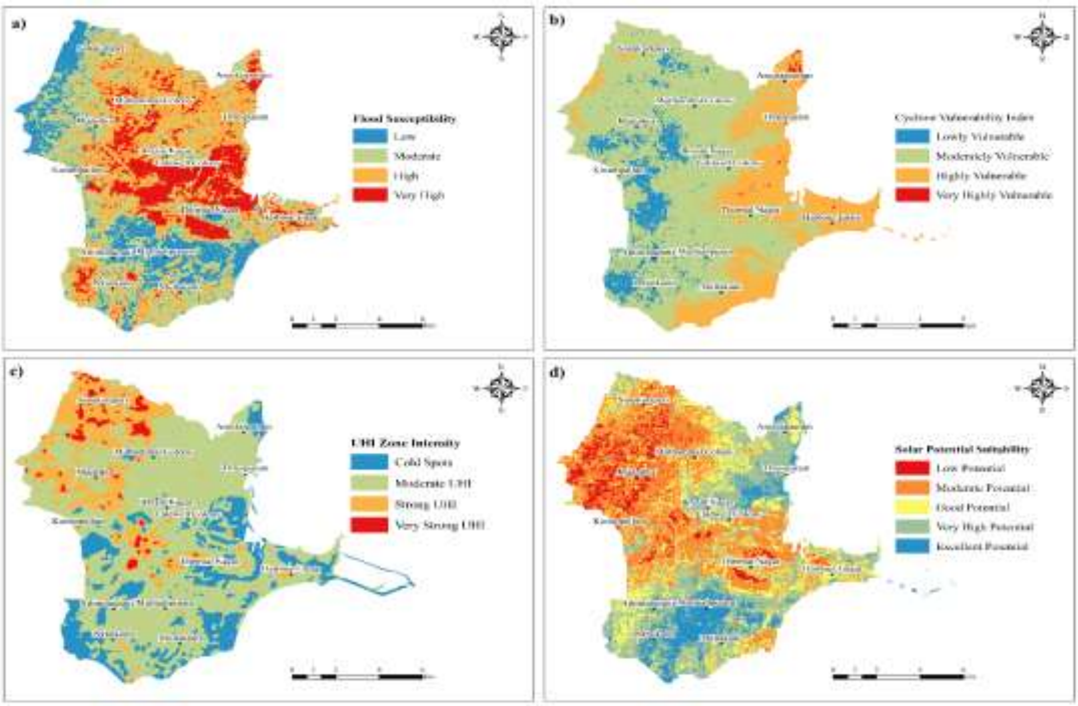

Figure 3. Spatial distribution maps of individual assessment parameters: (a) flood susceptibility zones, (b) cyclone vulnerability index, (c) urban heat island intensity zones and (d) solar energy potential suitability of the study area.

3.2 Index Development Evaluation

3.2.1 Compound Vulnerability Index

The compound vulnerability assessment revealed a predominantly moderate risk landscape of the study area with 78.88% (107.4 km²) classified as moderately vulnerable to combined environmental hazards (Figure 4). High vulnerability zones encompassed 14.21% of the total area (19.34 km²) concentrated primarily in the central urban core around Muthammal Colony, Bryant Nagar and Caldwell Colony extending southward through Thermal Nagar to the harbour industrial estate. These high-risk areas coincided with dense urban settlements, industrial facilities and low-lying coastal zones experiencing compound exposure to flood, cyclone and urban heat island effects. The low vulnerability areas comprised only 6.91% of the study region (9.41 km²) predominantly distributed along the western and southwestern peripheries near Korampallam, Pottalkadu and Mullakadu where higher elevations, reduced urban density and greater vegetation cover provided natural protection against multiple hazards.

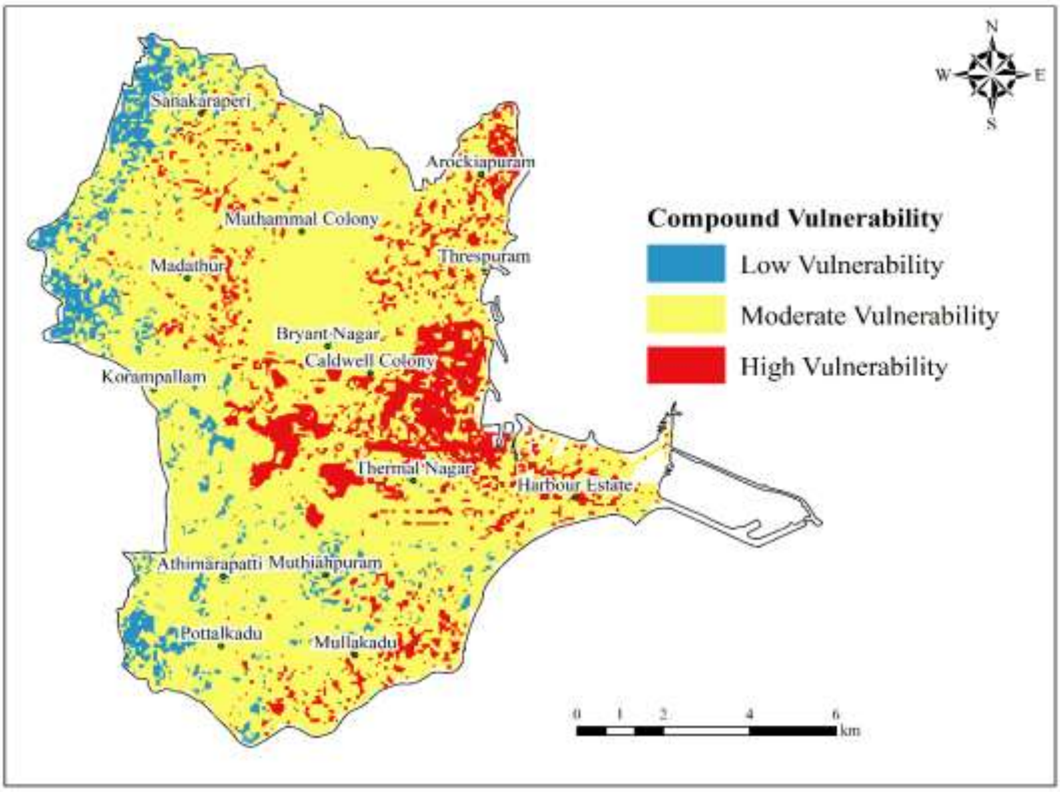

Figure 4. Spatial distribution of compound vulnerability index across the study area.

The spatial distribution of compound vulnerability exhibited a distinct east-west gradient with vulnerability intensities increasing toward the coastline and urban centre. The eastern coastal belt including Arockiapuram and areas adjacent to the harbour estate demonstrated consistently elevated vulnerability levels due to direct exposure to storm surge impacts, industrial heat generation and inadequate drainage infrastructure (Dharmarathne et al., 2024; Shrestha et al., 2023). Inland areas toward Sankaraperi and the northwestern sectors showed mixed vulnerability patterns reflecting the heterogeneous nature of land use transitions from urban to peri-urban environments. Notable vulnerability hotspots emerged in densely built-up residential areas where the convergence of limited green space, impervious surface coverage and proximity to flood-prone drainage channels created compound risk scenarios (Wu et al., 2025).

3.2.2 Development Opportunity Index

Development opportunity assessment demonstrated significant spatial variability with excellent to good development potential covering 36.51% of the study area (49.7 km²) indicating substantial capacity for sustainable infrastructure development (Figure 5). Excellent opportunity zones representing 11.26% of the total area (15.33 km²) were concentrated in the southern and southwestern regions particularly around Athimarapatti, Mullakadu and Pottalkadu, where favourable solar energy potential combined with relatively low environmental vulnerability to create optimal development conditions. Good opportunity areas comprising 25.25% of the study region (34.37 km²) formed extensive corridors connecting the southwestern excellent zones with scattered patches in the eastern coastal areas indicating strategic development pathways for renewable energy infrastructure and climate-resilient urban expansion.

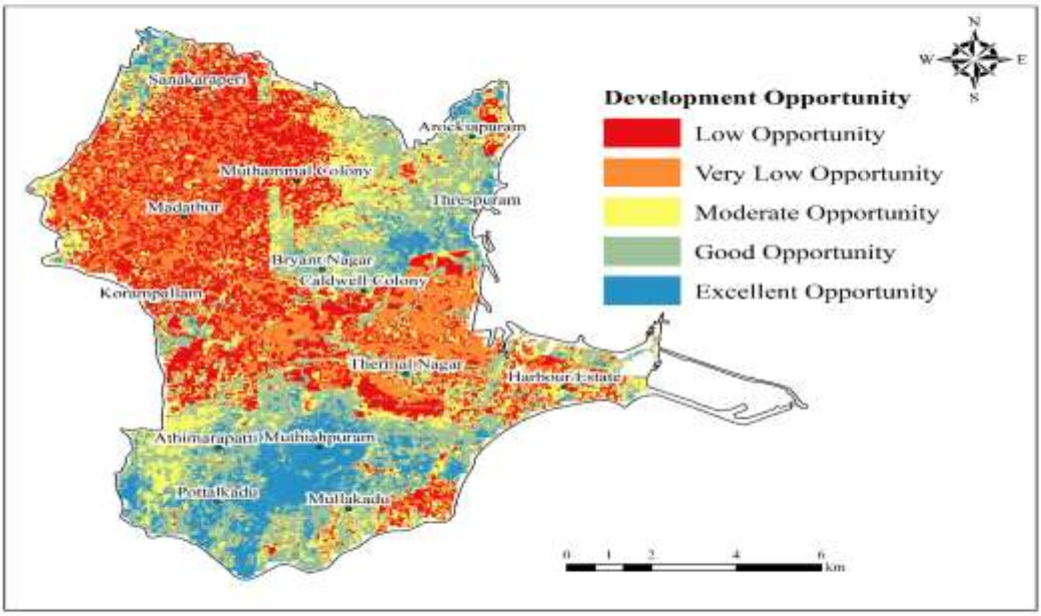

Figure 5. Development opportunity index distribution across the study area

Moderate development opportunity encompassed 22.65% of the study area (30.84 km²) primarily distributed through transitional zones between high and low opportunity areas suggesting locations suitable for managed development with appropriate risk mitigation measures. Low to very low opportunity zones collectively covered 40.84% of the total area (55.61 km²) concentrated in the central and northern urban sectors around Sankaraperi, Muthammal Colony and parts of the industrial corridor. These restricted development zones coincided with areas experiencing high compound vulnerability indicating the effective integration of risk considerations into opportunity mapping (Romshoo et al., 2024; Xue et al., 2024). The spatial pattern revealed an inverse relationship between development opportunity and existing urban density with peripheral areas demonstrating higher development potential due to lower environmental constraints and greater renewable energy accessibility (Romshoo et al., 2024).

3.2.3 Urban Resilience Index

The urban resilience assessment synthesized vulnerability and opportunity considerations to generate comprehensive planning guidance across a normalized scale from 0 (lowest resilience) to 1 (highest resilience) shown in Figure 6. The spatial distribution exhibited pronounced variability with resilience values demonstrating clear geographical clustering patterns that reflected the underlying integration of risk reduction and development potential factors (Rezvani et al., 2023b; J. Wang et al., 2023). High resilience zones were predominantly located in the southwestern quadrant encompassing areas around Pottalkadu, Mullakadu and southern Athimarapatti where low environmental vulnerability combined with excellent solar energy potential to create optimal conditions for sustainable urban development.

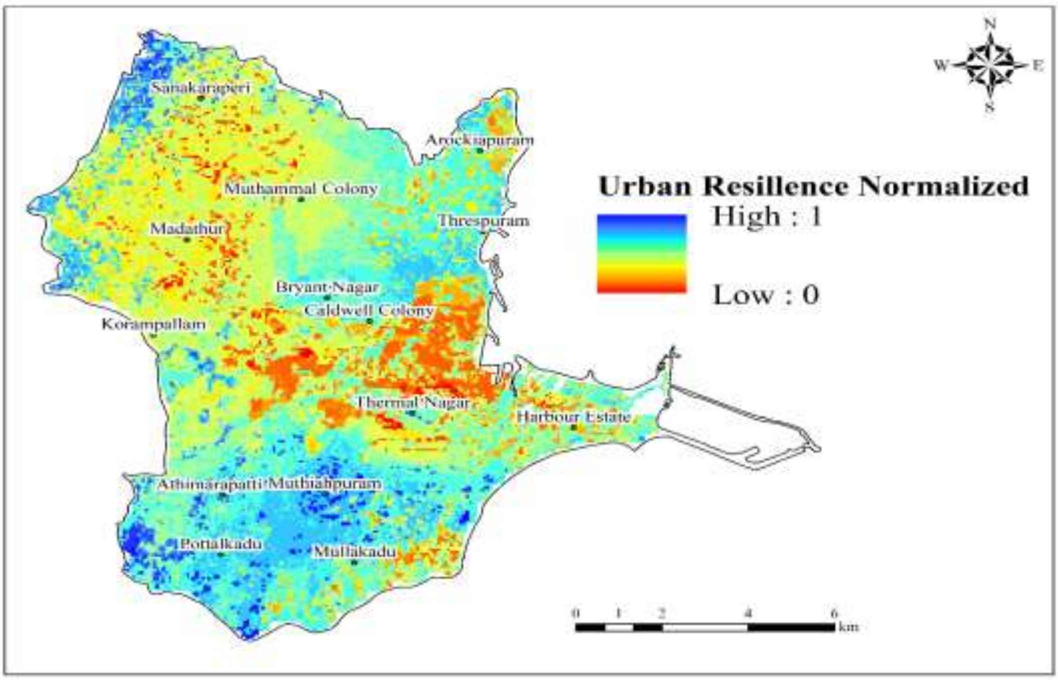

Figure 6. Urban resilience index in normalized values across the study area

Moderate resilience areas formed transitional corridors connecting high-resilience southwestern zones with scattered patches in the eastern coastal regions indicating strategic locations for controlled urban expansion and infrastructure development. These intermediate resilience areas offered balanced conditions suitable for managed growth with appropriate environmental safeguards and climate adaptation measures. Low resilience zones (values approaching 0.0) were concentrated in the central urban core and industrial areas around Thermal Nagar, Bryant Nagar and the harbour estate, where high compound vulnerability significantly constrained development opportunities and planning flexibility. The resilience index revealed a distinct spatial gradient from southwest to northeast, with resilience values systematically decreasing toward the established urban centre and industrial zones. This pattern reflected the cumulative impact of environmental constraints, existing development pressures and limited adaptive capacity in densely built areas (Rezvani et al., 2023; D. Wang et al., 2024). The resilience assessment identified strategic development corridors extending from high-resilience southwestern areas toward moderate-resilience zones providing clear guidance for phased urban expansion that balances growth objectives with environmental sustainability. The comprehensive integration of multiple factors in the resilience index successfully captured the complex interplay between vulnerability reduction and development enhancement offering a robust foundation for evidence-based urban planning decisions.

3.3 Smart Planning Zone Delineation

The smart planning zone classified into five distinct development categories based on the Urban Resilience Index thresholds providing comprehensive spatial guidance for evidence-based urban planning (Figure 7). The analysis revealed that preferred development zones constitute the largest planning category encompassing 34.63% of the study area (47.15 km^2) followed by restricted development zones covering 32.46% (44.19 km^2) indicating a predominantly cautious development approach necessitated by the coastal urban environment inherent vulnerabilities. Preferred development areas demonstrated favourable spatial distribution across multiple sectors with significant concentrations in the southwestern periphery around Pottalkadu and Mullakadu, eastern coastal areas near Arockiapuram and scattered patches throughout the central transitional zones. These zones represent optimal locations for strategic urban expansion, infrastructure development and renewable energy projects where moderate environmental risks combine with adequate development opportunities to support sustainable growth initiatives. The substantial coverage of preferred development areas provides municipal planners with considerable flexibility for accommodating future urban growth while maintaining environmental safety standards.

Restricted development zone represents the second-largest category at 32.46% of the total area formed extensive corridors through the central urban core encompassing densely populated areas around Sankaraperi, Muthammal Colony and portions of the industrial belt. These areas require stringent development controls enhanced risk mitigation measures and adaptive management strategies due to elevated compound vulnerability levels that constrain conventional development approaches. The prevalence of restricted zones reflects the challenging planning environment characteristic of established coastal cities, where existing development patterns limit future expansion options. Managed development areas covered

17.77% of the study region (24.19 km²) primarily distributed as transitional zones between restricted and preferred development areas creating strategic buffer zones that facilitate controlled urban growth with appropriate environmental safeguards. These intermediate zones offer opportunities for innovative planning approaches including climate-adaptive infrastructure, green building standards and integrated risk management systems that can serve as demonstration models for sustainable coastal urban development(Rezvani et al., 2023; D. Wang et al., 2024).

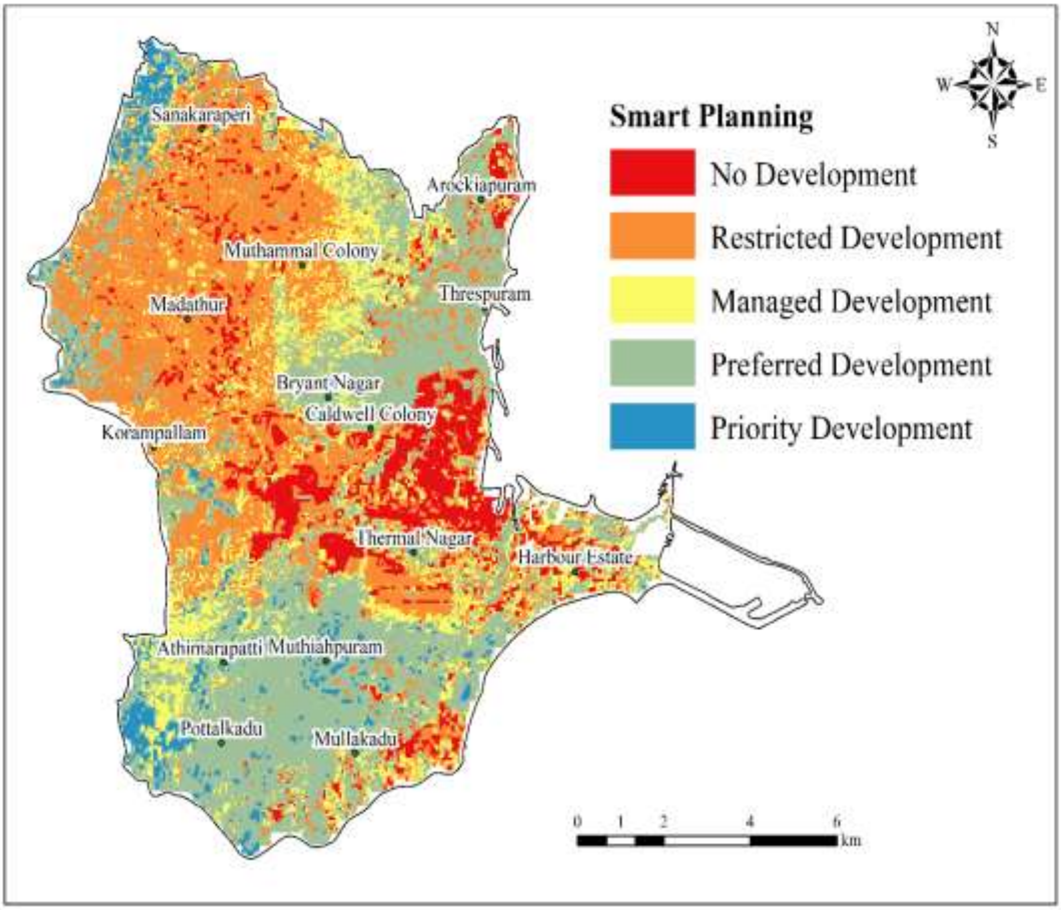

Figure 7. Smart planning zone classification based on Urban Resilience Index threshold analysis.

No development zones encompass 11.05% of the study area (15.04 km²) were concentrated in high-risk areas including portions of Thermal Nagar, the harbour industrial estate and scattered locations throughout the central urban core where compound vulnerability levels exceed acceptable thresholds for new development. These prohibition zones require immediate attention for disaster preparedness, existing infrastructure retrofitting and potential managed retreat strategies to reduce future risk exposure. The relatively limited extent of no development areas (11.05%) indicates that while significant environmental challenges exist, most of the study area retains some development potential under appropriate management frameworks. Priority development zones represented the smallest category at 4.1% of the total area (5.59 km²) concentrated primarily in the southwestern sectors around Pottalkadu and Mullakadu where excellent development opportunities coincide with low environmental vulnerability. These flagship zones offer optimal conditions for smart city initiatives, renewable energy infrastructure and innovative urban design projects that can demonstrate best practices for climate-resilient coastal development. Despite their limited spatial extent, priority zones provide crucial anchoring points for transformative development initiatives that can catalyse broader urban sustainability transitions (J. Wang et al., 2023).

4. DISCUSSION

4.1 Spatial Patterns and Relationships

The spatial analysis revealed distinct geographical patterns that reflect the complex interplay between environmental hazards, urban development pressures and renewable energy potential in coastal urban environments. The pronounced southwest-to-northeast vulnerability gradient observed across Thoothukudi demonstrates how distance from the coastline, elevation variations and urban density patterns collectively influence environmental risk exposure. This gradient aligns with established coastal vulnerability theories where proximity to the ocean increases exposure to storm surge, saltwater intrusion and wind-driven impacts while simultaneously reducing elevation-based protection against flooding events. The inverse relationship between compound vulnerability and development opportunity creates spatially coherent planning zones that reflect underlying environmental processes. Areas exhibiting high compound vulnerability particularly around Thermal Nagar and the central industrial corridor, consistently demonstrate reduced development opportunities due to the convergence of multiple environmental stressors. The southwestern peripheral areas around Pottalkadu and Mullakadu benefit from elevated topography, reduced urban heat island effects and optimal solar irradiation conditions that collectively enhance development suitability. This spatial coherence validates the integrated assessment approach and suggests that environmental factors operate synergistically rather than independently in determining urban development potential.

The dominance of moderate vulnerability category (78.88%) in the study area indicates that most coastal urban environments exist in transitional risk states rather than experiencing extreme vulnerability or complete safety. These finding challenges binary approaches to coastal risk management and supports the need for nuanced planning frameworks that can accommodate gradual risk transitions. The spatial clustering of similar vulnerability levels creates distinct risk neighbourhoods that require tailored management strategies, moving beyond uniform city-wide policies toward spatially differentiated approaches that recognize local environmental conditions. Correlation analysis between individual hazard components reveals that flood and cyclone vulnerabilities demonstrate strong spatial association, particularly in low-lying coastal areas where both hazards converge. The urban heat island intensity exhibits more heterogeneous patterns that reflect land use characteristics rather than pure topographic controls. This differential spatial behaviour among hazard types underscores the importance of multi-hazard approaches that capture both correlated and independent risk factors in comprehensive vulnerability assessments.

4.2 Planning Implications

The smart planning zone framework provides municipal authorities with actionable spatial guidance that addresses the fundamental challenge of balancing development needs with environmental safety in rapidly growing coastal cities. The identification of preferred development zones covering 34.63% of the study area offers substantial opportunities for accommodating urban growth while maintaining acceptable risk levels. These areas provide strategic locations for implementing smart city initiatives, renewable energy infrastructure and climate-adaptive building standards that can serve as demonstration projects for broader urban sustainability transitions. Restricted development zones encompassing 32.46% of the study area require immediate attention for implementing enhanced building codes, infrastructure retrofitting and disaster preparedness measures. These areas present opportunities for innovative planning approaches including vertical densification with climate-adaptive designs, green infrastructure integration and community-based disaster risk reduction programs. The spatial configuration of restricted zones suggests potential for creating resilience corridors that connect safer areas while providing strategic evacuation routes and emergency service access. Priority development zones cover only 4.1% of the study area offer crucial anchoring points for transformative urban development initiatives. These flagship areas can accommodate high-value investments in renewable energy infrastructure, smart grid systems and sustainable transportation networks that generate demonstration effects throughout the broader urban system. The concentration of priority zones in southwestern areas provides opportunities for creating integrated sustainable development clusters that can catalyse regional economic transformation while maintaining environmental integrity.

No development zones require comprehensive risk management strategies including potential managed retreat policies, enhanced early warning systems and restrictions on critical infrastructure placement. These areas offer opportunities for implementing nature-based solutions, urban wetland and green buffer zones that can provide ecosystem services while reducing overall urban vulnerability. The relatively limited extent of no development areas (11.05%) suggests that prohibition strategies should be coupled with intensive management approaches in adjacent zones to maximize overall urban resilience. The framework supports implementation of differential development standards across planning zones enabling municipalities to optimize resource allocation while maintaining appropriate safety margins. Higher-risk zones can implement stringent environmental impact assessments, mandatory climate adaptation measures and enhanced infrastructure standards, while lower-risk areas can accommodate streamlined approval processes and innovative development approaches that support economic growth objectives.

4.3 Methodological Contributions

The study significantly advances coastal urban planning by addressing critical gaps in vulnerability assessments and sustainable development frameworks through several key innovations. It pioneers the integration of multi-hazard vulnerability assessment with renewable energy potential mapping offering a novel, evidence-based approach that simultaneously addresses risk reduction and sustainable development unlike previous studies that treated these areas separately. The implementation of the Analytical Hierarchy Process (AHP) enhances transparency and reproducibility in decision-making by systematically determining weights for flood vulnerability (51%), cyclone vulnerability (38%) and urban heat island intensity (11%). A three-tier index framework supports multi-scale decision-making, comprising a compound vulnerability index for immediate safety, a development opportunity index for economic potential and an urban resilience index for balanced guidance. The smart planning zone classification system translates complex environmental data into five actionable categories bridging the gap between scientific assessments and practical policy implementation. The methodology's reliance on accessible data and standardized techniques ensures its transferability to other coastal cities making it adaptable to diverse environmental conditions and planning priorities. This comprehensive approach represents a significant step forward in climate-informed urban planning.

5. CONCLUSION

The study successfully developed and implemented an integrated GIS-based framework for delineating smart planning zones that simultaneously addresses multi-hazard vulnerability and renewable energy development opportunities in coastal urban environments. The methodology effectively synthesized flood vulnerability, cyclone exposure, urban heat island intensity and solar energy potential through systematic multi-criteria analysis to generate evidence-based spatial guidance for sustainable urban planning. The assessment revealed that study area exhibits predominantly moderate vulnerability patterns (78.88%) with significant spatial variability reflecting the complex interplay between environmental hazards and urban development pressures. The identification of preferred development zones covering 34.63% of the study area provides substantial opportunities for accommodating future urban growth while maintaining acceptable environmental risk levels. The delineation of restricted and no development zones (43.51% combined) highlights areas requiring enhanced risk management strategies and adaptive planning approaches.

The framework's integration of vulnerability and opportunity assessments through the Urban Resilience Index successfully captured the spatial trade-offs between environmental safety and development potential enabling balanced planning decisions that support both risk reduction and economic development objectives. The southwest-to-northeast development gradient identified through the analysis provides clear strategic direction for phased urban expansion that prioritizes environmental sustainability while accommodating growth pressures. The methodology's transferability and reliance on readily available satellite data enables application to other coastal cities facing similar climate challenges and development pressures. The smart planning zone classification system provides municipal authorities with actionable spatial guidance that can be implemented through existing regulatory frameworks while supporting climate adaptation and sustainable development goals. Future research should focus on incorporating temporal dynamics, social vulnerability indicators and climate change projections to enhance the framework's adaptive capacity and long-term planning utility. Integration of community-based assessment approaches and real-time environmental monitoring would further strengthen the methodology's effectiveness for supporting climate-resilient coastal urban development.

Acknowledgment
The First author expresses his sincere thanks to Shri. A.P.C.V. Chockalingam, Secretary and our Principal Dr C. Veerabhahu, V. O. Chidambaram College, Thoothukudi. This research work was conducted by Mrs. C Antony Zacharias Grace, (Reg. No: 19212232132011) as part of her doctoral studies.

Declarations

"**Funding**: This research has not received any funding from any source."
"**Ethics approval:** The manuscript is conducted in the ethical manner advised by the targeted journal."
"**Consent to participate:** Not applicable"
"**Clinical trial number**: Not applicable"
"**Consent for publication:** The research is scientifically consented to be published."
"**Conflict of interest:** The authors declare no competing interests."
"**Code availability:** Not applicable."
"**Availability of data and materials:** The data that support the findings of this study are available on request from the corresponding author."
"**Human face Consent to publish a declaration:** We have carefully reviewed all the images in our manuscript and confirm that no human faces are present."

Author Contributions statement:
C Antony Zacharias Grace – Conceptualization, Methodology, Writing - Original Draft and Data Curation. **John Prince Soundranayagam** - Supervision and Project administration. **A Antony Alosanai Promilton -** Data Collection, Software and Review and Editing**. Stephen Pitchaimani V** - Supervision and Writing - Review and Editing. **Ernest Amitha Roy** – Formal analysis, Writing - Review and Editing."

References

1. Abdalla, R., & Abdalla, R. (2024). Framework for Assessing the Impacts of Climate Change on Urban Agglomerations: A GIS and Remote Sensing Perspective. Urban Agglomeration - Extracting Lessons for Sustainable Development [Working Title]. https://doi.org/10.5772/INTECHOPEN.1004284
2. Adebayo, W. G. (2024). Resilience in the face of ecological challenges: Strategies for integrating environmental considerations into social policy planning in Africa. Sustainable Development, 33(1), 203–220. https://doi.org/10.1002/SD.3113;WGROUP:STRING:PUBLICATION
3. Barcellos-Paula, L., Castro-Rezende, A., & Gil-Lafuente, A. M. (2025). Understanding Urban Resilience and SDGs: A New Approach in Decision-Making for Sustainable Cities. Journal of Public Affairs, 25(1), e70007. https://doi.org/10.1002/PA.70007
4. Bendoni, M., Caparrini, F., Cucco, A., Taddei, S., Anton, I., Paranunzio, R., Mocali, R., Perna, M., Sacco, M., Vitale, G., Corongiu, M., Ortolani, A., Gharbia, S., & Brandini, C. (2025). Multiscale Modeling for Coastal Cities: Addressing Climate Change Impacts on Flood Events at Urban-Scale. https://doi.org/10.5194/EGUSPHERE-2025-270
5. Blakely, E. (2022). Urban planning for climate change. https://research.fit.edu/media/site-specific/researchfitedu/coast-climate-adaptation-library/united-states/gulf-coast/louisiana/Blakely.-2007.-New-Orleans-Urban-Planning-for-CC.pdf

6. Burayu, D. G., Karuppannan, S., & Shuniye, G. (2023). Identifying flood vulnerable and risk areas using the integration of analytical hierarchy process (AHP), GIS, and remote sensing: A case study of southern Oromia region. Urban Climate, 51, 101640. https://doi.org/10.1016/J.UCLIM.2023.101640
7. Calvin, K., Dasgupta, D., Krinner, G., Mukherji, A., Thorne, P. W., Trisos, C., Romero, J., Aldunce, P., Barrett, K., Blanco, G., Cheung, W. W. L., Connors, S., Denton, F., Diongue-Niang, A., Dodman, D., Garschagen, M., Geden, O., Hayward, B., Jones, C., … Ha, M. (2023). IPCC, 2023: Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, H. Lee and J. Romero (eds.)]. IPCC, Geneva, Switzerland. https://doi.org/10.59327/IPCC/AR6-9789291691647
8. Cissé, C. (2025). Urbanization in Sahelian Cities: A Nexus of Climate Change, Health Disparities, and Sustainable Planning. Https://Doi.Org/10.3138/Jccpe-2024-0001, 3(2/3), 410–426. https://doi.org/10.3138/JCCPE-2024-0001
9. Das, S., & Ghosh, T. (2024). Identifying the Gaps in Cyclone Vulnerability Mitigation in the Indian Sundarban Using AHP Based Multi Criteria Decision Analysis (MCDA) and GIS Techniques: Tool for the Policy Makers. Earth Systems and Environment, 1–19. https://doi.org/10.1007/S41748-024-00486-X/METRICS
10. Das, T., Talukdar, S., Shahfahad, Baig, M. R. I., Hang, H. T., Siddiqui, A. M., & Rahman, A. (2024). Assessing vulnerability to cyclones in coastal Odisha using fuzzy logic integrated AHP: towards effective risk management. Spatial Information Research, 32(3), 277–295. https://doi.org/10.1007/S41324-023-00556-8/METRICS
11. Dharmarathne, G., Waduge, A. O., Bogahawaththa, M., Rathnayake, U., & Meddage, D. P. P. (2024). Adapting cities to the surge: A comprehensive review of climate-induced urban flooding. Results in Engineering, 22, 102123. https://doi.org/10.1016/J.RINENG.2024.102123
12. Drakes, O., & Tate, E. (2022). Social vulnerability in a multi-hazard context: a systematic review. Environmental Research Letters, 17(3), 033001. https://doi.org/10.1088/1748-9326/AC5140
13. Ezimand, K., Aghighi, H., Ashourloo, D., & Shakiba, A. (2024). The analysis of the spatio-temporal changes and prediction of built-up lands and urban heat islands using multi-temporal satellite imagery. Sustainable Cities and Society, 103, 105231. https://doi.org/10.1016/J.SCS.2024.105231
14. Faqe Ibrahim, G. R., Mahmood, K. W., Mahmood, M., & Rasul, A. (2024). Enhancing Solar Power Plant Location Selection Through Multicriteria Decision-Making with the Analytic Hierarchy Process. Annals of the American Association of Geographers. https://doi.org/10.1080/24694452.2024.2373795
15. Gomes, A., Islam, N. M., & Karim, M. R. (2025). Data-Driven Environmental Risk Management and Sustainability Analytics (Second Edition). Journal of Computer Science and Technology Studies, 7(3), 812–825. https://doi.org/10.32996/JCSTS.2025.7.3.89
16. Hasan, I., Faruk, M. O., Katha, Z. T., Goni, M. O., Islam, M. S., Chakraborty, T. R., Faysal Sowrav, S. F., & Hossain, M. S. (2024). Geo-spatial based cyclone shelter suitability assessment using analytical hierarchy process (AHP) in the coastal region of Bangladesh. Heliyon, 10(21), e39831. https://doi.org/10.1016/J.HELIYON.2024.E39831
17. Imam, A. A., Abusorrah, A. M., & Marzband, M. (2024). Potential of Concentrated Solar Power in the Western Region of Saudi Arabia: A GIS-Based Land Suitability Analysis and Techno-Economic Feasibility Assessment. IEEE Access, 12, 1570–1598. https://doi.org/10.1109/ACCESS.2023.3344752
18. Kader, Z., Islam, M. R., Aziz, M. T., Hossain, M. M., Islam, M. R., Miah, M., & Jaafar, W. Z. W. (2024). GIS and AHP-based flood susceptibility mapping: a case study of Bangladesh. Sustainable

Water Resources Management, 10(5), 1–18. https://doi.org/10.1007/S40899-024-01150-Y/METRICS

19. Kapucu, N., Ge, Y., Rott, E., & Isgandar, H. (2024). Urban resilience: Multidimensional perspectives, challenges and prospects for future research. Urban Governance, 4(3), 162–179. https://doi.org/10.1016/J.UGJ.2024.09.003
20. Kasniza Jumari, N. A. S., Ahmed, A. N., Huang, Y. F., Ng, J. L., Koo, C. H., Chong, K. L., Sherif, M., & Elshafie, A. (2023). Analysis of urban heat islands with landsat satellite images and GIS in Kuala Lumpur Metropolitan City. Heliyon, 9(8). https://doi.org/10.1016/j.heliyon.2023.e18424
21. Mariano, C., & Marino, M. (2022). Urban Planning for Climate Change: A Toolkit of Actions for an Integrated Strategy of Adaptation to Heavy Rains, River Floods, and Sea Level Rise. Urban Science 2022, Vol. 6, Page 63, 6(3), 63. https://doi.org/10.3390/URBANSCI6030063
22. McMichael, C., Dasgupta, S., Ayeb-Karlsson, S., & Kelman, I. (2020). A review of estimating population exposure to sea-level rise and the relevance for migration. Environmental Research Letters, 15(12), 123005. https://doi.org/10.1088/1748-9326/ABB398
23. Mehmood, R., Yigitcanlar, T., & Corchado, J. M. (2024). Smart Technologies for Sustainable Urban and Regional Development. Sustainability 2024, Vol. 16, Page 1171, 16(3), 1171. https://doi.org/10.3390/SU16031171
24. Metternicht, G. (2018). Land Use and Spatial Planning. https://doi.org/10.1007/978-3-319-71861-3
25. Mohammadi, S., De Angeli, S., Boni, G., Pirlone, F., & Cattari, S. (2024). Review article: Current approaches and critical issues in multi-risk recovery planning of urban areas exposed to natural hazards. Natural Hazards and Earth System Sciences, 24(1), 79–107. https://doi.org/10.5194/NHESS-24-79-2024
26. Mumtaz, M., Jahanzaib, S. H., Hussain, W., Khan, S., Youssef, Y. M., Qaysi, S., Abdelnabi, A., Alarifi, N., & Abd-Elmaboud, M. E. (2025). Synergy of Remote Sensing and Geospatial Technologies to Advance Sustainable Development Goals for Future Coastal Urbanization and Environmental Challenges in a Riverine Megacity. ISPRS International Journal of Geo-Information, 14(1), 30. https://doi.org/10.3390/IJGI14010030/S1
27. Rezvani, S. M. H. S., Falcão, M. J., Komljenovic, D., & de Almeida, N. M. (2023a). A Systematic Literature Review on Urban Resilience Enabled with Asset and Disaster Risk Management Approaches and GIS-Based Decision Support Tools. Applied Sciences 2023, Vol. 13, Page 2223, 13(4), 2223. https://doi.org/10.3390/APP13042223
28. Rezvani, S. M. H. S., Falcão, M. J., Komljenovic, D., & de Almeida, N. M. (2023b). A Systematic Literature Review on Urban Resilience Enabled with Asset and Disaster Risk Management Approaches and GIS-Based Decision Support Tools. Applied Sciences 2023, Vol. 13, Page 2223, 13(4), 2223. https://doi.org/10.3390/APP13042223
29. Romshoo, S. A., Amin, M., & Qazi, A. us S. (2024). Opportunity mapping to inform rural development planning at village level using geospatial techniques. Environment, Development and Sustainability, 1–32. https://doi.org/10.1007/S10668-024-05822-9/METRICS
30. Saaty, T. (1980). The analytic hierarchy process: Planning, priority setting, resource allocation: Thomas L. SAATY McGraw-Hill, New York, 1980, xiii. European Journal of Operational Research, 9(1), 97–98. https://search.worldcat.org/title/5352839
31. Saranya, A., Sivakumar, V., Satheeshkumar, S., & Logeshkumaran, A. (2024). Assessment of Flood Risk in the High Rainfall Coastal Area of Cuddalore Taluk, Southeast India, Using GIS-Based Analytic Hierarchy Process Techniques. Journal of the Indian Society of Remote Sensing, 53(1), 67–80. https://doi.org/10.1007/S12524-024-01998-9/METRICS

32. Sharma, M., & Khan, S. (2023). Coastal Resilience and Urbanization Challenges in India. International Handbook of Disaster Research, 1–16. https://doi.org/10.1007/978-981-16-8800-3_27-1
33. Shrestha, A., Howland, G. J., Chini -, C. M., Berlin Rubin, N., Rose Garfin, D., Wong-Parodi -, G., Ikonomova, M., & MacAskill, K. (2023). Climate change hazards, physical infrastructure systems, and public health pathways. Environmental Research: Infrastructure and Sustainability, 3(4), 045001. https://doi.org/10.1088/2634-4505/ACFABD
34. Subramanian, A., Nagarajan, A. M., Vinod, S., Chakraborty, S., Sivagami, K., Theodore, T., Sathyanarayanan, S. S., Tamizhdurai, P., & Mangesh, V. L. (2023). Long-term impacts of climate change on coastal and transitional eco-systems in India: an overview of its current status, future projections, solutions, and policies. RSC Advances, 13(18), 12204–12228. https://doi.org/10.1039/D2RA07448F
35. Ukoba, K., Yoro, K. O., Eterigho-Ikelegbe, O., Ibegbulam, C., & Jen, T. C. (2024). Adaptation of solar energy in the Global South: Prospects, challenges and opportunities. Heliyon, 10(7), e28009. https://doi.org/10.1016/J.HELIYON.2024.E28009
36. Vinayachandran, P. N., Seng, D. C., & Schmid, F. A. (2022). Climate Change and Coastal Systems. Blue Economy: An Ocean Science Perspective, 341–377. https://doi.org/10.1007/978-981-19-5065-0_12
37. Wang, D., Xu, P. Y., An, B. W., & Guo, Q. P. (2024). Urban green infrastructure: bridging biodiversity conservation and sustainable urban development through adaptive management approach. Frontiers in Ecology and Evolution, 12, 1440477. https://doi.org/10.3389/FEVO.2024.1440477/BIBTEX
38. Wang, J., Wang, J., & Zhang, J. (2023). Spatial distribution characteristics of natural ecological resilience in China. Journal of Environmental Management, 342, 118133. https://doi.org/10.1016/J.JENVMAN.2023.118133
39. Wu, H., Zhang, M., He, Y., Chen, P., Pasquier, U., Hu, H., & Wen, J. (2025). Scenario-based flood adaption of a fast-developing delta city: Modeling the extreme compound flood adaptations for shanghai. International Journal of Disaster Risk Reduction, 117, 105207. https://doi.org/10.1016/J.IJDRR.2025.105207
40. Xue, C., Yang, G., Ma, X., Zhen, J., Sun, H., Zhang, X., Ruan, X., Jiang, H., & Shou, W. (2024). Mapping Compound Flooding Risks for Urban Resilience in Coastal Zones: A Comprehensive Methodological Review. Remote Sensing 2024, Vol. 16, Page 350, 16(2), 350. https://doi.org/10.3390/RS16020350
41. Yu, D., & Fang, C. (2023). Urban Remote Sensing with Spatial Big Data: A Review and Renewed Perspective of Urban Studies in Recent Decades. Remote Sensing 2023, Vol. 15, Page 1307, 15(5), 1307. https://doi.org/10.3390/RS15051307
42. Zhao, C., Pan, Y., Wu, H., & Zhu, Y. (2024). Quantifying the contribution of industrial zones to urban heat islands: Relevance and direct impact. Environmental Research, 240, 117594. https://doi.org/10.1016/J.ENVRES.2023.117594