Assessing flood susceptibility in the Godavari River Basin, Bhadrachalam Region, Sothern India: A GIS-AHP Multi-Criteria Approach

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Abstract
Floods, as recurrent natural disasters, exert significant impacts on both the environment and human settlements. This study focuses on evaluating the flood susceptibility of the Bhadradri Kothagudem district in Telangana, situated within the Godavari River Basin. The research integrates Geographic Information System (GIS) and the Analytic Hierarchy Process (AHP) in a multi-criteria approach to analyze and map flood susceptibility. Landsat-8 data, digital elevation model data and rainfall serve as inputs for assessing the flood susceptibility. The study considers various topographical features such as elevation, slope, roughness, contours and aspect, along with factors like land use land cover, flow accumulation, stream direction, stream network, drainage density, flow length, distance from the river, soil, normalized difference vegetation index and topographic wetness index. These variables are rescaled on a scale of one to five and combined to generate a comprehensive flood susceptibility map of the Kothagudem district using GIS. The AHP is implemented through GIS, assigning weightages on a scale of one to five based on the priority of spatial classes within thematic maps.

The flood susceptibility map is produced on a scale of five, designating scale class five as of very high susceptibility and scale class one as low. Scale classes two, three and four represent intermediate levels of susceptibility. The resulting flood susceptibility maps offer valuable insights for disaster preparedness, risk mitigation and land-use planning in the Kothagudem district. The integration of GIS and AHP provides a robust methodology for assessing and visualizing flood susceptibility, enabling informed decision-making for resilient and sustainable development in flood-prone regions.

Keywords: Bhadradri Kothagudem, Godavari Basin, GIS, AHP Method and Flood susceptibility.

Introduction

Floods, as devastating natural disasters, pose significant threats to both the environment and human settlements. The Godavari River, one of India's major rivers, has a rich history of flooding events, contributing to the urgency of understanding and managing flood susceptibility in its basin[19,26]. The Kothagudem district, situated within the Godavari River Basin and encompassing the Bhadrachalam Region in Telangana State, has experienced recurrent floods, making it a focal point for comprehensive flood susceptibility assessment. The region's vulnerability to floods necessitates a systematic and data-driven approach to assess and map flood susceptibility. This research aims to contribute valuable insights for disaster preparedness, risk mitigation and land-use planning in the study area. Historical records reveal the susceptibility of Kothagudem district to floods, emphasizing the urgency of developing effective strategies for flood management. The Bhadrachalam Region, with its proximity to the Godavari River, is particularly prone to flooding events, underscoring the critical need for a detailed flood susceptibility mapping study.

The study employs advanced geospatial tools including Landsat-8 data, digital elevation model (DEM) data and rainfall, as inputs for flood susceptibility assessment[15]. Landsat-8 satellite imagery provides high-resolution data, capturing dynamic changes in land cover and aiding in the identification of vulnerable areas. DEM data, representing the terrain's elevation, offers insights into topographical features crucial for understanding flood dynamics[28]. Additionally, rainfall data serves as a key parameter in assessing the hydrological aspects of flood susceptibility[5].

The integration of Geographic Information System (GIS) and the Analytic Hierarchy Process (AHP) enhances the robustness of the study[31,32]. GIS provides a spatial platform for data analysis, visualization and mapping while AHP facilitates a systematic approach to prioritize and assign weights to various spatial factors. This combined GIS-AHP approach ensures a comprehensive and accurate flood susceptibility mapping methodology. Spatial features such as elevation, slope, roughness, contours, land use land cover, flow accumulation, stream direction, stream network, drainage density, flow length, distance from the river, soil composition, normalized difference vegetation index (NDVI) and topographic wetness index (TWI) are critical variables considered in the study. These factors, rescaled on a scale of one to five, are integrated to develop a detailed flood susceptibility map of the Kothagudem district.

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The literature review underscores the importance of flood susceptibility mapping in flood-prone regions, emphasizing the significance of utilizing advanced geospatial tools for accurate and timely assessments. This research builds upon existing knowledge and aims to provide a nuanced understanding of flood vulnerability in the Kothagudem district, contributing to informed decision-making and sustainable development practices in flood-prone areas.

A critical appraisal of the literature

The literature on flood susceptibility mapping demonstrates the diverse methodologies and approaches employed to assess and mitigate the impact of floods in various regions. Swain et al[36] pioneered the use of GIS-AHP techniques, incorporating cloud technology for flood susceptibility mapping, showcasing the potential for advanced technological integration in such studies. Vilasan and Kapse[41] focused on the evaluation of prediction capabilities, comparing AHP and F-AHP methods in flood susceptibility mapping of Ernakulam district, India.

Goumrasa et al[13] applied GIS and AHP methods to assess flood hazard susceptibility in the Chiffa wadi watershed along the first section of the Algeria North-South highway, emphasizing the versatility of these techniques across different geographies. Khosravi et al[18] contributed a comparative study of GIS-based flood susceptibility assessment in Iran, employing frequency ratio, weights-of-evidence bivariate statistical models and multi-criteria decision-making techniques.

Gigović et al[12] introduced GIS-interval rough AHP methodology for flood hazard mapping in urban areas, providing a unique perspective on the application of interval rough AHP in GIS-based flood susceptibility assessments. Selvam and Antony Jebamalai[30] applied the AHP for flood susceptibility mapping in the Thamirabarani river basin, highlighting the significance of GIS techniques in the Southern India region.

These points were drawn from recent literature which focused on flood susceptibility mapping in the Baitarani River basin, implementing a cloud-based GIS-AHP technique, showcasing the evolving role of cloud technology in advancing flood risk assessment. Vaddiraju and Talari[40] conducted an urban flood susceptibility analysis of the Saroor Nagar Watershed in India, utilizing a Geomatics-based multi-criteria analysis framework, emphasizing the importance of tailored approaches in urban settings. Collectively, these studies contribute to the evolving field of flood susceptibility mapping, showcasing advancements in GIS technology, AHP methodology and the integration of cloud-based solutions for more accurate and efficient flood risk assessments.

Flood susceptibility mapping in perennial river basins like Godavari is crucial for proactive disaster management. Integrating advanced GIS-AHP techniques as seen in literature, allows for precise risk assessments. This approach aids in developing targeted strategies, ensuring the resilience of communities against recurrent floods in the Godavari River Basin of Kothagudem district, Telangana.

Study area

Bhadradri Kothagudem, an eastern district in Telangana, emerged from the former Khammam district, surrounded by Bhoopalapalle, Mahabubabad and Khammam districts, as well as Andhra Pradesh and Chhattisgarh. Boasting 23 mandals and two revenue divisions, Kothagudem and Bhadrachalam, the district's hub is Kothagudem town, well-connected through the Bhadrachalam Road railway station and extensive bus services. Encompassing Bhadrachalam, Manuguru, Bergampahad, Kothagudem and Yellandu, it holds the title of the largest forest area, yielding significant forest produce like teak and bamboo.

As the second-largest district in Telangana at 7015.69 km², it shares borders with Khammam, Mahabubabad, Mulugu, Eluru, East Godavari and Chhattisgarh. With 24 mandals and two revenue divisions, Kothagudem serves as the district headquarters, hosting a population of 1,069,261 as of the 2011 Census[4]. The district is famed for its cultural richness and diverse landscapes, featuring notable sites such as Bhadrachalam, a pilgrimage hub, the Kinnerasani project in the Godavari Basin and Parnashala, a popular tourist destination. The geographic coordinates are approximately 17.7331° N latitude and 80.7214° E longitude. The geographical location map of the study area is shown in figure 1.

Material and Methods

The study employs established geographical tools for spatial distribution mapping, encompassing seismic hazard, landslides, fire safety, ground water evaluation and temperature forecasting. Landsat-8 data, digital elevation model (DEM) data and rainfall serve as key inputs for flood susceptibility assessment. Various topographical features such as elevation, slope, roughness, contours and aspect, alongside factors like land use land cover, flow accumulation, stream direction, stream network, drainage density, flow length, distance from the river, soil, normalized difference vegetation index and topographic wetness index are drawn[17]. The methodology is visually represented in figure 2, outlining the step-by-step process adopted for the current study.

Results and Discussion

Data processing begins by highlighting the pivotal role of spatial distribution maps, encompassing elevation, slope, roughness, aspect and contour features, in the creation of comprehensive flood susceptibility maps for a specific area. In this study focused on Kothagudem, the foundational dataset for GIS analysis is established through the utilization of Landsat 8 (Level-2) data downloaded from the USGS website, coupled with USGS-SRTM DEM data[2,9]. The GIS techniques employed, such as band-composting and mosaic, result in the generation of a color infrared map depicted in figure 3a, showcasing elevation as a crucial component for flood susceptibility assessment.

The meticulous preparation of slope, roughness, aspect and contour maps at varying scales is detailed in figure 4. The interconnected spatial distribution maps offer a comprehensive understanding of topographical features, aiding in identifying flood-prone areas and significantly contributing to the formulation of effective flood susceptibility maps for the targeted region[42].

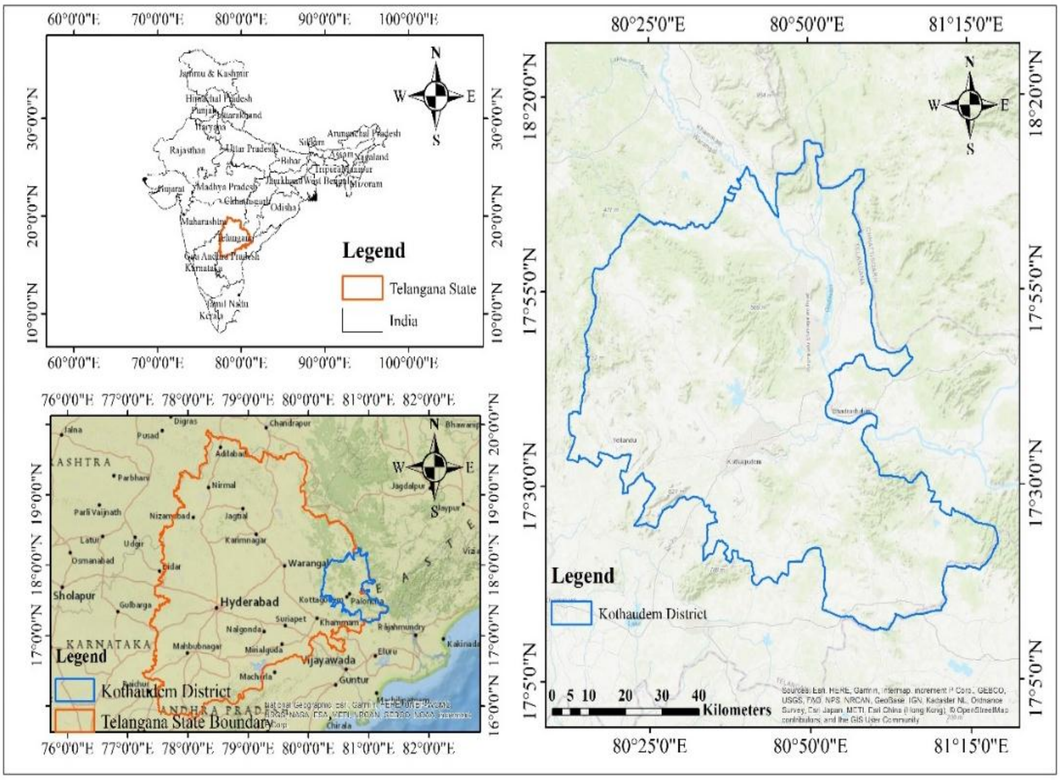

Fig. 1: Kothagudem district boundary map from India.

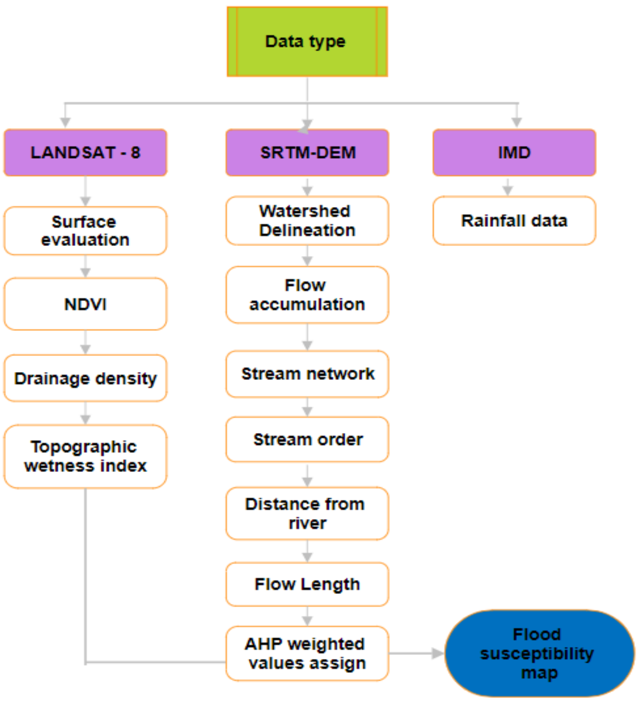

Fig. 2: Methodology used in this study for flood susceptibility analysis.

The flood susceptibility analysis for Kothagudem delves into the thorough evaluation of elevation, slope, roughness, aspect and contour features. The elevation map (Fig. 3b) provides crucial insights into the varying heights of the terrain, influencing drainage patterns, river flow and overall landscape vulnerability to flooding. The slope map, prepared on a scale of five classes with a mean slope of 66.97 degrees, sheds light on the steepness of the terrain and its impact on water runoff and potential flood risks. Additional layers of information are contributed by roughness, aspect and contour maps, detailing surface irregularities, directional orientation and topographical variations respectively.

The spatial distribution maps, generated using Landsat 8 data and USGS- SRTM DEM data through GIS techniques, laid the foundation for flood susceptibility mapping. Rescaling thematic maps, including elevation and slope, into five classes adheres to the AHP method, facilitating a holistic assessment[9]. This integrated approach significantly contributes to the formulation of effective flood susceptibility maps tailored to the unique characteristics of Kothagudem. The study underscores the urgency of proactive flood risk management, emphasizing its relevance and timeliness for the region.

Rainfall intensity and distance from River

Highlighting key statistics such as an average annual rainfall of 147.76 millimeters and 135.35 rainy days, the information notes a notable event of 4.0 millimeters in September 2023 and a -100% deviation in November 2023. The peak rainfall during 2022-2023 occurred in Karkagudem mandal at 2756.9 millimeters. Figure 5a presents a rainfall map, crucial for understanding rainfall intensity in the region. In terms of flood susceptibility, proximity to rivers is crucial with areas nearest to rivers most severely affected by overflow-induced floods[3,39]. The likelihood of flooding is higher in regions with abundant surface water[40]. Emphasizing the importance of the distance from rivers, the content notes that water flows from higher elevations, making areas around rivers more susceptible to flooding. Figure 5b illustrates the distance-from-river map, generated using GIS, showcasing flood-prone regions in the Kothagudem district.

Watershed Delineation

Watershed delineation, a pivotal process in hydrology, entails the identification of drainage area boundaries, facilitating the analysis of water flow within a specified region[7]. In the context of Kothagudem, this delineation was executed through the application of GIS techniques. The procedure typically includes acquiring DEM followed by extracting terrain information such as slope, aspect, flow direction and flow accumulation[29]. Subsequent steps involve calculating flow accumulation to define the drainage or stream network. Employing GIS tools and algorithms enables the delineation of watersheds by pinpointing areas where water converges ultimately outlining the boundaries of each watershed.

Figure 6a illustrates the resultant watershed delineation for Kothagudem, offering a visual representation of the spatial distribution of drainage areas in the region. This GIS-centric methodology imparts valuable insights into the hydrological characteristics of the area, bolstering effective water resource management and environmental planning.

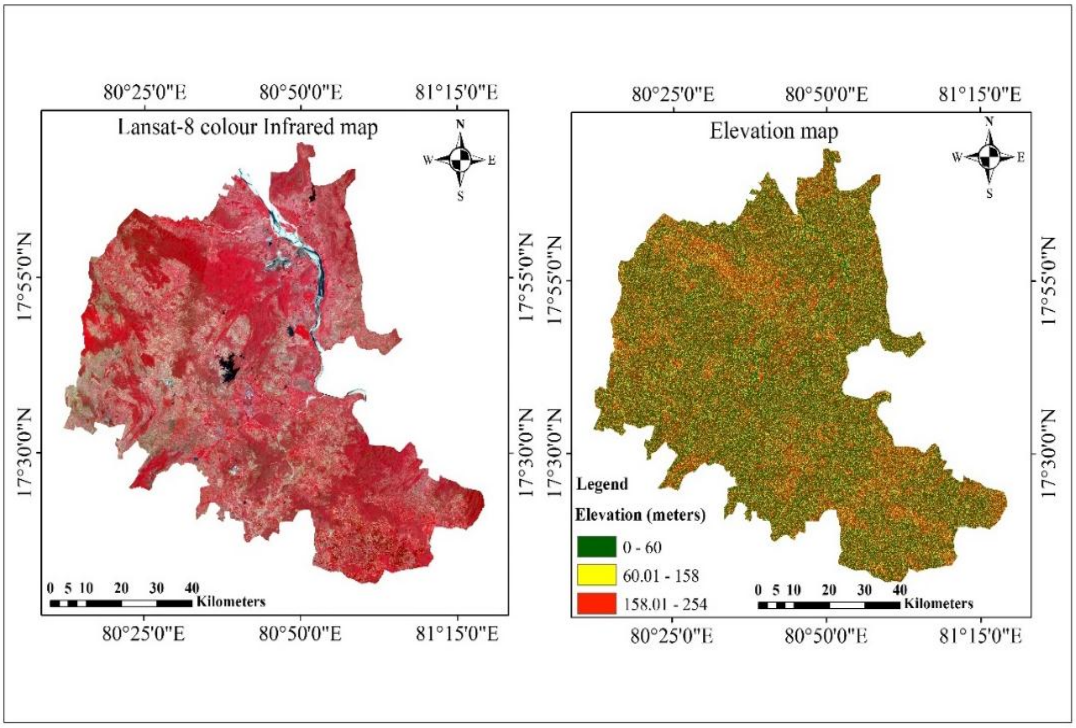

Fig. 3: Color infrared map generated with GIS techniques (bands 5, 4 and 3) and elevation map of Kothagudem district.

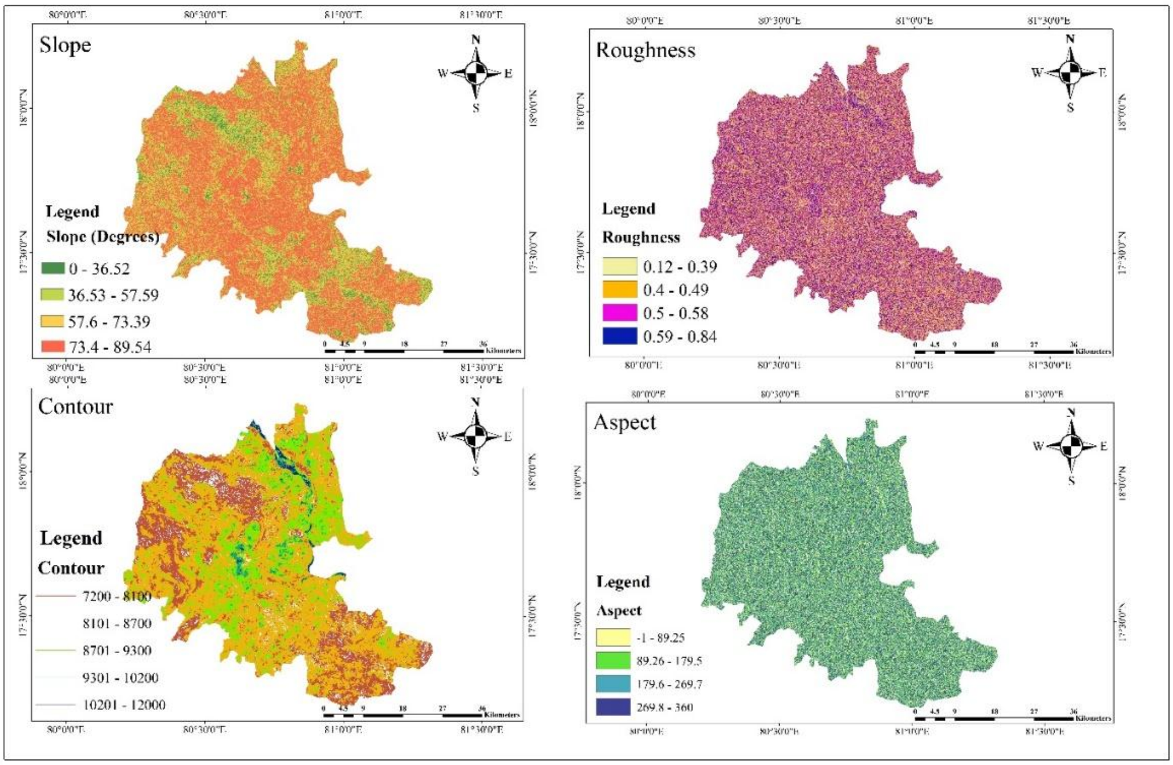

Fig. 4: Topographical features at varying scales (slope, roughness, aspect and contour)

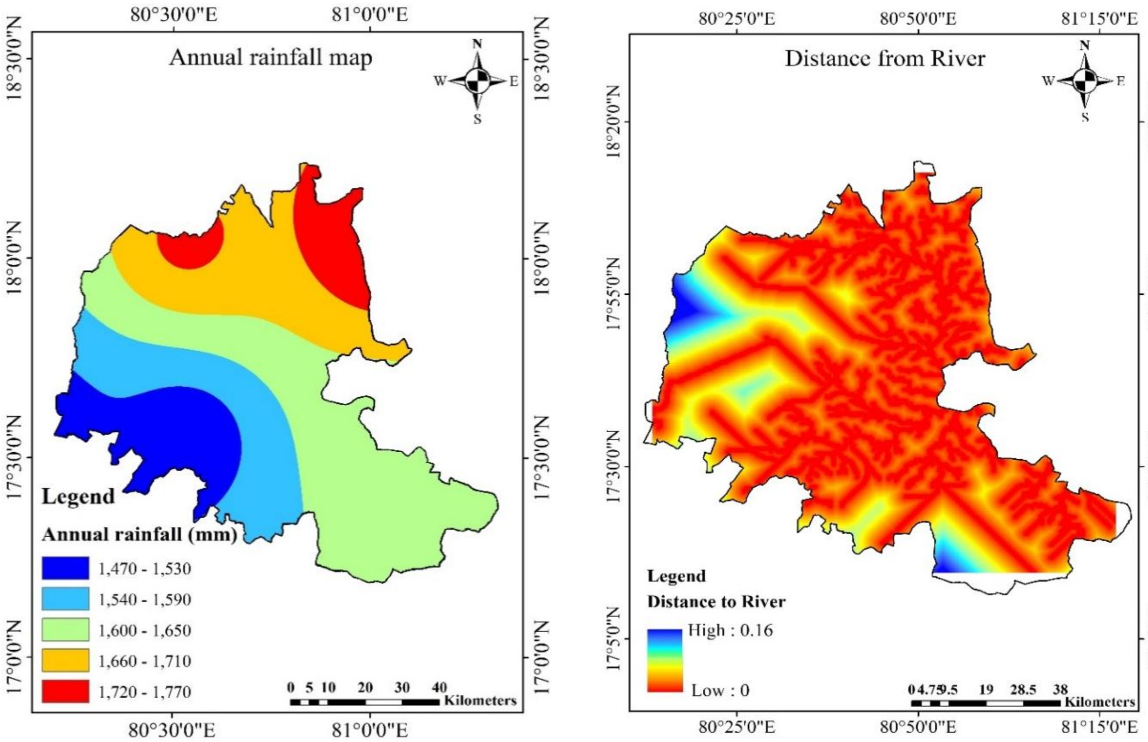

Fig. 5: Hydro-geospatial analysis for rainfall and distance from river in Kothagudem district

Watershed delineation, complemented by the stream network map, has been meticulously crafted for the Kothagudem district, as depicted in figure 6b. The stream network is thoughtfully categorized into four classes. These classes encompass short, medium, moderate and long, providing a nuanced understanding of the drainage patterns within the region. This comprehensive analysis contributes to a more detailed and insightful representation of the hydrological dynamics in Kothagudem, enhancing our ability to comprehend and manage water resources effectively.

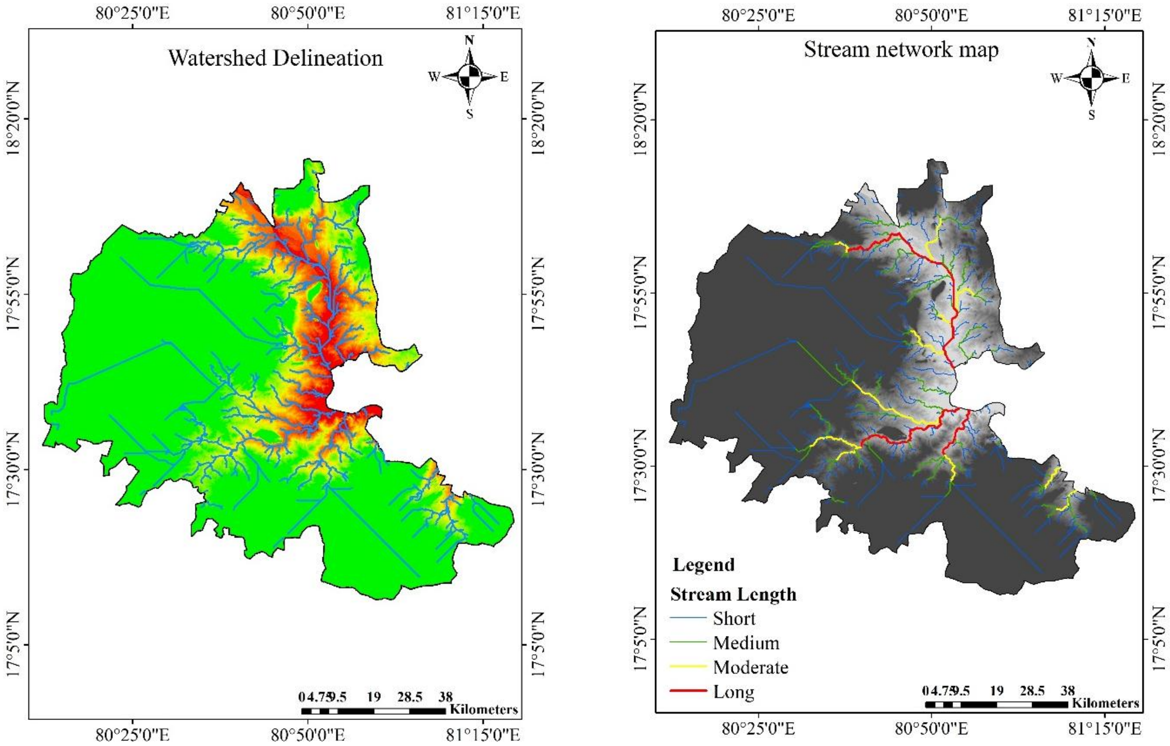

Fig. 6: Watershed and stream network integration map of the Kothagudem district.

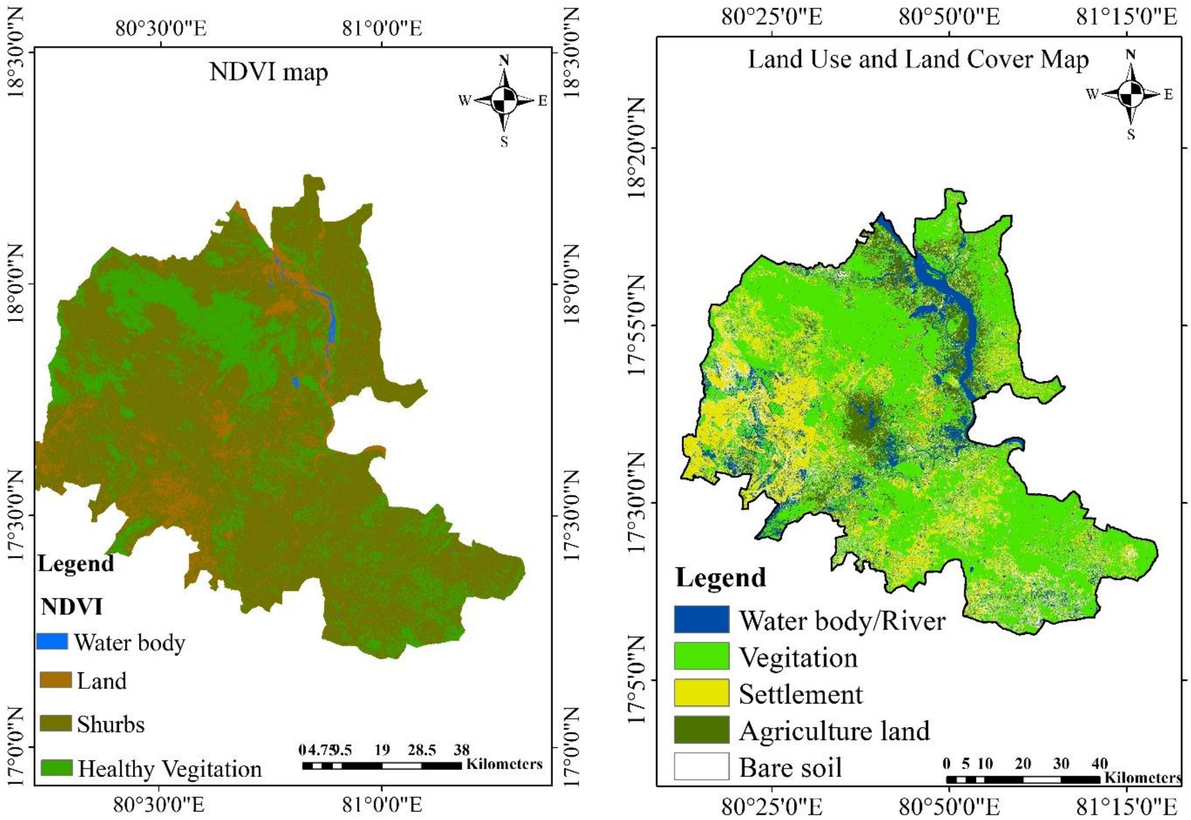

Fig. 7: NDVI and LULC map of Kothagudem district

NDVI and Land Use Land Cover (LULC) Map: Normalized Difference Vegetation Index (NDVI) serves as a crucial numerical indicator for assessing vegetation health and density by analyzing the reflective properties of plants in both the near-infrared and visible light regions of the electromagnetic spectrum, computed through a specific formula:

$$NDVI = \frac{B5-B4}{B5+B4}$$

where notation "B stands for band", NDVI values span from -1 to 1, with elevated values denoting flourishing and densely vegetated areas. Negative values such as -1 are indicative of non-vegetated surfaces like snow, water bodies, or clouds, where red reflectance surpasses near-infrared[35,38]. Conversely, values close to 0 are associated with bare soil where red and near-infrared reflectance are similar. A positive NDVI, around 1, signifies healthy vegetation, typically ranging between 0.1 and 0.7. To harness the utility of NDVI in flood susceptibility mapping, an NDVI map for Kothagudem has been meticulously crafted using GIS techniques as illustrated in figure 7a. This map is categorized into four classes including water bodies, land, shrubs and healthy vegetation, offering insights into the varying vegetation conditions across the region.

Furthermore, the integration of LULC maps, depicted in figure 7b, enhances the understanding of environmental dynamics crucial for flood susceptibility assessments. The LULC map is structured into five levels, encompassing water bodies/rivers, vegetation, settlements, agricultural land and soil.

This detailed classification aids in deciphering the interplay between human activities and land characteristics, providing essential information for flood susceptibility modeling. By combining NDVI which illuminates vegetation patterns, with LULC data that delineates diverse land uses, the flood susceptibility map gains depth and accuracy[6]. The synergy between these datasets not only aids in identifying vulnerable areas but also contributes to formulating targeted strategies for flood management and mitigation in the Kothagudem district.

Drainage density: The complex drainage pattern of a terrain serves as a visual representation of both surface and subsurface features, offering valuable insights into the hydrological characteristics of the earth[8]. Influenced by factors such as lithology, this pattern becomes a crucial indicator of water percolation rates[11,20]. Lithology, which determines natural drainage rates, intricately shapes the drainage network through variables like slope, rock resistance, structural controls, deformations and morphological changes. This intricate pattern aids in understanding geomorphic properties and tracing the evolution of landforms[33]. Utilizing data extracted from a DEM map within GIS program, figure 8a illustrates the drainage density map for Kothagudem, categorized into four levels ranging from very low to very high.

For flood susceptibility mapping, the drainage density map categorizes areas into low, medium, high and very high susceptibility levels, allowing a nuanced assessment of flood risks. Analyzing drainage density helps to identify areas prone to rapid water accumulation. Integrating this data with land use, land cover and NDVI is crucial for crafting a comprehensive flood susceptibility map[22]. This multidimensional approach facilitates a holistic evaluation of flood risk in the Kothagudem district, aiding effective planning and management.

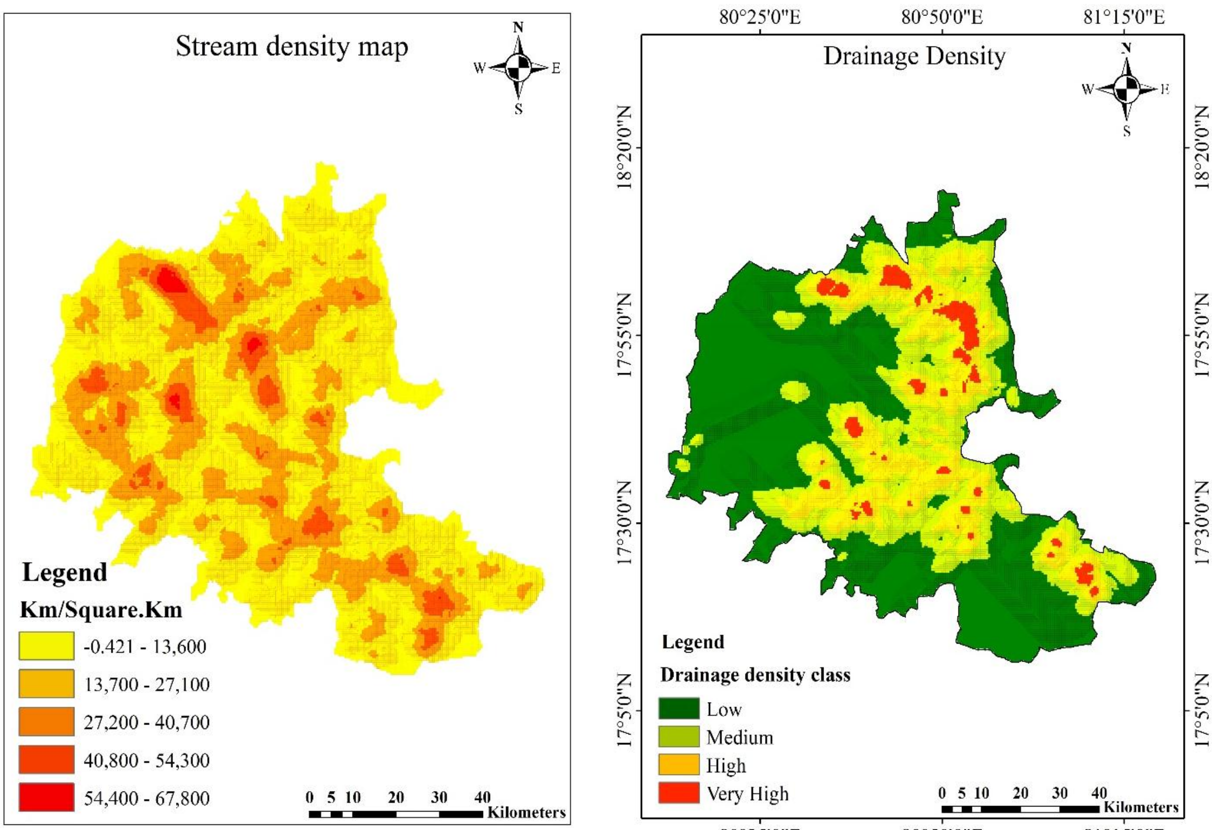

Fig. 8: Hydrological density analysis: stream and drainage patterns in Kothagudem

Additionally, figure 8b, the stream density map enhances our understanding of the hydrological network, contributing to a comprehensive grasp of flood susceptibility in the region.

Topographic Wetness Index (TWI): The TWI is a pivotal measure for assessing both the accumulation of water flow and gravitational water movement in a drainage basin as seen in figure 9a. It is calculated through the combination of slope and specific catchment area incorporating parameters such as area (a) and length (L):

$$TWI = Ln\frac{a}{\tan(\beta)}$$

where "L represents the slope in degrees". This computation yields the catchment area, underscoring the connection between topography and water flow dynamics. In environmental research, TWI proves beneficial for understanding spatial variations in factors like soil organic matter, nutrients and texture.

Diverse methods exist for estimating TWI involving both catchment area and slope calculations. The researchers noted that the choice of flow algorithm significantly impacts the relationship between TWI and observed soil moisture after comprehensive testing. Using ArcGIS, a TWI map was generated and manually categorized into five susceptibility levels, ranging from extremely low (negative) to high (positive), as shown in figure 9a. This categorization plays a vital role in flood susceptibility map preparation, offering valuable insights into water accumulation-prone areas and contributing to effective flood management strategies[22].

Flood Susceptibility Map: In the realm of flood susceptibility analysis for Kothagudem district, the AHP emerges as a robust methodology[37]. Leveraging spatial data integration, a comprehensive flood susceptibility map has been meticulously crafted, amalgamating nine crucial themes: TWI, elevation, slope, precipitation, LULC, NDVI, distance from river, drainage density and distance from road. Each theme, evaluated on a scale of one to five contributes to the susceptibility class ranging from very low to high[14]. The AHP approach with fundamental scales (Table 1) derived from Saaty, assigns weights to each vulnerability theme according to standards. Notably, the flood susceptibility map, depicted in figure 9b, showcases vulnerability classes on a scale of one to five, with high susceptibility rated as one and low susceptibility as five.

The assigned weights, detailed in table 2, elucidate the percentage allocation against each vulnerability theme. This GIS-AHP based flood susceptibility analysis for Kothagudem integrates the earlier discussed drainage density, emphasizing a multidimensional approach that incorporates both hydrological and spatial factors. The combination of AHP-derived weights with the GIS-based overlay method enriches the flood susceptibility mapping process, offering a holistic understanding of the region's vulnerability to potential flooding.

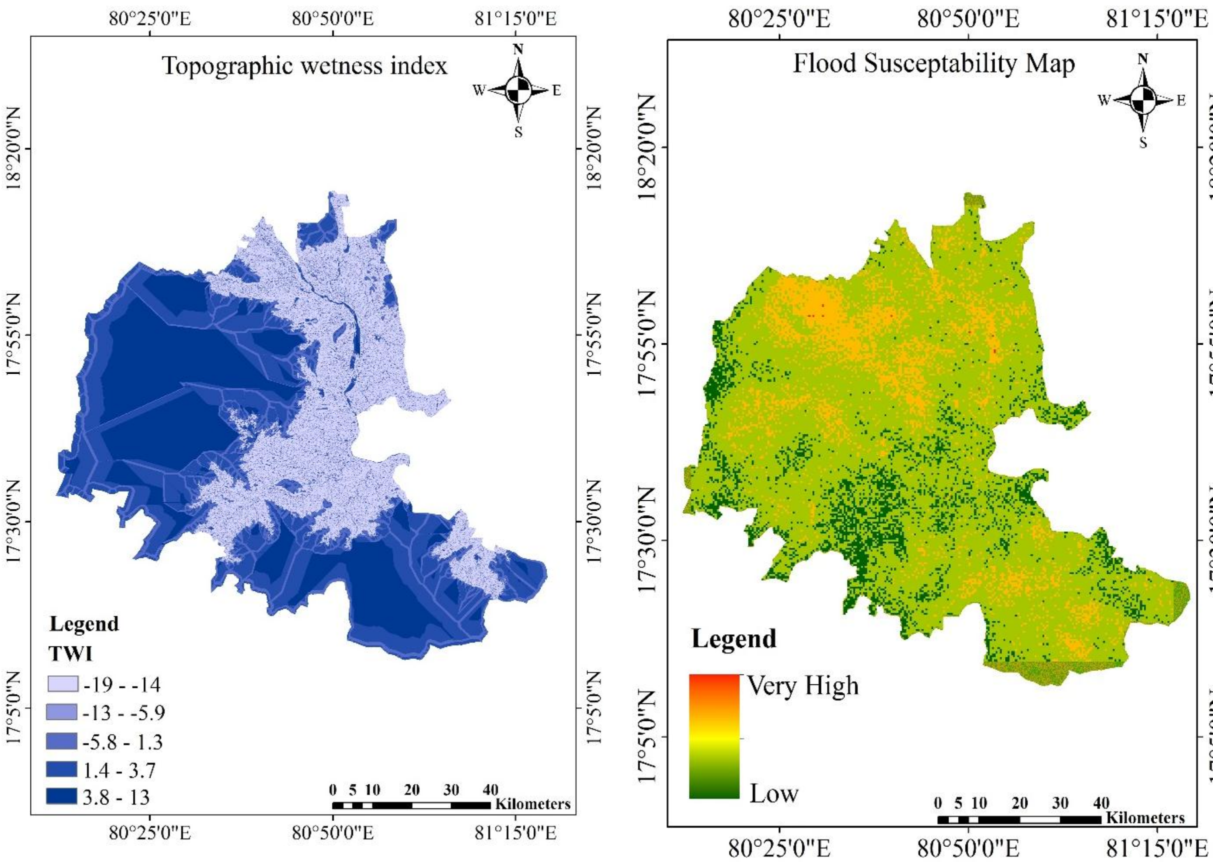

Fig. 9: TWI and Flood Susceptibility Map of Kothagudem

Table 1
The fundamental 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		

Table 2
Flood Susceptibility Assessment using weight overlay criteria.

Flood Causative Creation	Unit	Susceptibility Class Ranges and Ratings	Susceptibility Class Ratings	Weight (%)
TWI	%	Very Low	1	18
		Low	2	
		Moderate	3	
		High	4	
		Very High	5	
Elevation	meters	Very High	5	13
		High	4	
		Moderate	3	
		Low	2	
		Very Low	1	
Slope	degrees	Very High	5	10
		High	4	
		Moderate	3	
		Low	2	
		Very Low	1	
Precipitation	mm/year	Very Low	1	13
		Low	2	
		Moderate	3	
		High	4	
		Very High	5	
LULC	Level	Very High	5	15
		High	4	
		Moderate	3	
		Low	2	
		Very Low	1	
NDVI	Level	Very High	5	7
		High	4	
		Moderate	3	
		Low	2	
		Very Low	1	
Distance from River	meters	Very High	5	10
		High	4	
		Moderate	3	
		Low	2	
		Very Low	1	
Drainage Density	m/Km	Very Low	1	8
		Low	2	
		Moderate	3	
		High	4	
		Very High	5	
Distance from Road	meters	Very High	5	6
		High	4	
		Moderate	3	
		Low	2	
		Very Low	1	

Conclusion

In conclusion, the flood susceptibility analysis for Kothagudem district has been conducted through a comprehensive and multidimensional approach. The integration of GIS techniques including the generation of drainage density maps and the utilization of the AHP, has yielded a nuanced understanding of the region's vulnerability to flooding. By incorporating diverse spatial themes such as TWI, elevation, slope, precipitation, LULC, NDVI, distance from river, drainage density and distance from road, the study captures various hydrological and environmental factors influencing flood susceptibility.

The assignment of vulnerability classes on a scale of one to five, coupled with AHP-derived weights, provides decision-makers with a clear and actionable framework for effective flood management and mitigation strategies. This holistic evaluation not only enhances our comprehension of flood risk but also contributes to informed planning in the face of potential environmental challenges in Kothagudem.

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