Review Paper:

Empowering Cyclone Preparedness: An Integrated GIS-AHP based Site Shelter Suitability Mapping of Visakhapatnam, Andhra Pradesh

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Abstract
This study presents a comprehensive approach in mapping Cyclone Shelters in Visakhapatnam using the Analytic Hierarchy Process (AHP) and weighted overlay techniques. The research integrates multiple geospatial datasets including road networks, elevation (ranging from 18 to 1677 meters), slope, aspect, roughness, hillshade, distance from rivers, distance from the seashore and Land Use Land Cover (LULC). Additionally, population growth data was incorporated, showing an increase from 105,000 in 1950 to 2,385,000 in 2024, with a forecasted population of 3,041,000 by 2035, reflecting a growth rate of 2.32%. Windrose analysis categorized wind speeds into six groups, which are crucial for assessing cyclone impacts.

These nine specific themes were re-scaled into five classes to create a Cyclone Shelter suitability map, classifying areas as not suitable, less suitable, moderately suitable, suitable and highly suitable. Covering 550 square kilometers, the study area is located at 17°69'N latitude and 83°22'E longitude, with an altitude of 900 meters. The resulting Cyclone Shelter map provides a valuable tool for disaster preparedness and response planning in Visakhapatnam, offering critical insights into shelter placement and suitability.

Keywords: Cyclone Shelter Mapping, AHP Techniques, Weighted Overlay, Visakhapatnam, Disaster Preparedness.

Introduction
Tropical cyclones pose a significant threat to the eastern coast of India, particularly to the city of Visakhapatnam, which lies on the Bay of Bengal. The North Indian Ocean, characterized by water temperature exceeding 27^0C, the presence of Coriolis forces and varying vertical wind speeds, provides ideal conditions for the formation of these cyclones[8]. Visakhapatnam, due to its geographical location and the shape of the eastern coastline, is highly susceptible to cyclones, particularly during the monsoon and post-monsoon seasons[14]. Historical data indicates that 26 of the 35 deadliest tropical cyclones in world history have originated in the Bay of Bengal, with many affecting Visakhapatnam directly. The most devastating cyclone occurred in 1839, resulting in over 300,000 fatalities and the destruction of 20,000 ships.

Subsequent centuries have witnessed numerous cyclones including the infamous 1977 Diviseema cyclone and more recent storms like Phailin (2013), Hudhud (2014), Titli (2018) and Gulab (2021)[41]. These cyclones have repeatedly demonstrated the region's vulnerability, necessitating enhanced disaster preparedness and response mechanisms[17,39-42]. The objective of this study is to empower cyclone preparedness in Visakhapatnam by developing a GIS-AHP-based cyclone shelter mapping system that identifies and categorizes shelter suitability across the region[18].

Background and Motivation: Visakhapatnam's history is marked by repeated encounters with severe cyclones, which have highlighted the city's vulnerability and underscored the need for robust disaster management strategies[25]. The region's flat coastal plains and its geographical orientation make it a natural target for cyclones, especially during the monsoon seasons[54]. Historical records reveal that the city has been struck by numerous severe cyclones, with the 1839 cyclone being the most catastrophic, leading to massive loss of life and property[36]. The 20th century continued to witness several severe cyclones, culminating in the deadly 1999 super cyclone that significantly impacted the region[45].

In the 21st century, the frequency and intensity of cyclones such as Phailin, Hudhud and Fani have further accentuated the region's need for comprehensive cyclone preparedness. Hudhud, in particular, devastated Visakhapatnam in 2014, leaving the city with long-lasting scars[9-12]. The increasing intensity of cyclones, as predicted by the Intergovernmental Panel on Climate Change (IPCC), makes it imperative to develop effective shelter mapping systems that can guide emergency response efforts and can mitigate the impact of future cyclones[52].

Study Area - Visakhapatnam
Visakhapatnam, often referred to as Vizag, is the largest city in Andhra Pradesh, covering an area of approximately 550 square kilometers within the district's total area of 11,161 square kilometers. Geographically positioned at 17°69'N

latitude and 83°22'E longitude with an altitude of 900 meters, it is situated along the Eastern Ghats and the coast of the Bay of Bengal. As of 2024, Visakhapatnam's metro area population is estimated to be 2,385,000, reflecting steady growth in recent years. This growth underscores the city's significance as a major urban center in the region.

Visakhapatnam's coastal location makes it particularly vulnerable to cyclones, emphasizing the need for enhanced disaster preparedness and mitigation strategies. The objective of this study is to empower cyclone preparedness in Visakhapatnam through the development of a GIS-AHP based shelter mapping approach, ensuring that the city is better equipped to handle the impacts of these natural disasters[56-59].

A critical review on GIS-AHP based Shelter mapping

In recent years, the integration of Geographic Information Systems (GIS) and the Analytic Hierarchy Process (AHP) has become pivotal in enhancing disaster preparedness, particularly in cyclone-prone regions. Pradhan[35] demonstrated the efficacy of GIS-AHP in identifying landslide hazard zones, emphasizing its potential for broader disaster management applications, including cyclone shelter mapping. Similarly, Kousalya and Sudha[21] applied AHP and GIS to identify suitable locations for tsunami shelters, showcasing the method's adaptability to different types of disaster scenarios. Yariyan et al[59] employed GIS-based AHP for flood hazard mapping, underscoring the method's robustness in multi-criteria decision-making processes critical for disaster mitigation.

Further, Sarkar and Mandal[46] explored the use of GIS-AHP for cyclone risk assessment, providing a framework that can be adapted for shelter suitability analysis in cyclone-prone regions like Visakhapatnam. Singh and Bhatt[49] utilized GIS-AHP for the selection of emergency shelters in urban areas, highlighting the importance of spatial analysis in optimizing shelter locations based on various risk factors. The study by Sahana et al[44] focused on the integration of GIS and AHP for flood shelter site selection in the coastal regions of India, reinforcing the relevance of this approach in cyclone preparedness[6].

Additionally, Saeed et al[43] applied GIS and AHP in earthquake shelter site selection, demonstrating its cross-disaster applicability, which is relevant for cyclone shelters as well[31,34]. Collectively, these studies illustrate the critical role of GIS-AHP in disaster preparedness and its potential to empower cyclone preparedness in regions like Visakhapatnam by ensuring that shelter locations are strategically identified and optimized[2,7].

Data Collection and Methodology: For data sources and acquisition, this study was primarily derived from reputable sources including the Bhukosh website, USGS (Landsat-8, DEM) website and other relevant databases. These sources provided critical geospatial data essential for analyzing various factors influencing cyclone shelter mapping[23]. The Landsat-8 imagery and Digital Elevation Model (DEM) data from the USGS were particularly valuable in generating the necessary thematic maps[1]. Multiple thematic maps were created to aid in the analysis of cyclone shelter suitability. The elevation map, with values ranging from 18 to 1677 meters, is crucial as it helps in identifying areas at risk of storm surges and flooding. The slope map, which records slope values with a maximum of 74.66 degrees, is instrumental in determining the gradient of the terrain, as steeper slopes may be prone to landslides during heavy rainfall associated with cyclones.

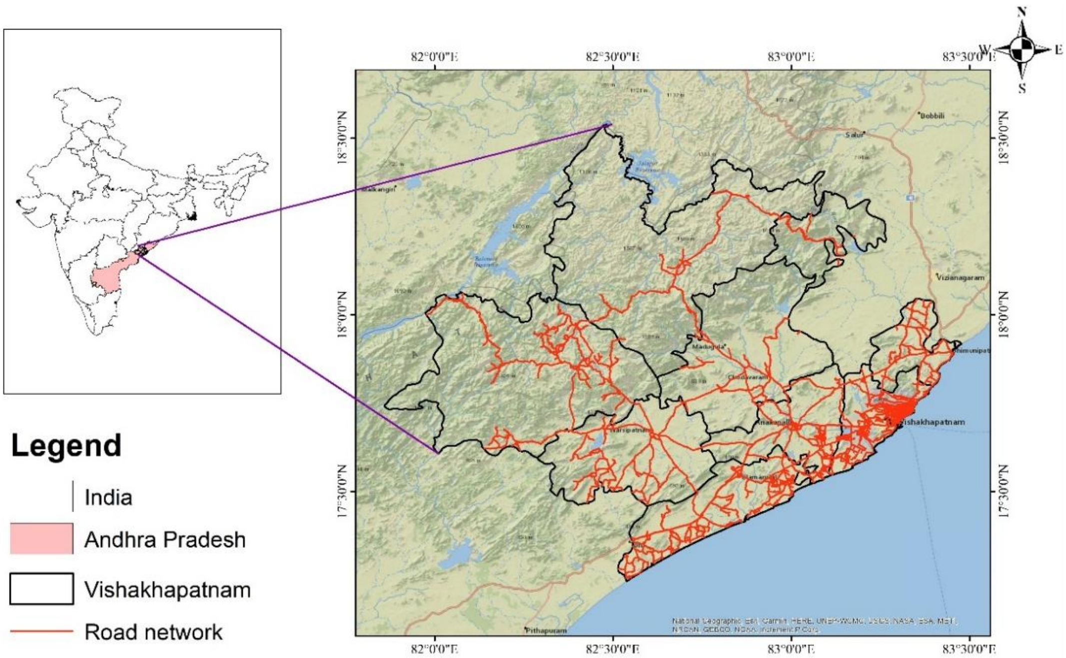

Fig. 1: Geographical location map of the Vishakhapatnam with major road network, Andhra Pradesh, India

Aspect, classified into five groups, indicates the orientation of the slope and is useful in understanding sun exposure and wind direction, which can impact shelter stability[51]. Roughness, with a maximum value of 231, measures the variability in the surface texture, aiding in identifying areas that may be more difficult to access during emergencies. Hillshade, varying from 1 to 255, provides a simulated visual of the terrain under specific lighting conditions, which can help in understanding shadow effects and visibility during a cyclone event[26-28].

For population growth rate analysis, considers data spanning from 1950 to 2024. This analysis reveals significant insights into the demographic changes in Visakhapatnam, with the population growth rate experiencing fluctuations over the decades.

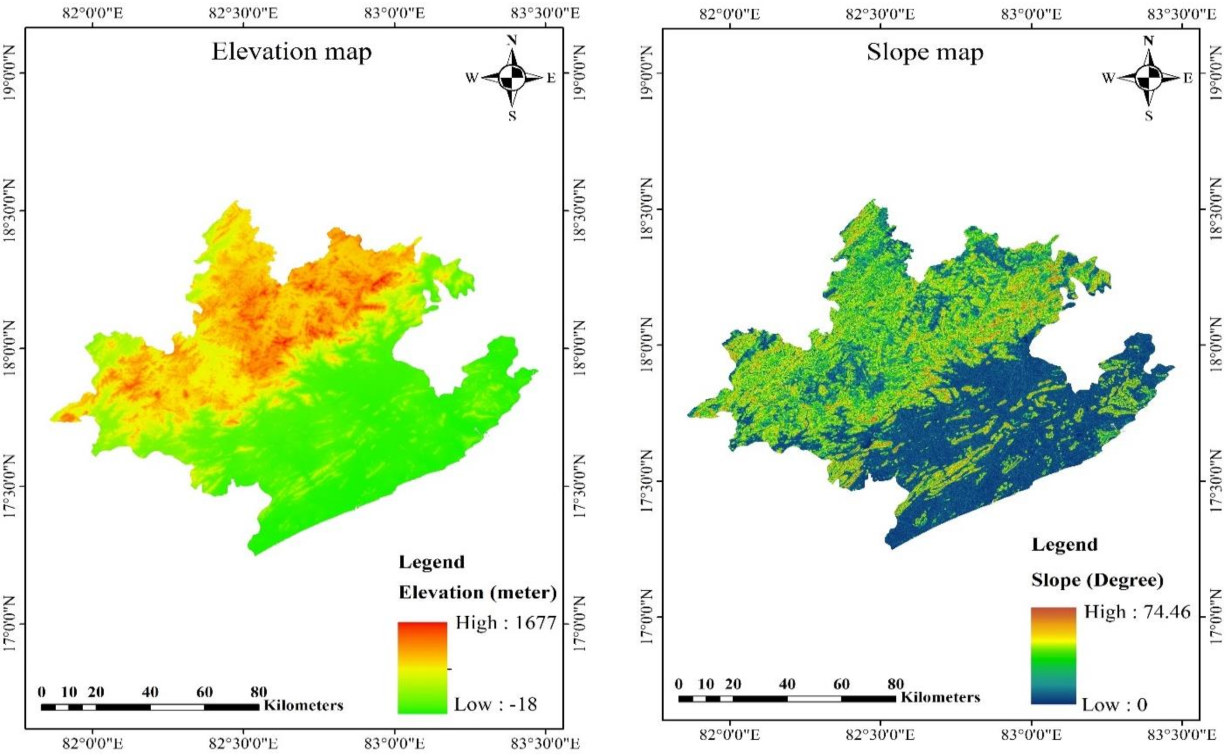

Fig. 2: Maps showing the spatial variation of the Elevation and slope of the Vishakhapatnam

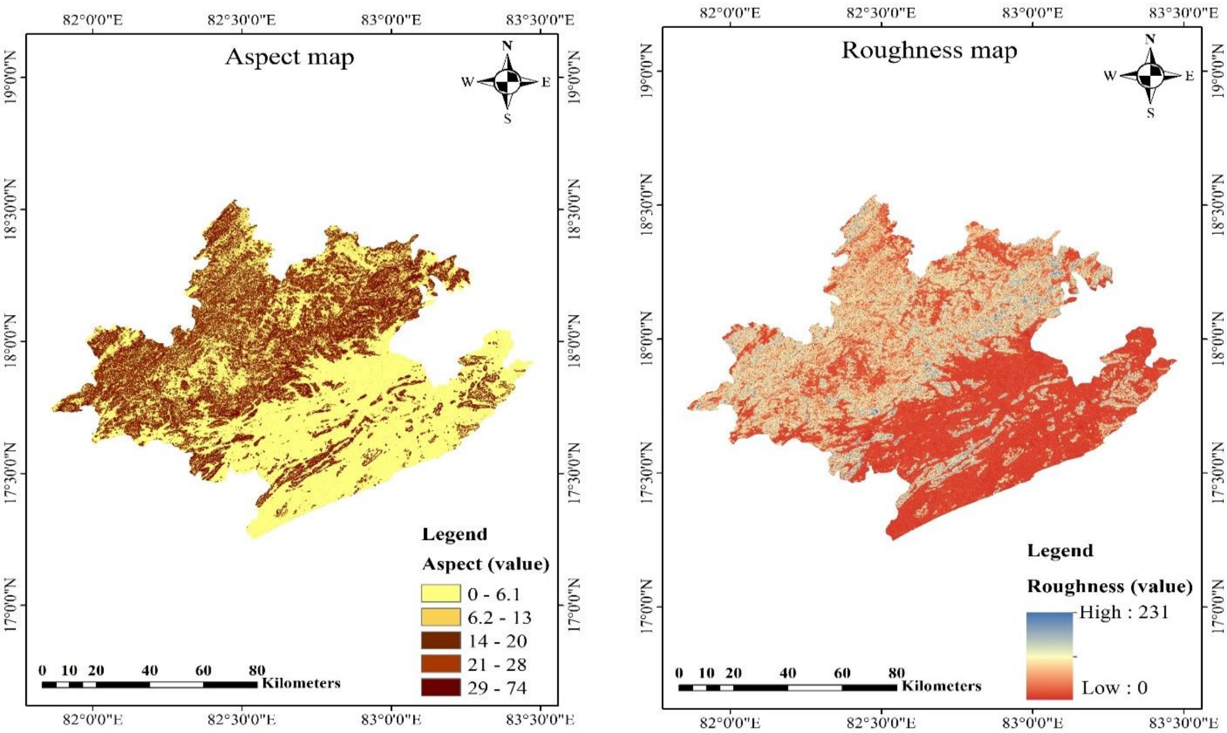

Fig. 3: Maps showing maximum and minimum of the aspect and roughness of the Vishakhapatnam

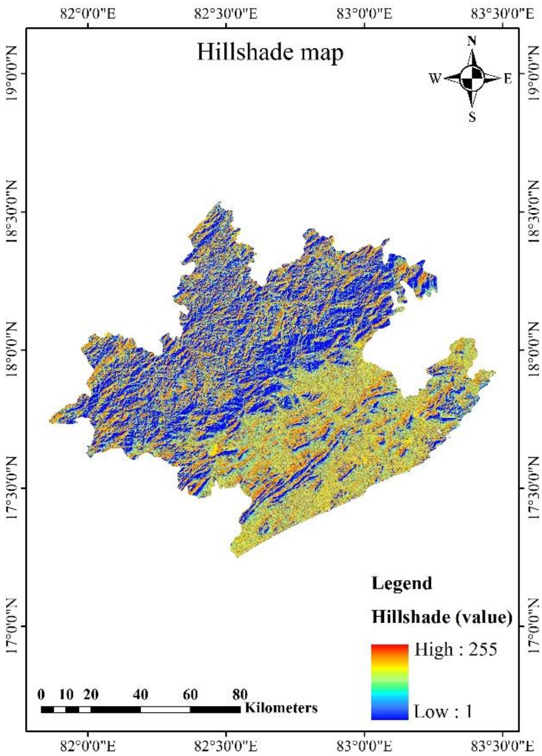

Fig. 4: Hillshade map showing the topography of a landscape over the Vishakhapatnam

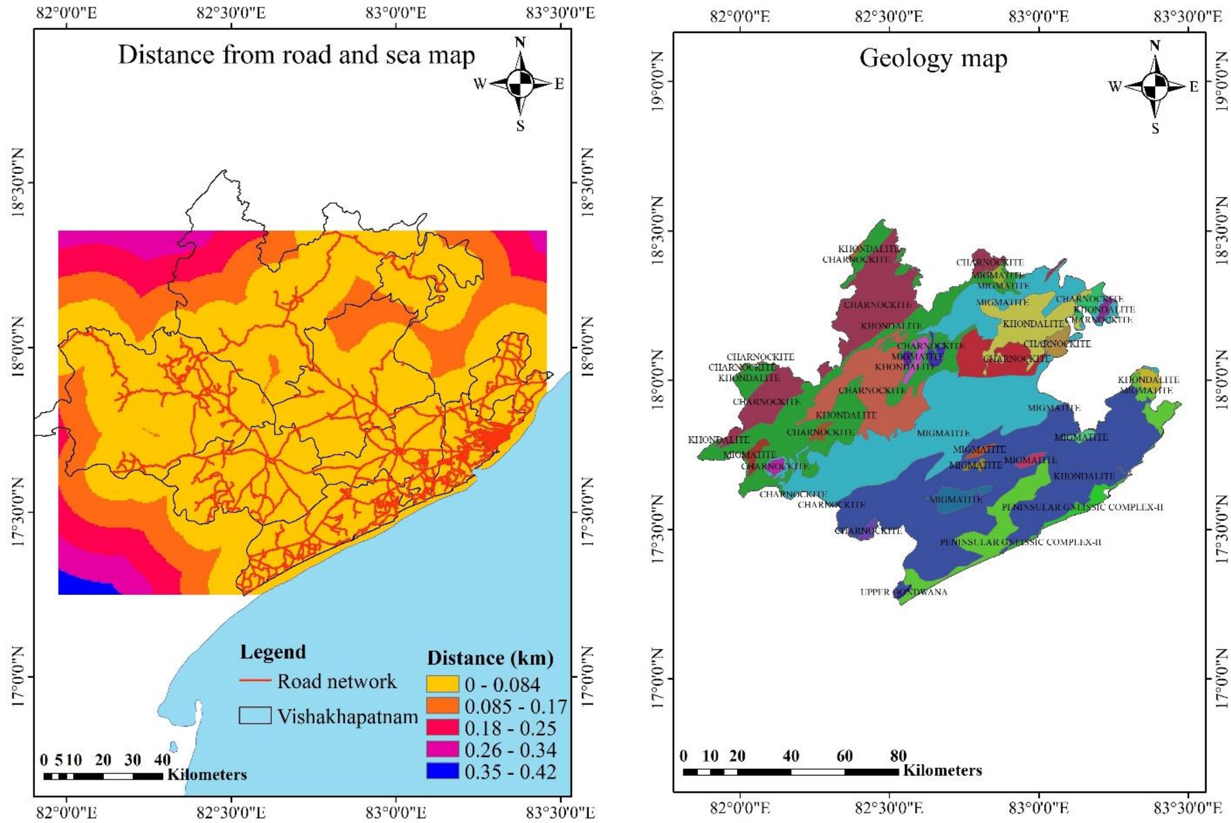

Fig. 5: Road network map and geology map of the Vishakhapatnam showing the distance from road and seashore, geological groups over the study region

Notably, the growth rate was exceptionally high in the mid-20th century, peaking at 7.27% in 1958, reflecting the city's rapid urbanization and economic development[3]. However, the growth rate gradually stabilized, decreasing to around 2.32% by 2024. Understanding population trends is essential for cyclone shelter mapping, as it directly impacts the demand for shelters and the capacity required to accommodate the population safely during a cyclone. This demographic data is crucial for ensuring that shelter locations are adequately distributed and accessible to the population, particularly in densely populated areas that are more vulnerable to the impacts of cyclones.

Distance from road, seashore and geology mapping: The analysis of distance from the river, seashore and geology mapping in the study region plays a pivotal role in the identification and placement of cyclone shelters. The Euclidean distance from roads is classified into five groups ranging from 0 to 0.42 km and the distance from the seashore is similarly categorized into five classes from 0 to 1.4 km. This classification is essential for assessing the accessibility and safety of potential cyclone shelter locations. Proximity to roads ensures that shelters are easily reachable during emergencies, while distance from the seashore is crucial to minimize the risk of storm surges and coastal flooding, which are common during cyclonic events. The geology of the region, comprising a complex mix of migmatite, charnockite, khondalite and upper Gondwana formations, significantly influences the stability and suitability of shelter locations.

Migmatite and charnockite are generally known for their hardness and resistance to weathering, making them ideal substrates for constructing durable cyclone shelters[13]. Conversely, khondalite, depending on its composition and weathering profile, may present challenges in terms of foundation stability. Understanding the distribution of these geological formations helps in selecting sites that offer both structural integrity and safety from landslides or erosion, particularly in areas closer to the seashore or on sloping terrain[4,5].

By integrating these spatial elements, distance from rivers, seashore and geological characteristics, the study provides a comprehensive approach to cyclone shelter mapping[19,20]. The goal is to ensure that selected shelter locations not only provide protection from the immediate threats posed by cyclones but also remain structurally sound and accessible during and after such events, thereby maximizing their effectiveness in disaster management.

Land Use Land Cover (LULC) mapping: The Land Use Land Cover (LULC) map of the study region in Visakhapatnam is an essential component in determining the suitability of locations for cyclone shelters. The LULC map categorizes the region into various land cover types including barren land, shrubland, mixed forest, built-up land, cropland, deciduous broadleaf forest, evergreen broadleaf forest, grassland, aquaculture, plantations, water bodies, wasteland, fallow land and areas covered by snow and ice[15,16]. Each of these land cover types plays a significant role in the analysis.

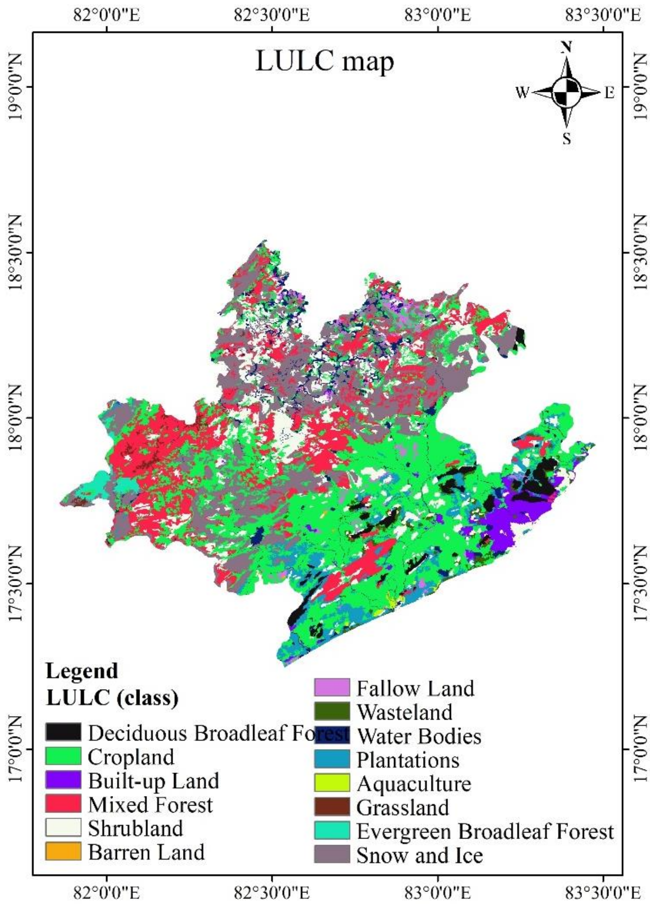

Fig. 6: LULC map of the Vishakhapatnam showing the physical land types and how humans use the land on Earth's surface

For instance, built-up land is crucial because it represents densely populated areas where shelters are most needed to protect residents during a cyclone[22]. Barren land and wasteland, on the other hand, may be considered for shelter construction due to their typically unoccupied nature, allowing for easy conversion into safe spaces. Forest areas, such as mixed and broadleaf forests, present both opportunities and challenges. While they offer natural protection against wind and erosion, their dense vegetation may hinder access or evacuation efforts, making them less ideal for shelter sites[24].

Conversely, croplands and plantations might not be suitable due to the need to preserve agricultural productivity and the potential for flooding. Water bodies and aquaculture areas are generally unsuitable for shelter placement due to the risk of flooding and isolation during cyclonic events[29,30]. However, their proximity to other land types can be useful for understanding drainage patterns and flood risk, which are critical for ensuring that shelters are located on safe, dry ground. By analyzing the spatial distribution of these LULC types, the study can identify the most appropriate areas for cyclone shelters[32]. The goal is to locate shelters in places that maximize safety, accessibility and utility for the local population, while avoiding areas prone to flooding, erosion, or other hazards exacerbated by cyclonic conditions[47].

Windrose categorization: The wind data collected from January 2022 to January 2024 was categorized into six distinct classes based on wind speed, measured in kilometers per hour (KMPH). This categorization is essential for cyclone shelter mapping, as it helps in identifying areas prone to varying degrees of wind intensity during cyclonic events. The wind speeds were classified into six groups: ≥ 11.10 m/s, 8.80 to 11.10 m/s, 5.70 to 8.80 m/s, 3.60 to 5.70 m/s, 2.10 to 3.60 m/s and 0.50 to 2.10 m/s. These classes correspond to different levels of wind force that structures must withstand during a cyclone, which directly impacts the suitability and safety of designated cyclone shelters[53]. The data shows that the highest wind speeds, which exceed 11.10 m/s, are critical for determining the locations most vulnerable to extreme winds, where the construction of highly resilient shelters is necessary.

Similarly, areas with moderate to high wind speeds (8.80 to 11.10 m/s) still require robust shelter infrastructure to protect against potential damage. The categorization also includes gentle and light winds, which, while less likely to cause significant damage, are still important for understanding the overall wind environment of Visakhapatnam. Furthermore, the calm conditions, recorded in 4.45% of the total hours, provide a baseline understanding of the region's wind patterns, contributing to a comprehensive analysis of wind behavior in Visakhapatnam. By integrating this detailed wind speed categorization with other spatial elements such as elevation, slope and roughness, the study ensures that cyclone shelters are optimally located to offer maximum protection to the population, particularly in areas where wind intensity is most likely to peak during a cyclone[33]. This geospatial analysis is crucial for effective disaster preparedness and resilience planning in the region[37,38].

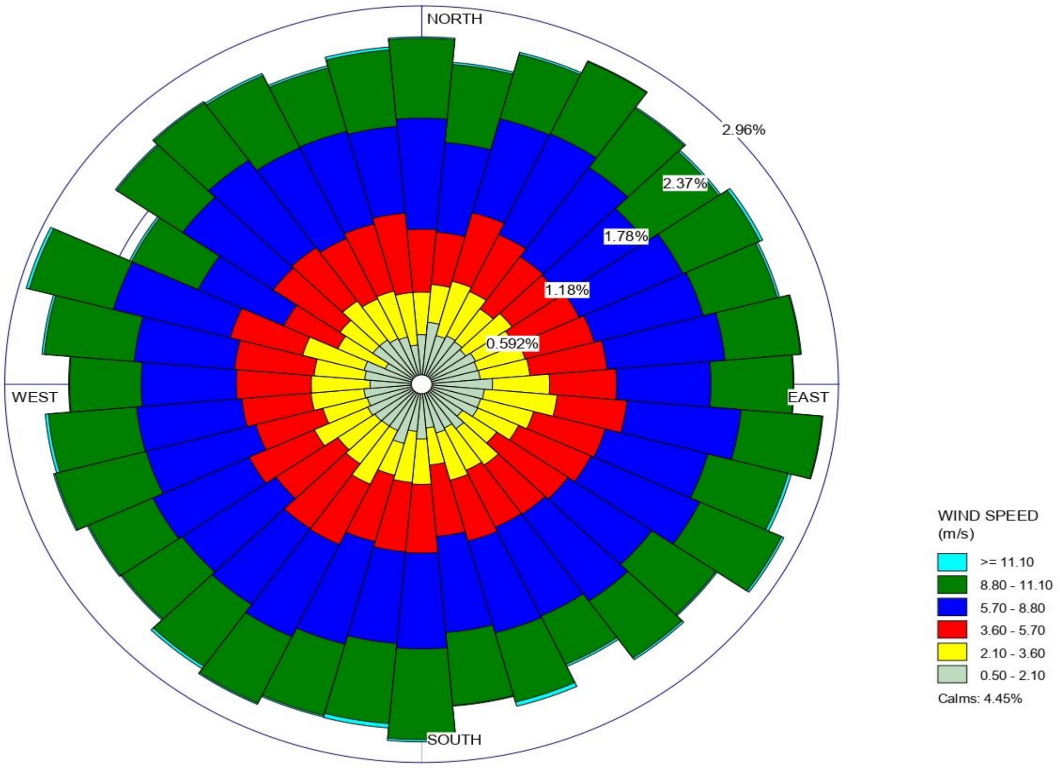

Fig. 7: Windrose diagram showing the wind velocity in North, South, East and West directions of the Vishakhapatnam

AHP Techniques and Weighted Overlay Methods: In the present study, the AHP and Weighted Overlay Methods (WoM) have been employed to systematically evaluate and to combine multiple spatial variables to create a comprehensive cyclone shelter map for Visakhapatnam. The AHP technique involves structuring these variables into a hierarchical framework where each factor's relative importance is assessed through pairwise comparisons. This process results in a set of weights that reflect the contribution of each variable to the overall suitability of a location for a cyclone shelter. The weighted overlay method then applies these weights to the nine selected variables: distance from road, elevation, slope, aspect, roughness, hillshade, population density, distance from the seashore and LULC. Each of these variables influences the safety and accessibility of cyclone shelters differently. For instance, elevation and slope are crucial for avoiding flood-prone areas, while proximity to roads ensures accessibility during emergencies[50].

Population density indicates where shelters are most needed and LULC helps to identify areas suitable for construction. By integrating these weighted variables, the WOM produces a composite suitability map, classifying the study area into categories ranging from highly suitable to not suitable for cyclone shelters. This approach ensures that the cyclone shelters are strategically located, maximizing safety and accessibility for the population during cyclonic events[55].

Integrating the GIS-AHP Techniques for a suitable shelter mapping: Implementing GIS-AHP techniques for cyclone shelter mapping in Visakhapatnam offers a comprehensive approach in identifying optimal locations for shelters by incorporating various spatial and demographic factors. The AHP serves as a structured decision-making tool that assigns relative weights to nine critical variables: distance from roads, elevation, slope, aspect, roughness, hillshade, population density, distance from the seashore and LULC[16]. Each of these factors plays a vital role in determining the suitability of a location for a cyclone shelter. In this method, pairwise comparisons were performed to evaluate the relative importance of each factor, creating a hierarchical structure that reflects their impact on shelter suitability[25].

The AHP technique's inherent subjectivity is mitigated by its robustness, making it a widely adopted approach for regional studies. The comparison matrix for 'n' criteria is condensed into a summarized matrix, with criteria weights represented as coefficients (a_{ij}, where i, j = 1,2, 3,…n) as shown in equation 1:

$$A = \begin{bmatrix} a11 & a12 \ldots\ldots & a1n \\ a21 & a22 \ldots\ldots & a2n \\ an1 & an2 \ldots\ldots & ann \end{bmatrix}, a_{ii} = 1, a_{ij} = \frac{1}{a_{ij}}, a_{ij} \neq 0 \quad (1)$$

The WOM then applies these weights to the selected variables, rescaling each to a maximum of five classes. The overall suitability index for cyclone shelter mapping is calculated using a weighted overlay technique (WOT) as expressed by equation 2:

$$RI = \sum W_i R_j \quad (2)$$

In this equation, 'W' represents the weight allocated to each layer and 'R' indicates the rank assigned to each theme within a layer[47]. The variable 'i' denotes the number of layers, while 'j' represents the number of themes within each layer. This results in the final suitability map:

$$RI = W1 \times R1 + W2 \times R2 + W3 \times R3 + W4 \times R4 + W5 \times R5 + W6 \times R6 + W7 \times R7 + W8 \times R8 + W9 \times 9 \quad (3)$$

For example, proximity to roads ensures accessibility during emergencies while elevation and slope are crucial for avoiding areas prone to flooding or landslides. Aspect and hillshade inform the potential exposure to wind and sun, impacting the shelter's comfort and durability. Roughness, which reflects surface irregularities, is important for construction feasibility, while population density highlights areas with higher demand for shelters[8]. Distance from the seashore is critical for minimizing the risk of storm surges and the LULC map provides insights into the existing land cover, helping to avoid areas that are environmentally sensitive or already developed.

By integrating these spatial elements through GIS-based weighted overlay techniques, the AHP approach ensures that cyclone shelters are strategically located to maximize safety and accessibility, thereby empowering Visakhapatnam's preparedness against cyclonic events. The allocated weights and rankings, as outlined in table 1, provide a clear visualization of the relative importance of each factor, enabling a thorough understanding of the region's cyclone shelter suitability.

In the context of the AHP, a scale from 1 to 9 is used to represent the relative importance of elements when comparing them. A score of 1 indicates that two elements are equally important, contributing equally to the objective. A score of 3 suggests moderate importance, where experience and judgment slightly favor one element over the other. A score of 5 reflects strong importance, indicating that one element is significantly more important based on experience and judgment. A score of 7 denotes very strong importance, where one element is heavily favored over another.

Finally, a score of 9 represents extreme importance where the evidence strongly supports the superiority of one element to the highest degree. The values 2, 4, 6 and 8 are used to express intermediate levels of importance between these main categories. The influence percentage and ranking of each selected theme were determined using the weighted overlay technique and are summarized in table 1. The cyclone shelter site suitability map for Visakhapatnam was then developed (Fig. 8) and was classified into five groups:

not suitable, less suitable, moderately suitable, suitable and highly suitable.

Conclusion and Limitations

This study presents a detailed cyclone shelter suitability map for Visakhapatnam, covering an area of 550 square kilometers, situated at 17°69'N latitude and 83°22'E longitude, with an elevation ranging from 18 to 1677 meters. Using the AHP and WOT, the research integrated critical geospatial datasets including road networks, slope, aspect, roughness, hillshade, distance from rivers, distance from the seashore and LULC.

Table 1
Rating and weightage of each variable used for mapping the Cyclone Shelter mapping over the Visakhapatnam

Parameter	Rescale	suitability class	Ratings	% of influence
Distance from Road	1	Highly suitable	5	17
	2	suitable	4	
	3	Moderately suitable	3	
	4	Less suitable	2	
	5	Not suitable	1	
Elevation	1	Not suitable	5	12
	2	Less suitable	4	
	3	Moderately suitable	3	
	4	suitable	2	
	5	Highly suitable	1	
Slope	1	Less suitable	2	9
	2	Highly suitable	5	
	3	suitable	4	
	4	Moderately suitable	3	
	5	Not suitable	1	
Aspect	1	Highly suitable	1	6
	2	suitable	2	
	3	Moderately suitable	3	
	4	Less suitable	4	
	5	Not suitable	5	
Waterbody/river	1	Not suitable	1	9
	2	Less suitable	2	
	3	Moderately suitable	3	
	4	suitable	4	
	5	Highly suitable	5	
Hillshade	1	Very High	5	12
	2	High	4	
	3	Moderate	3	
	4	Low	2	
	5	Very Low	1	
Population density	1	Not suitable	1	15
	2	Less suitable	2	
	3	Moderately suitable	3	
	4	suitable	4	
	5	High suitable	5	
Distance from the seashore	1	Not suitable	1	13
	2	Less suitable	2	
	3	Moderately suitable	3	
	4	suitable	4	
	5	High suitable	5	
Land Use Land Cover	1	Moderately suitable	3	7
	2	suitable	2	
	3	Highly suitable	5	
	4	Less suitable	2	
	5	Not suitable	1	

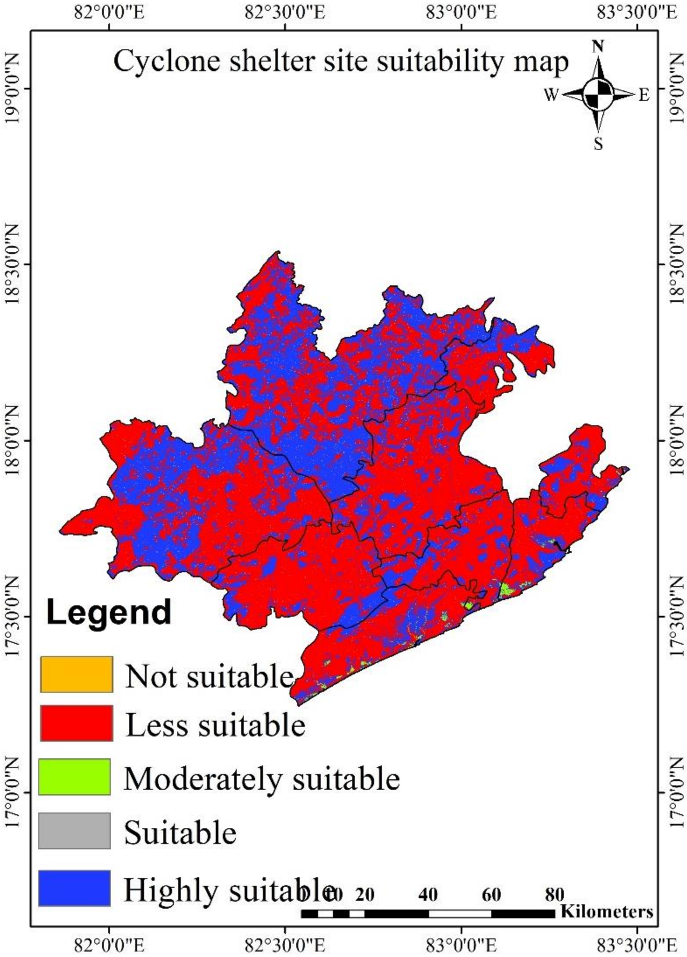

Fig. 8: Cyclone site suitability mapping of the Vishakapatnam with five suitable classes

Additionally, the study incorporated population growth data, which increased from 105,000 in 1950 to 2,385,000 in 2024, with a forecasted population of 3,041,000 by 2035, representing a growth rate of 2.32%.

A crucial component of this analysis involved categorizing wind data collected from January 2022 to January 2024 into six classes based on wind speed (measured in meters per second), which is vital for identifying areas susceptible to varying degrees of wind intensity during cyclonic events. The wind speeds were grouped into six categories: ≥ 11.10 m/s, 8.80 to 11.10 m/s, 5.70 to 8.80 m/s, 3.60 to 5.70 m/s, 2.10 to 3.60 m/s and 0.50 to 2.10 m/s. The highest wind speeds, exceeding 11.10 m/s, highlight areas most vulnerable to extreme winds, necessitating the construction of highly resilient shelters. The Windrose diagram revealed that calm conditions occurred in 4.45% of the total recorded hours, contributing to the understanding of the overall wind environment in Visakhapatnam.

By integrating these wind data with other spatial variables, the study provides a comprehensive approach to cyclone shelter placement, ensuring that shelters are strategically located to offer maximum protection, particularly in areas where wind intensity is likely to peak during cyclonic events. This geospatial analysis serves as an essential tool for disaster preparedness and resilience planning in Visakhapatnam.

Despite the robustness of the study, several limitations should be considered. The analysis did not include internal road networks which could affect access to shelters during emergencies. Population density was considered on a broad scale, without accounting for localized variations that might influence shelter demand. The study also lacked a detailed inventory of major hospitals and the number of available rescue teams, which are crucial for assessing the adequacy of shelter locations in terms of medical and emergency response capabilities. Lastly, while the AHP and WOT provided a solid foundation for this analysis, future research could benefit from incorporating machine learning techniques to further refine the model and to enhance the accuracy and predictive power of cyclone shelter suitability assessments.

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