Cyclone Shelter Suitability and Flood Risk Assessment Mapping of Amaravati Capital Region, Andhra Pradesh, India

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Abstract
Amaravati, the capital region of Andhra Pradesh, is highly vulnerable to flood hazards due to its proximity to the Krishna River and exposure to cyclonic influences from the Bay of Bengal. The Amaravati is situated at 16.5131° N latitude and 80.5165° E longitude, approximately 40 km inland from Machilipatnam, the region experiences recurrent riverine flooding and storm impacts. This study integrates Geographic Information System (GIS) and the Analytical Hierarchy Process (AHP) within a Multi-Criteria Decision-Making (MCDM) framework to assess flood susceptibility and map cyclone shelters for disaster preparedness and sustainable regional planning.

A total of 12 thematic layers including elevation, slope, aspect, hillshade, distance from rivers and roads, land use/land cover (LULC), soil, geology, geomorphology, population density and water bodies have been analyzed using the Weighted Overlay Technique (WoT) and AHP to determine flood-prone zones and optimal locations for cyclone shelters. The relative weights for each factor were assigned based on their influence on flooding and site suitability, ensuring a comprehensive risk assessment with 5 classes from very high to low. The study also incorporated a wind-rose diagram derived from three years of wind data (2022-2024) from the Global Wind Atlas to evaluate wind patterns, aiding in cyclone shelter site selection. The results highlight flood-prone zones in low-lying areas with poor drainage conditions while identifying elevated and geologically stable regions as suitable for cyclone shelters.

Keywords: Cyclone Shelter Mapping, Flood Risk Assessment, GIS-AHP, Multi-Criteria Decision-Making, Sustainable Regional Planning and Disaster Resilience.

Introduction

Amaravati, the capital region of Andhra Pradesh, has been experiencing rapid urbanization since its designation as the capital following the bifurcation of Telangana in 2014. The region, located at 16.5131° N latitude and 80.5165° E longitude, is situated on the right bank of the Krishna river and is approximately 40 km from Machilipatnam, the nearest coastal city. The location map of the Amaravati region is shown in figure 1. Due to its geographical location, Amaravati is highly vulnerable to flooding and cyclonic storms, making disaster preparedness and risk assessment essential for sustainable regional planning. The confluence of riverine flooding, extreme rainfall events and coastal cyclonic impacts poses significant risks to both infrastructure and human settlements, necessitating a comprehensive approach to flood susceptibility assessment and cyclone shelter planning[1,4,12].

Geospatial technologies such as Geographic Information System (GIS) and Remote Sensing (RS) have become indispensable tools for disaster risk assessment, enabling precise spatial analysis and multi-criteria decision-making (MCDM). The Analytical Hierarchy Process (AHP), a widely used MCDM technique, allows for the assignment of weighted values to various influencing parameters based on their relative importance in determining flood and cyclone risk[16,18].

In this study, a GIS-AHP-based approach is utilized to develop flood susceptibility and cyclone shelter maps for Amaravati, integrating multiple thematic layers such as elevation, slope, aspect, roughness, hillshade, flow accumulation, flow direction, distance from roads and rivers, land use/land cover (LULC), normalized difference vegetation index (NDVI) and topographic wetness index (TWI). These parameters play a crucial role in determining flood-prone zones and identifying suitable locations for cyclone shelters[21].

The study further incorporates wind data analysis using a wind-rose diagram, derived from three years (2022-2024) of meteorological records obtained from the Global Wind Atlas, to assess wind flow characteristics and their implications for cyclone shelter planning[18,19].

By combining hydrological, topographical and meteorological data, this research aims to provide a systematic and spatially accurate assessment of flood risks while ensuring the strategic placement of cyclone shelters to enhance disaster resilience in the Amaravati region[4,6].

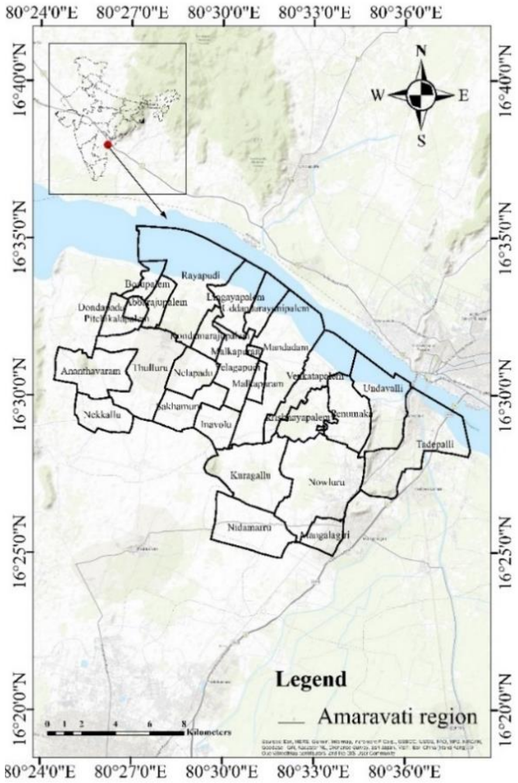

Fig. 1: Geographical location map of the Amaravati capital region.

The primary objective of this study is to develop a flood susceptibility map and cyclone shelter mapping using GIS-AHP methodologies, offering critical insights for policymakers, urban planners and disaster management authorities to formulate effective mitigation strategies and sustainable development plans for Amaravati.

Review of Literature

Cyclone shelter mapping plays a crucial role in disaster risk management, ensuring safe evacuation and minimizing casualties during extreme weather events. In previous studies, many of the researchers have employed GIS-based spatial analysis and MCDM approaches to optimize shelter locations. Paul and Routray[19] examined the accessibility and efficiency of cyclone shelters in Bangladesh, highlighting the importance of shelter capacity, proximity and structural resilience. Their study emphasized the need for integrating socio-economic parameters such as population density and vulnerable communities in shelter site selection.

Dhar and Khire[7] applied AHP in cyclone shelter mapping along the eastern coastline of India, demonstrating how a weighted overlay analysis improves decision-making by prioritizing high-risk areas for shelter placement[14,15]. Furthermore, Ahmed et al[1] used remote sensing and Least-Cost Path LCP analysis to determine optimal evacuation routes leading to cyclone shelters.

Flood susceptibility mapping is a key component of disaster risk reduction, aiding in urban planning and infrastructure resilience[23]. Various methodologies including GIS-based hydrological modeling, machine learning algorithms and MCDM techniques, have been widely used to predict flood-prone areas. Tehrany et al[33] compared frequency ratio (FR), analytical AHP and logistic regression models for flood susceptibility assessment, concluding that hybrid approaches enhance accuracy by combining statistical and expert-driven analyses.

Rahmati et al[20] highlighted the significance of remote sensing data, particularly Landsat imagery and digital elevation models (DEM), in assessing flood risks. Their study emphasized that factors such as slope, drainage density, distance to rivers and land use/land cover (LULC) significantly influence flood susceptibility. Additionally, Saha et al[28] integrated machine learning techniques such as Support Vector Machines and Random Forest (RF) into flood risk mapping, demonstrating superior predictive capabilities over traditional MCDM methods. However, machine learning models often require extensive training data and suffer from overfitting issues, making them less adaptable to rapidly changing flood patterns[3,4].

The GIS-AHP-based approach has been widely favored for flood susceptibility analysis due to its ability to incorporate multiple environmental parameters. Reddy et al[27] successfully applied AHP in flood hazard zoning, assigning weighted scores in influencing factors and generating a risk classification system for urban planning of Hyderabad (GHMC region), Telangana.

Material and Methods

Sustainable construction plays a pivotal role in enhancing resilience against cyclones and floods by incorporating disaster-resistant materials, eco-friendly designs and climate-adaptive infrastructure. UN-Habitat[34] emphasized the importance of green infrastructure, including elevated buildings, permeable pavements and rainwater harvesting systems, to mitigate flood risks in coastal urban areas. Berardi[3] explored sustainable building materials for cyclone-prone regions, advocating for the use of reinforced concrete, bamboo structures and lightweight composite materials that withstand high wind speeds and heavy rainfall[13,14]. Furthermore, Yoon et al[37] analyzed post-disaster reconstruction efforts in the Philippines, demonstrating how modular prefabrication techniques accelerate rebuilding processes while ensuring environmental sustainability. The detailed methodology adopted in this study is shown in figure 2.

GIS-AHP based multi-criteria analysis: The AHP, implemented within a GIS framework, provides a robust methodology for flood susceptibility assessment and cyclone shelter mapping in Amaravati[8]. AHP is a structured decision-making tool that assigns relative weights to various spatial data layers based on their influence on flood susceptibility[16,17]. This process involves pairwise comparisons to evaluate the relative importance of each factor, resulting in a hierarchical structure that reflects their respective impacts[9-11]. In the context of Amaravati, the criteria are hierarchically structured and rated on a scale from 1 to 9 to indicate varying degrees of importance summarized in table 1. The comparison matrix for 'n' criteria is expressed as a summarized matrix, with criteria weights represented as coefficients in the following equations 1 and 2.

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

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

where W denotes the weight allocated to each layer, R represents the rank assigned to each theme within a layer, i is the number of layers and j is the number of themes[22]. For Amaravati, the equation 3 expands as follows:

$$I = W1 \times R1 + W2 \times R2 \ldots\ldots\ldots\ldots\ldots\ldots\ldots + W12 \times R12 \quad (3)$$

where W1×R1, W2×R2 ……….. W12×R12 are the weightage and ranking of Elevation, Slope, Aspect, Precipitation, TWI, LULC, NDVI, Proximity to River, Proximity to Road and Drainage Density respectively.

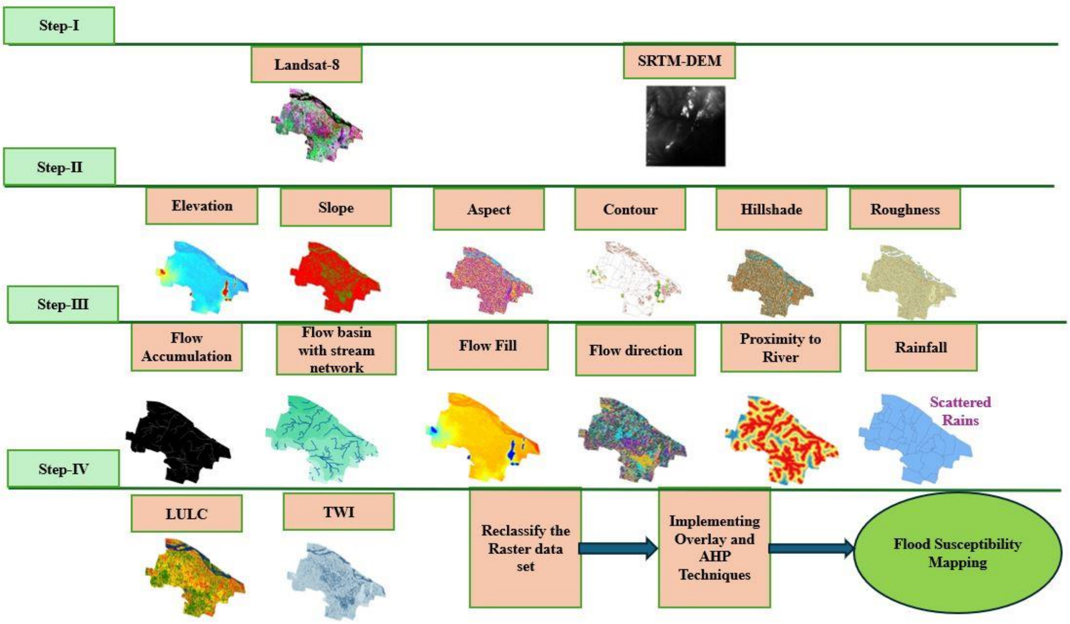

Fig. 2: Methodology used for flood susceptibility and cyclone shelter mapping of Amaravati capital region

Table 1
The core scales of AHP

Intensity	Definition	Explanation
1	Equal importance	Two elements contribute equally to the objective.
3	Moderate importance	Experience and judgement slightly favor one element over another.
5	Strong importance	Experience and judgement slightly strong one element over another.
7	Very strong importance	One element favored very strongly over another.
9	Extreme importance	The evidence favoring one element over another is of the highest possible order of affirmation.
2, 4, 6 and 8 are used to express intermediate values		

Results and Discussion

Landsat-8 satellite imagery and SRTM-DEM data were acquired from the USGS website and processed using GIS software. The band composition was applied to align with natural color representation, utilizing the bands of 4, 3 and 2 respectively. The elevation map was generated from the DEM data, revealing that the maximum elevation in the study area is 256 meters above mean sea level[24]. Thematic maps illustrating Landsat-8 imagery and elevation characteristics are presented in figure 3. To analyze the surface characteristics of the Amaravati region, various thematic features, including slope, aspect, Hillshade, contour and roughness, were developed and are displayed in figures 4-6. These features play a crucial role in flood susceptibility mapping, as they help to identify low-lying and steep-slope areas prone in water accumulation and landslides[2,25].

Hydrological flow characteristics, such as basin delineation, flow accumulation, stream network, flow direction and proximity to roads, were analyzed and mapped (Figures 6-8). These parameters are essential in understanding flood pathways, identifying vulnerable settlements and strategically planning drainage systems and evacuation routes for cyclone shelter mapping[26]. LULC classification for Amaravati was conducted using supervised techniques. The classified features include cropland, built-up land, shrubland, fallow land, water bodies and plantations[36]. The LULC map shown in figure 8 indicates that a significant portion of the region is dominated by cropland, water bodies and plantations.

Understanding LULC is vital for flood risk assessment, as built-up areas and water bodies influence runoff patterns, while cropland and vegetation impact soil permeability and water retention. This information is crucial for determining safe locations for cyclone shelters and mitigating flood risks in the region[29]. The NDVI and TWI mapping of the Amaravati region were developed and are presented in figure 9. The NDVI classification distinguishes key land cover types, including water bodies, barren land, shrubs and healthy vegetation[31]. This classification is essential for flood susceptibility assessment, as vegetation cover influences surface runoff, water retention and soil erosion, while water bodies help to identify flood-prone areas.

The TWI was categorized into five distinct classes, as shown in figure 9. TWI is a crucial factor in flood susceptibility mapping, as it helps to determine areas prone to water accumulation based on terrain characteristics[35]. The higher TWI values indicate regions with greater potential for water retention, critical for identifying flood-prone zones and planning drainage systems. The flood susceptibility mapping of the Amaravati region was developed using 12 selected thematic layers, with weights assigned based on their relative importance[36]. These weights help to prioritize factors influencing flood risk, such as elevation, slope, drainage density, land use and soil type. A summary of the assigned weights for each theme is provided in table 2. This weighted analysis plays a significant role in identifying high-risk areas and strategically locating cyclone shelters to ensure effective disaster preparedness and response in the region.

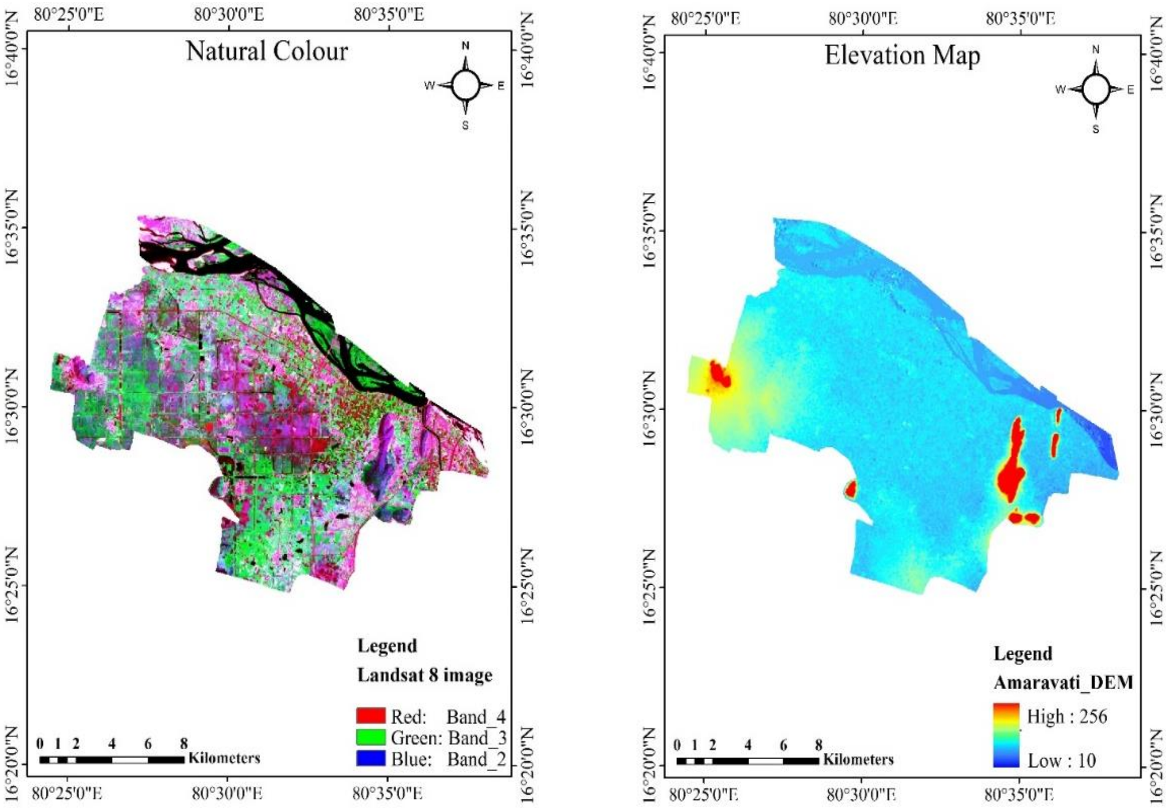

Fig. 3: Landsat-8 with representing the natural colour and elevation map of the Amaravati

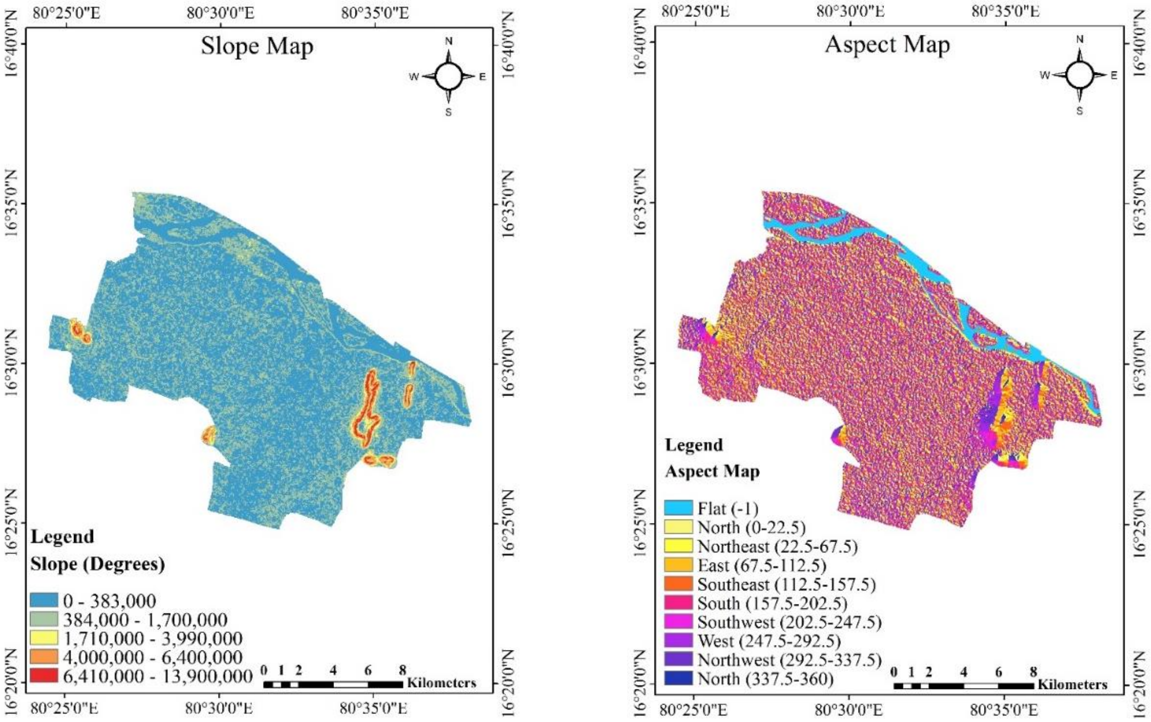

Fig. 4: Slope and aspect map of the Amaravati capital region.

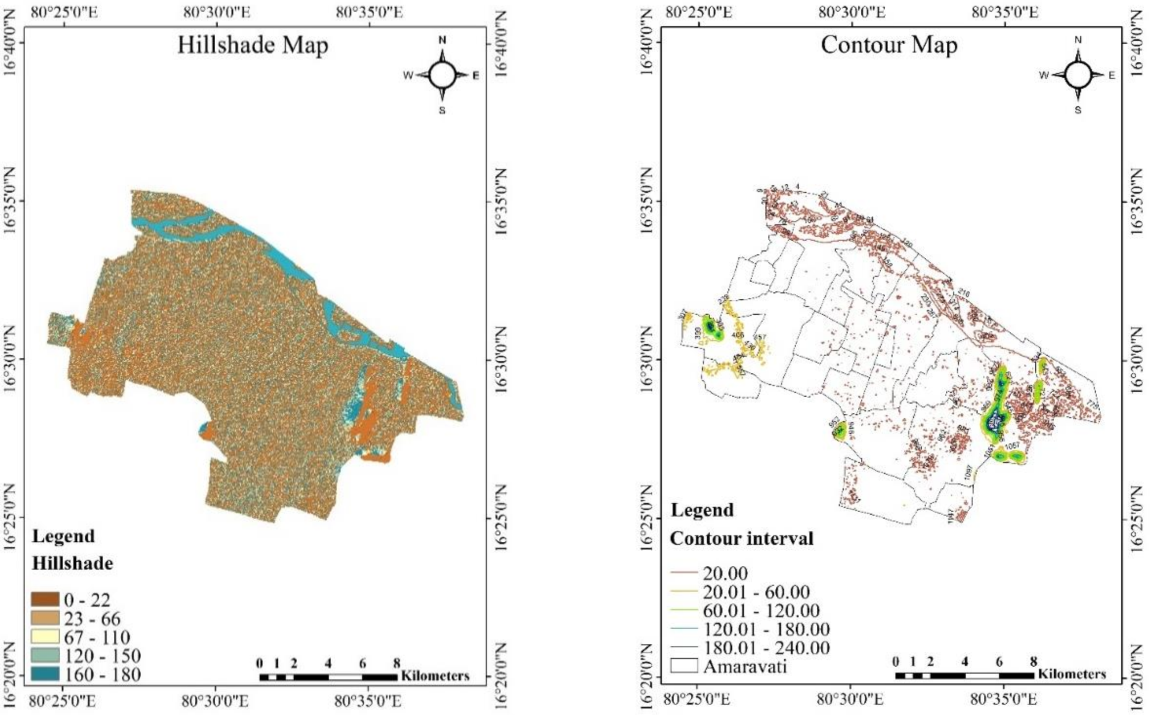

Fig. 5: Hillshade and contour maps of the Amaravati capital region.

Cyclone shelter mapping of the Amaravti region: Effective cyclone preparedness is crucial for mitigating the impacts of cyclonic events, particularly in vulnerable urban areas. GIS technology provides a robust platform for the integration and analysis of spatial data, enabling comprehensive assessment and visualization of risk factors associated with cyclones[30]. By mapping various data layers such as elevation, land use, infrastructure and population density, GIS facilitates the identification of high-risk zones and optimizes the placement of cyclone shelters. Cyclonic storms have historically caused severe devastation in coastal regions, particularly in Andhra Pradesh and Odisha. The region has witnessed several major cyclones including the Diviseema Cyclone (1977), the 1990 Andhra Pradesh Cyclone, the 1996 Kakinada Cyclone, the 1999 Odisha Super Cyclone and more recent storms such as Cyclone Laila (2010), Cyclone Helen (2013), Cyclone Hudhud (2014) and Cyclone Titli (2018). These events have led to significant loss of life, property damage and disruption of essential services. Given the recurrent nature of cyclones and their impacts, it is imperative to enhance preparedness through effective cyclone shelter mapping[32]. The integration of GIS and the AHP provides a scientific approach to identifying optimal locations for cyclone shelters, ensuring the safety of vulnerable populations.

Geology, Geomorphology and Soil features of Amaravati region: The geomorphological characteristics of the Amaravati region play a crucial role in determining flood susceptibility. The presence of flood plains (moderate and deep) indicates areas prone to periodic inundation due to their lower elevation and proximity to river channels. The channel bars, located at elevations of 8-10 meters, also signify active sediment deposition zones that may be vulnerable to sudden flooding, particularly during heavy rainfall or cyclonic events. The spatial distribution of geology and geomorphology of the Amaravati region is shown in figure 11.

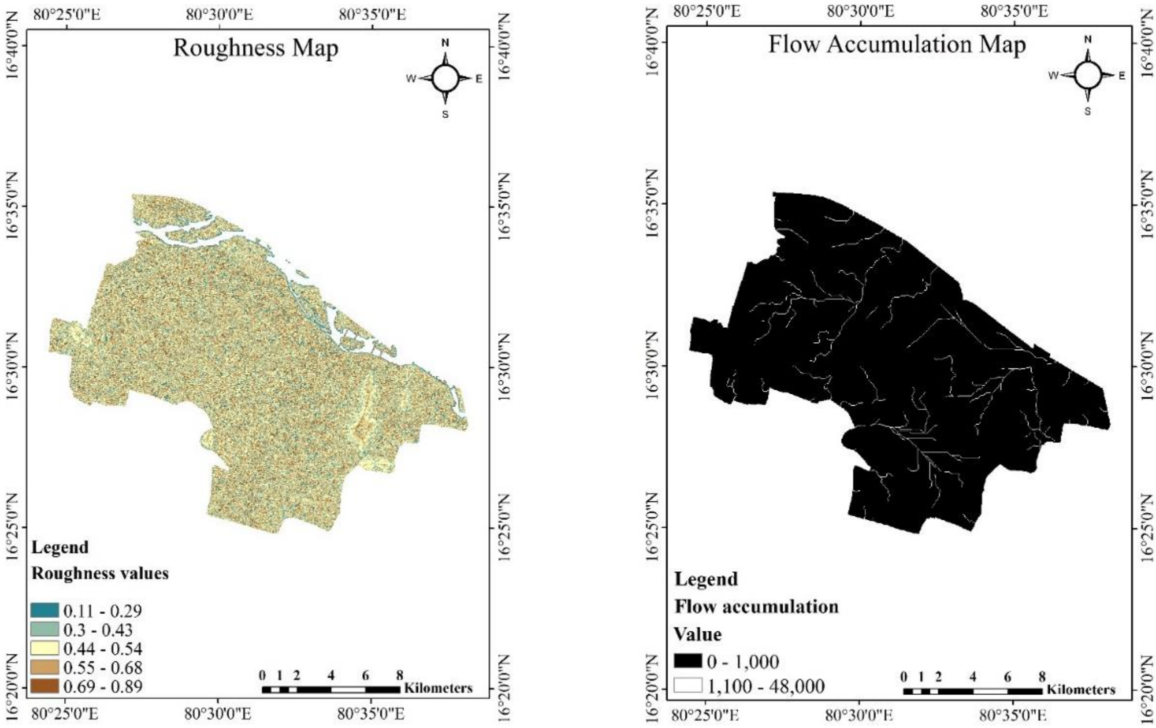

Fig. 6: Roughness and flow accumulation mapping of the Amaravati region.

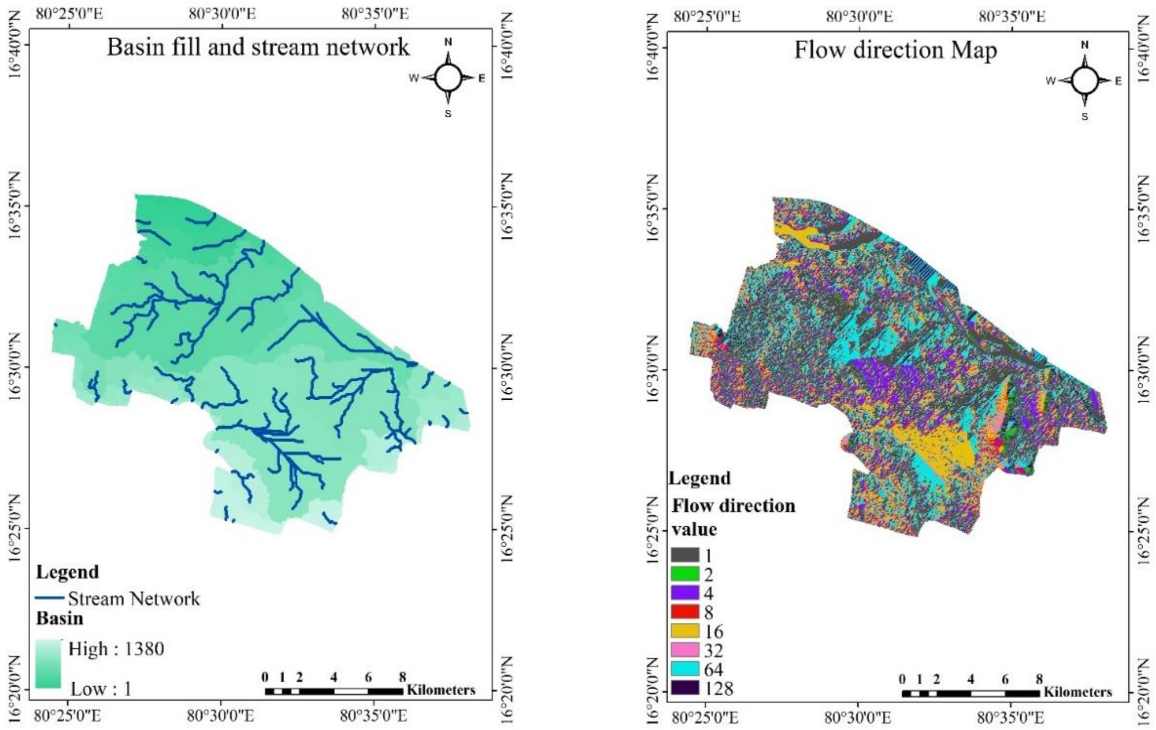

Fig. 7: Flow basin including flow network and directions over the Amaravati region

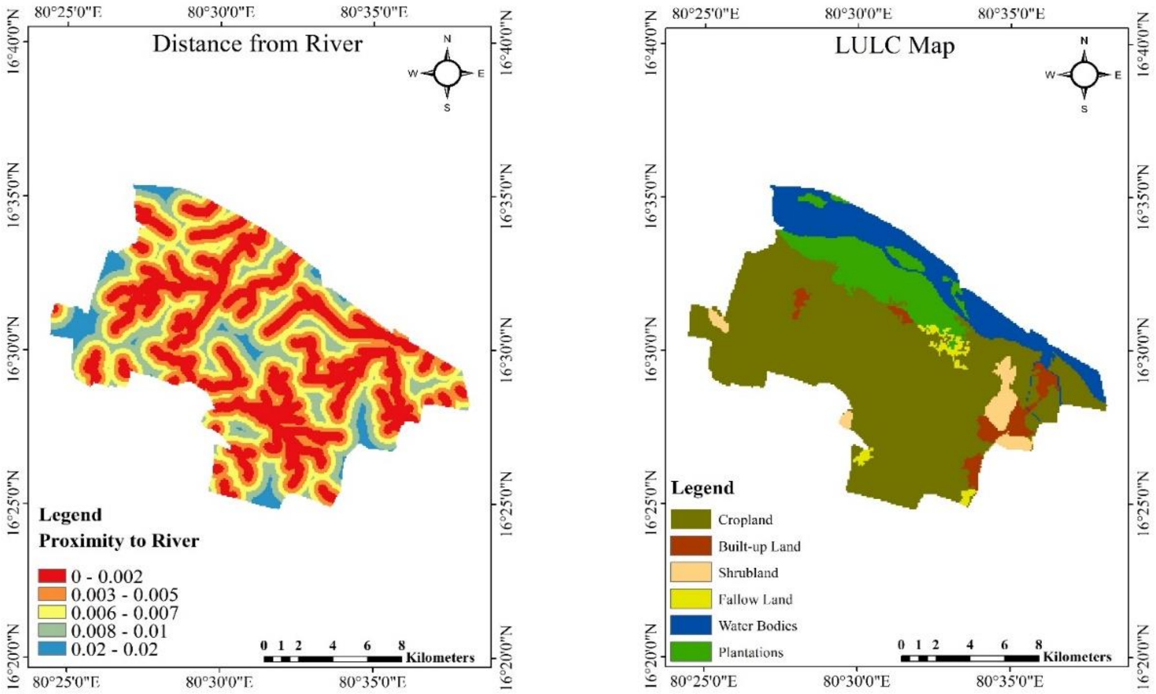

Fig. 8: Distance from river and LULC mapping of the Amaravati region

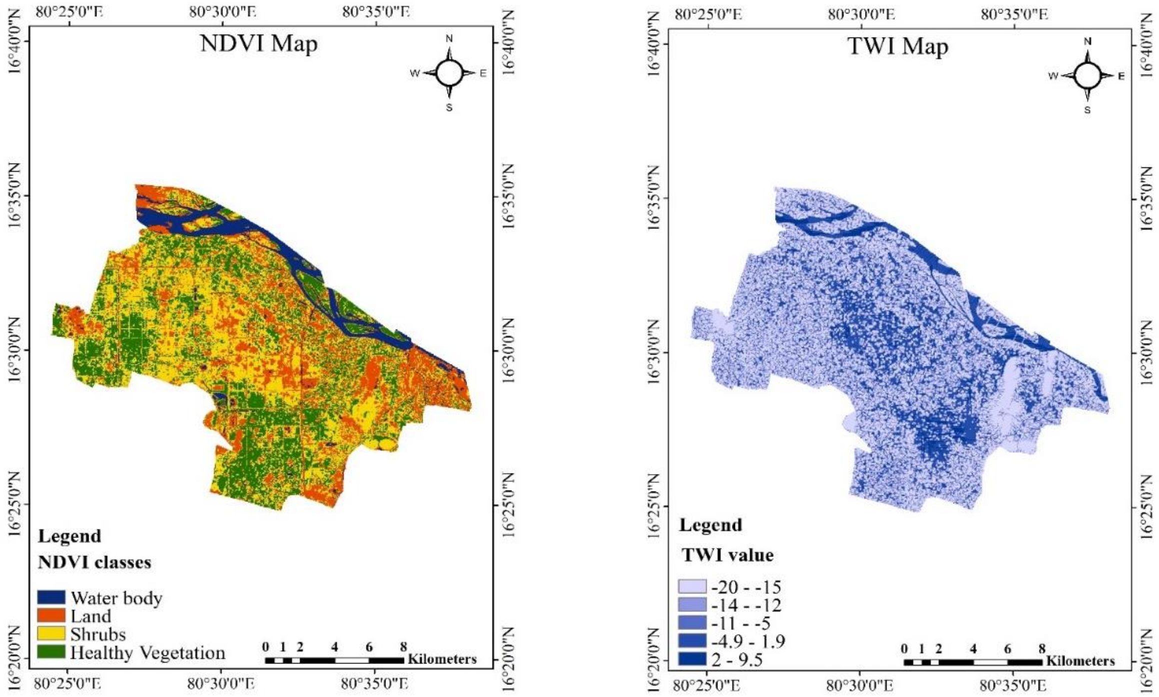

Fig. 9: NDVI and TWI mapping of the Amaravati capital region

In contrast, the structural hills (SH), denudational hills (DH) and inselbergs (I), due to their elevated and rocky nature, serve as natural barriers against floodwaters but can contribute to surface runoff, increasing flood risks in adjacent lower-lying areas such as pediments (PD) and palaeochannels (PC). The pediplain with moderate weathering, covering significant portions of the northwest, central and southern regions, may exhibit moderate infiltration capacity, influencing localized water retention and runoff dynamics. From a geological perspective, the charnockite and charnockite-khondalite complex dominate the central and southeastern parts, representing hard, resistant rock formations with limited water permeability.

Such formations can lead to rapid surface runoff, increasing flood risks in downstream alluvial and sedimentary zones. The presence of alluvium-sand and unconsolidated sediments in the floodplain areas suggests high susceptibility to water saturation and erosion, exacerbating flood impacts. The dry river channels and sand deposits further indicate past hydrological activity, which may become active during extreme rainfall events, altering flood pathways.

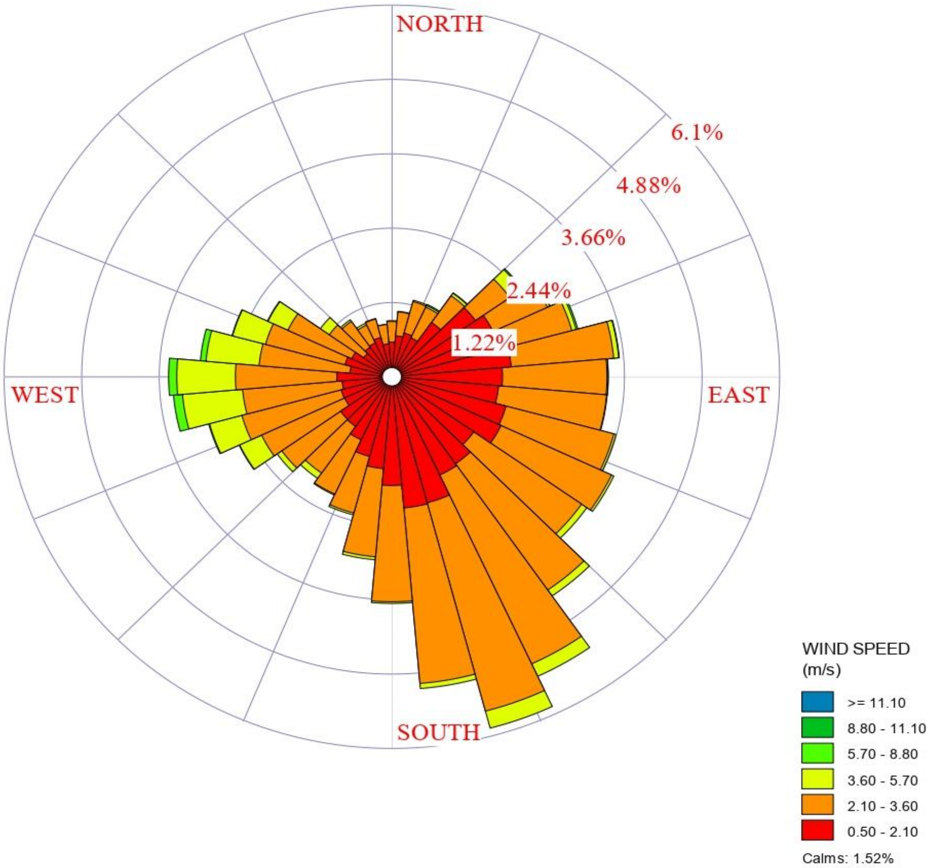

Fig. 10: The wind-rose diagram representing the wind direction and speed (m/s) of Amaravati, Andhra Pradesh

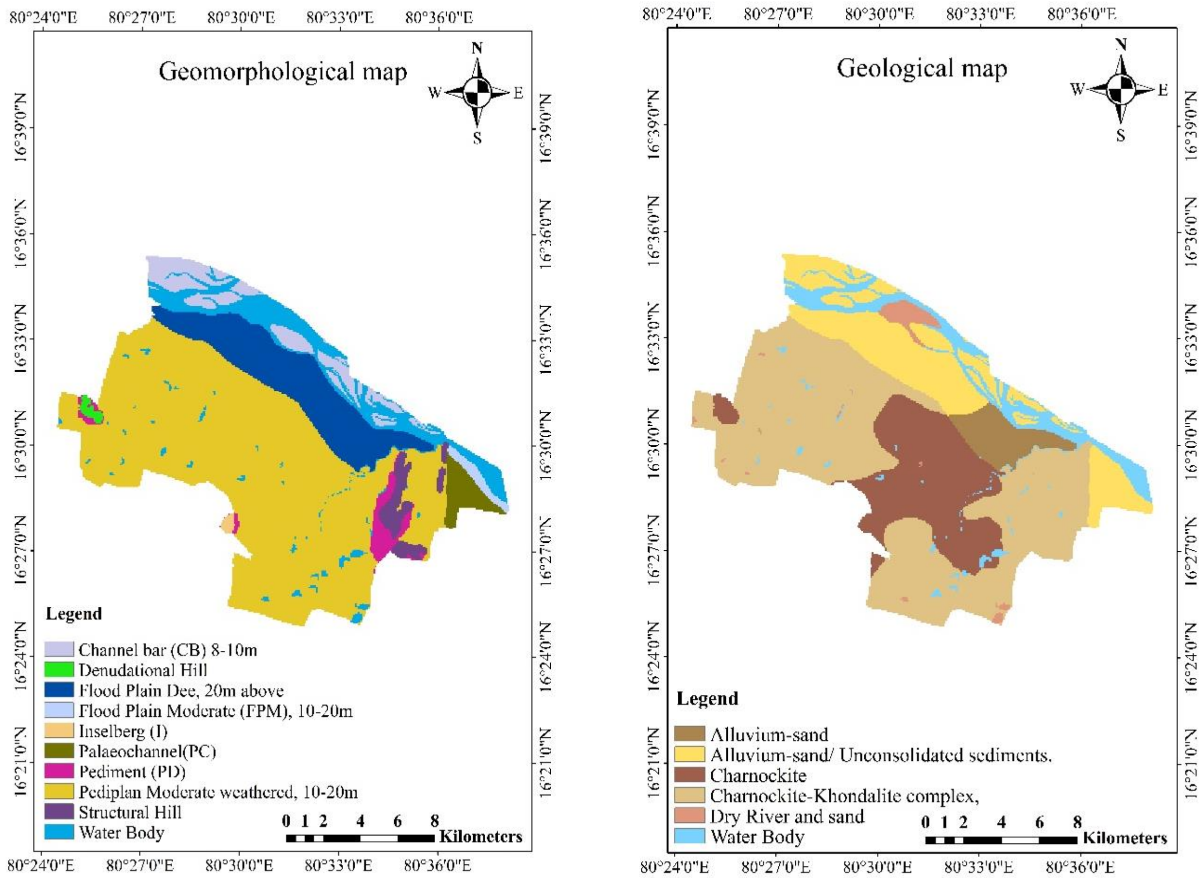

Fig. 11: Geomorphological and geological maps of the Amaravati region

The soil characteristics further influence water retention, infiltration and flood dynamics. The predominance of clayey to gravelly clayey soils across the region suggests poor drainage conditions, making these areas susceptible to prolonged waterlogging after heavy rains or cyclones. Additionally, the moderately deep black clayey soils, known for their high shrink-swell capacity, can retain water for extended periods, increasing the risk of standing water and soil destabilization.

In contrast, loamy to clayey skeletal deep reddish-brown soils may offer better drainage, reducing water stagnation but still contributing to moderate runoff. These geomorphological, geological and soil factors collectively influence cyclone shelter mapping. Cyclone shelters should be strategically placed in elevated and geologically stable areas, such as structural hills and pediments, to minimize flood risks.

Areas covered by alluvium and deep floodplains should be avoided for shelter placement due to their high susceptibility to inundation and soil instability. Additionally, areas with well-drained loamy to skeletal soils are preferable for constructing cyclone shelters, as they provide a stable foundation while preventing excessive water retention. The insights gained from these spatial analyses can enhance disaster preparedness, ensuring the safe location of cyclone shelters and reducing flood-related vulnerabilities in Amaravati. The surface distribution of the soil classes is shown in figure 12.

Weighted Overlay Technique (WoT): The WoT is a MCDA method widely used in GIS-based spatial analysis to determine flood susceptibility and optimal locations for cyclone shelters[3,8]. This technique assigns numerical weights to different thematic layers based on their relative influence on the phenomenon being studied. In the context of cyclone shelter mapping and flood susceptibility assessment, 12 thematic layers elevation, slope, aspect, hillshade, distance from river, road, water bodies, population density, soil, geology, geomorphology and LULC are integrated using GIS software. The assigned weights for these themes range from 6 to 11, with distance from roads (8 %), soil (10%), geology (10%) and geomorphology (10%) being the most influential factors. These weights help in prioritizing locations based on their suitability for shelter construction or their vulnerability to flooding.

Analytic Hierarchy Process (AHP): The AHP is another MCDA method used to rank and evaluate spatial factors by converting them into a standardized scale (1 to 5) based on their importance. This technique involves pairwise comparisons of thematic layers to establish priority weights. In flood susceptibility and cyclone shelter mapping, AHP ensures that each theme is assigned a weight based on expert judgment and quantitative analysis. Figure 13 pairwise matrix shows a total of 10 themes. The methodology incorporates classification of each theme into sub-categories, each receiving specific weights as summarized in table 2, allowing for a more refined analysis. The pair wise matrix with weights of each theme is shown in figure 13.

Application in Cyclone Shelter Mapping and Flood Susceptibility Analysis: Both techniques are instrumental in disaster management and planning.

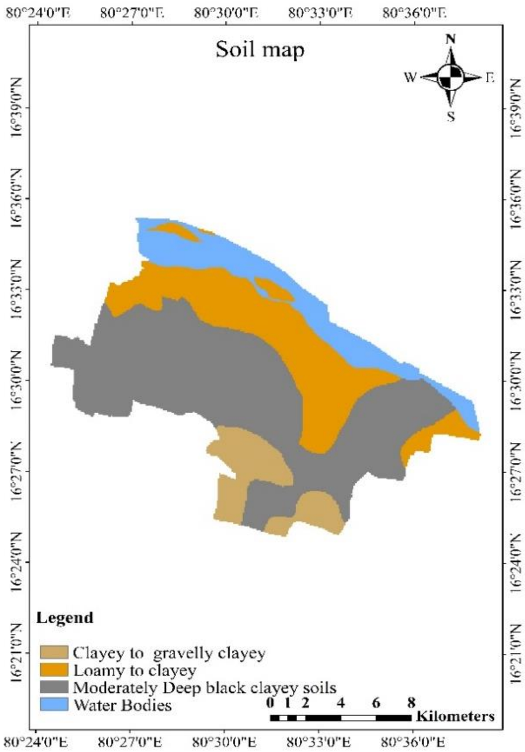

Fig. 12: Soil classification map of the Amaravati region

Matrix		TWI	Elevation	Slope	Precipitation	LULC	NDVI	Distance from river	Distance from road	Drainage densit	Soil type
		1	2	3	4	5	6	7	8	9	10
TWI	1	1	1	1	1	4	4	2	3	1	1
Elevation	2	1	1	1	1	2	2	1	2	1	1
Slope	3	1	1	1	1	3	2	1/2	1	1	1
Precipitation	4	1	1	1	1	3	2	2	3	1	1
LULC	5	1/4	1/2	1/3	1/3	1	1	1/3	3	1	1
NDVI	6	1/4	1/2	1/2	1/2	1	1	1/4	1	1	1
Distance from river	7	1/2	1	2	1/2	3	4	1	2	1	1
Distance from road	8	1/3	1/2	1	1/3	1/3	1	1/2	1	1	1
Drainage density	9	1	1	1	1	1	1	1	1	1	1
Soil type	10	1	1	1	1	1	1	1	1	1	1

Fig. 13: Pairwise matrix with weights of each theme developed using WoT

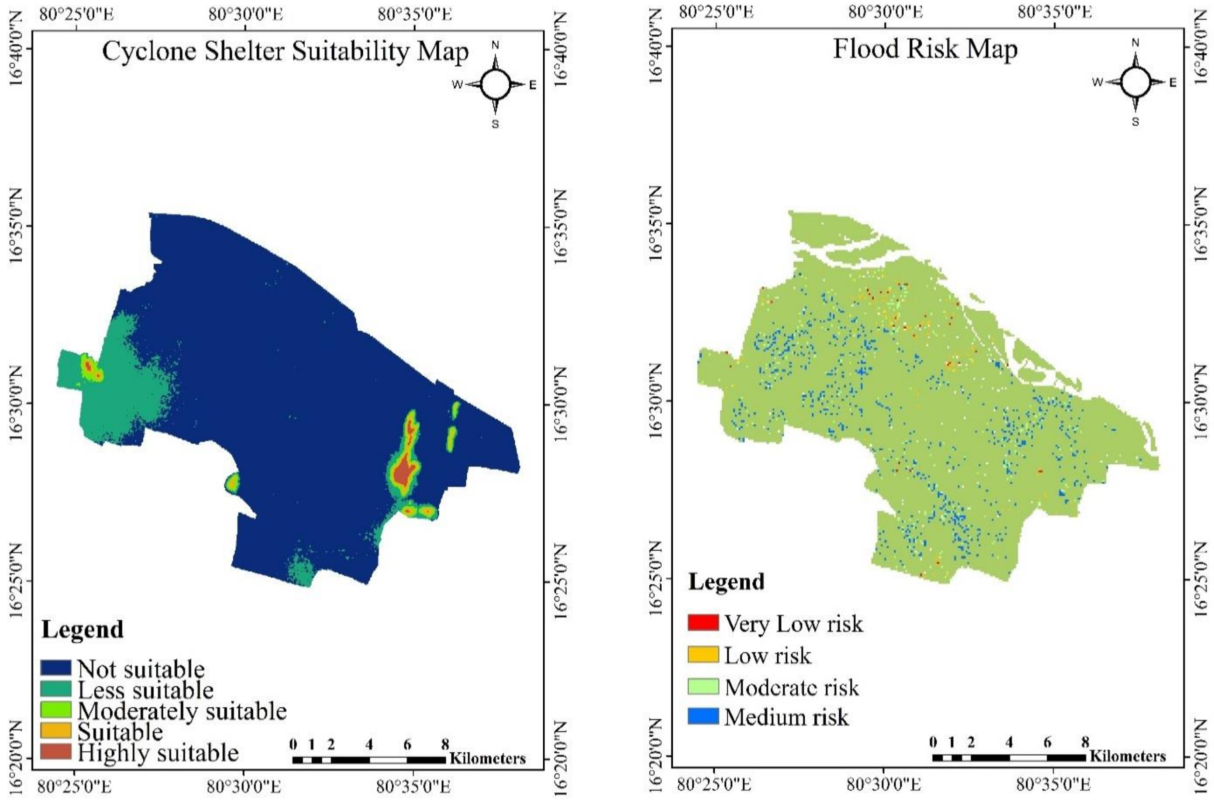

Fig. 14: Cyclone Shelter Suitability and flood risk susceptibility mapping of the Amaravati region

Flood susceptibility mapping: WoT and AHP help to identify flood-prone zones by integrating elevation, slope, distance from rivers, soil type and land use factors. Areas with low elevation, proximity to water bodies and poor drainage soil (e.g. clayey soils) are assigned higher flood susceptibility scores.

Cyclone shelter mapping: By analyzing population density, road accessibility, geomorphology and elevation, AHP and WoT assist in identifying stable, elevated and accessible locations for cyclone shelters. Areas with good road connectivity, higher elevation and stable geological formations are prioritized.

Table 2
Rating and weightage of each variable used for mapping the Cyclone Shelter mapping over the Amaravati

Parameter	Suitability class	Ratings	% of influence
Elevation (m)	Not suitable	5	09
	Less suitable	4	
	Moderately suitable	3	
	suitable	2	
	Not suitable	5	
Slope	Less suitable	2	06
	Highly suitable	5	
	suitable	4	
	Moderately suitable	3	
	Not suitable	1	
Aspect	Highly suitable	1	06
	suitable	2	
	Moderately suitable	3	
	Less suitable	4	
	Not suitable	5	
Hillshade	Very High	5	**07**
	High	4	
	Moderate	3	
	Low	2	
	Very Low	1	
Distance from Road	Highly suitable	5	08
	suitable	4	
	Moderately suitable	3	
	Less suitable	2	
	Not suitable	1	
Distance from the River	Not suitable	1	11
	Less suitable	2	
	Moderately suitable	3	
	suitable	4	
	High suitable	5	
Waterbodies	Not suitable	1	08
	Less suitable	2	
	Moderately suitable	3	
	suitable	4	
	Highly suitable	5	
Population density	Not suitable	1	06
	Less suitable	2	
	Moderately suitable	3	
	suitable	4	
	High suitable	5	
Soil	Very high	5	10
	High	3	
	Moderate	2	
	Low	1	
	Very low	4	
Geology	Very high	5	10
	Very high	4	
	High	3	
	Moderate	2	
	Low	1	
Geomorphology	Very high	5	10
	Very high	3	

	High	3	
	Moderate	2	
	Low	1	
Land Use Land Cover	Moderately suitable	3	09
	suitable	2	
	Highly suitable	5	
	Less suitable	4	
	Not suitable	1	

By using GIS-based WoT and AHP approaches, decision-makers can enhance disaster preparedness, optimize cyclone shelter locations and mitigate flood risks efficiently. An integrated flood susceptibility map of the Amaravati capital region is shown in figure 14.

Conclusion

This study successfully assessed flood susceptibility and cyclone shelter mapping in Amaravati using a GIS-AHP-based WoT within a MCDA framework. Given Amaravati's geographical vulnerability to riverine flooding from the Krishna River and cyclonic impacts from the Bay of Bengal, these findings provide essential insights for disaster preparedness and risk mitigation. Spanning 217 sq. km with a projected population of 10-20 million by 2030, Amaravati requires robust flood and cyclone shelter planning. The study utilized 12 thematic layers including elevation, slope, proximity to rivers and roads, soil, geology and LULC developed using GIS tools with data sourced from USGS. The AHP technique assigned relative weights (6 to 11) to establish a pairwise comparison matrix, classifying risk zones into five categories from high to low. A wind-rose diagram (Figure 10) further refined cyclone shelter site selection based on wind patterns.

The results highlight low-lying flood-prone areas and identify geologically stable, elevated and accessible locations for cyclone shelters. These findings provide critical guidance for policymakers, urban planners and disaster response authorities to enhance flood mitigation strategies, emergency response planning and long-term resilience in Amaravati capital region of Andhra Pradesh.

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