Enhanced Flood Risk Evaluation in Ferozepur District, Punjab through GIS and Analytic Hierarchy Process

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Abstract
Effective disaster risk management and urban planning require robust flood vulnerability assessment methodologies, particularly in regions susceptible to flooding. Ferozepur district, Punjab, confronts substantial challenges concerning flood risk, underscoring the necessity for a comprehensive vulnerability assessment approach. This study presents an exhaustive investigation into flood vulnerability assessment in Ferozepur district, Punjab, employing Geographic Information Systems (GIS) and the Analytic Hierarchy Process (AHP) as a multi-criteria framework.

The primary aim is to develop a robust flood vulnerability assessment framework, integrating various thematic maps such as aspect, distance to river, elevation, flow accumulation, flow direction, drainage density, contour, Landsat 8 imagery, normalized difference vegetation index (NDVI), land use and land cover (LULC), annual rainfall, roughness, slope, stream network and topographic wetness index (TWI). Through the synthesis of these thematic maps, areas susceptible to flooding within Ferozepur district have been accurately delineated.

The study underscores the significance of employing multiple criteria and GIS methodologies for precise flood vulnerability assessment. Findings reveal that regions characterized by high drainage density, low elevation and proximity to rivers exhibit heightened vulnerability to flooding. Factors such as land cover, rainfall intensity and terrain roughness exert substantial influence on flood vulnerability. Specifically, the study delineates regions highly susceptible and less susceptible to flood risks. The newly established flood vulnerability assessment framework provides essential guidance for policymakers, urban planners and emergency response agencies to mitigate flood risks.

Keywords: Flood vulnerability assessment, Geographic Information Systems, Analytic Hierarchy Process, Landsat-8 and Urban flood risk management.

Introduction

Floods, as one of the most recurrent and devastating natural disasters, pose significant threats to human lives, economic stability and environmental sustainability. Nowhere is this more evident than in Ferozepur District, Punjab, India where the interplay of geographical factors and human settlements creates a perfect storm of vulnerability. With the Sutlej River snaking through its terrain and major drainage systems converging, Ferozepur finds itself perennially on the edge, susceptible to the whims of nature's fury. The importance of understanding and mitigating flood risks in Ferozepur cannot be overstated. As the lifeline of the district, the Sutlej river sustains agricultural livelihoods, facilitates transportation and serves as a vital water source. However, its benevolent flow can quickly transform into a destructive force, inundating fields, displacing communities and disrupting essential services.

Recent history bears witness to the havoc wreaked by floods as evidenced by the alarming discharge of 169,916 cubic feet per second upstream of Harike head works in 2019, leading to berm erosion and widespread anxiety among residents. Against this backdrop, the imperative for robust flood susceptibility mapping and management strategies becomes clear. The delineation of flood-prone areas, the identification of vulnerable populations and the assessment of infrastructure vulnerabilities are essential steps toward enhancing resilience and minimizing losses.

In particular, the recognition of approximately 25 border villages, including those in Fazilka, facing imminent threats from escalating water flows underscores the urgency of proactive measures and evidence-based decision-making. In response to these challenges, the integration of Geographic Information Systems (GIS) and the Analytic Hierarchy Process (AHP) emerges as a promising approach. GIS enables the spatial analysis of diverse factors influencing flood susceptibility, ranging from topography and land use patterns to proximity to water bodies and drainage infrastructure. Concurrently, AHP provides a structured framework for prioritizing these factors based on expert judgment and stakeholder inputs, facilitating informed decision-making and resource allocation.

However, the significance of this endeavour extends beyond immediate hazard mitigation efforts[1-3]. By identifying vulnerable groups within the district, such as children, pregnant women and the elderly, it underscores the imperative of inclusive disaster risk reduction strategies. Moreover, by aligning with broader developmental goals including the Sustainable Development Goals (SDGs), it contributes to the resilience-building agenda and promotes sustainable growth in the face of mounting climate challenges.

In this context, this study seeks to undertake a comprehensive flood susceptibility mapping of Ferozepur district, Punjab, harnessing the combined power of GIS and AHP methodologies. By elucidating the spatial distribution of flood vulnerability and prioritizing mitigation measures, it endeavours to empower policymakers, planners and communities to make informed choices and to build a more resilient future[7,8].

Objectives of the study

In light of Ferozepur district's susceptibility to floods and the imperative to mitigate associated risks, the development of a comprehensive flood susceptibility map emerges as a critical endeavour. With the overarching objective of enhancing resilience and minimizing vulnerability, this study aims to create a GIS-based environmental database, incorporating crucial factors such as topography, land use/land cover (LULC) and proximity to water bodies. Leveraging the AHP, the identified factors will be systematically prioritized and weighted, refining the accuracy of the susceptibility mapping process.

Ultimately, the integration of GIS-derived data with AHP-driven analysis will yield a precise flood susceptibility map for Ferozepur district, Punjab, empowering stakeholders with evidence-based insights for proactive flood risk management strategies.

- Develop a comprehensive GIS-based environmental database encompassing topography, LULC and water body proximity for Ferozepur district.
- Utilize the AHP to prioritize and assign weights to identified factors, enhancing the accuracy of the flood susceptibility mapping process.
- Integrate GIS-derived environmental data with AHP-prioritized factors to create a precise flood susceptibility map for Ferozepur district, Punjab.

The study area, Ferozepur district, Punjab, India, lies in the north-western part of the country. Ferozepur city, the capital of the district, is situated on the banks of the Sutlej river. It is bordered by the districts of Jalandhar, Kapurthala and Amritsar to the north and it shares its western border with Pakistan. The geographical location map of the Ferozepur district is shown in figure 1.

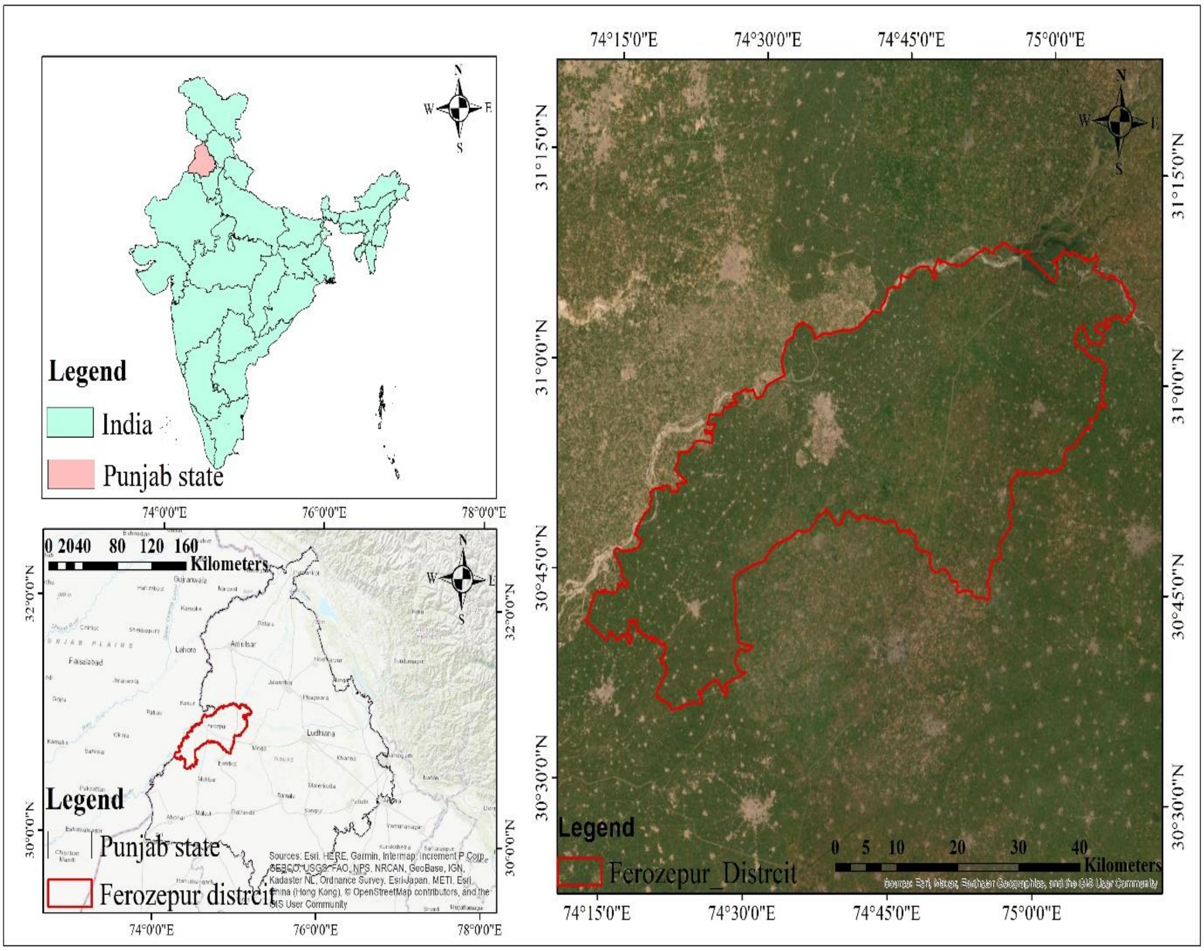

Figure 1: Location map of the Ferozepur District

Review of Literature

Conducting a thorough literature review specific to the selected study on flood susceptibility mapping is crucial for several reasons. First, it provides valuable insights into existing methodologies, data sources and analytical techniques utilized in similar contexts, aiding in the formulation of an effective research framework. Secondly, it helps to identify gaps and limitations in current literature, guiding researchers towards areas requiring further investigation or refinement. Additionally, a comprehensive review of past studies facilitates the integration of established best practices and theoretical frameworks into the research design, thereby enhancing the robustness and reliability of the findings.

Sahana and Patel[24] compared frequency ratio and fuzzy logic models for flood susceptibility assessment of the lower Kosi river basin in India. They found fuzzy logic more accurate in predicting flood susceptibility, despite the simplicity of the frequency ratio model. They devised a hybrid method incorporating both models, producing an accurate flood susceptibility map.

The study in Ghaggar basin, Haryana, India reveals high flood risk due to insufficient river channel capacity. It emphasizes integrating hydrological and socioeconomic data for flood hazard assessment. Satellite imagery and census data aid in identifying vulnerable areas. GIS mapping enhances flood vulnerability analysis for local-level applications, assisting planners, insurers and emergency services[25].

Waterlogging poses significant challenges in urban areas, leading to damage and health issues. Using AHP and GIS, a waterlogging risk analysis was conducted for Patiala city, Punjab. Criteria like elevation, slope, land use and soil type were assessed to create a risk map[5]. Five zones were identified, aiding decision-makers in addressing flood risks.

Land suitability assessment for sugarcane cultivation in Bijnor district, India utilized ten criteria such as rainfall, texture and slope etc. Weighted multi-criteria evaluation in GIS, employing fuzzy analytical hierarchy process, determined suitability. Results categorized areas as highly, moderately, marginally suitable, or unsuitable. Majority of cultivable land was highly suitable, emphasizing attention to areas needing improvement like Nagina, Najibabad and Bijnor sub-districts[9].

The Ghaggar river basin in northern India faces recurrent flash floods despite its semi-arid/arid nature. Due to limited flood-related data, identifying flood risk zones is crucial. This study proposes graph theory for this purpose, utilizing spatial data like elevation, land cover and population. Results show that graph theory accurately identifies flood risk zones with 100% of the area deemed high risk, surpassing AHP[6].

The present study addresses the need for comprehensive flood risk assessment and management in Ferozepur district, Punjab, exacerbated by urbanization, climate change and inadequate infrastructure. Focusing on vulnerable areas along the river Sutlej and challenges faced by protective structures like the flood protection bandh upstream of Harike head works, it integrates GIS and AHP methodologies. By analyzing spatial data on terrain, hydrology, land use and infrastructure vulnerabilities, the study aims to provide decision-makers with insights for proactive disaster preparedness and response.

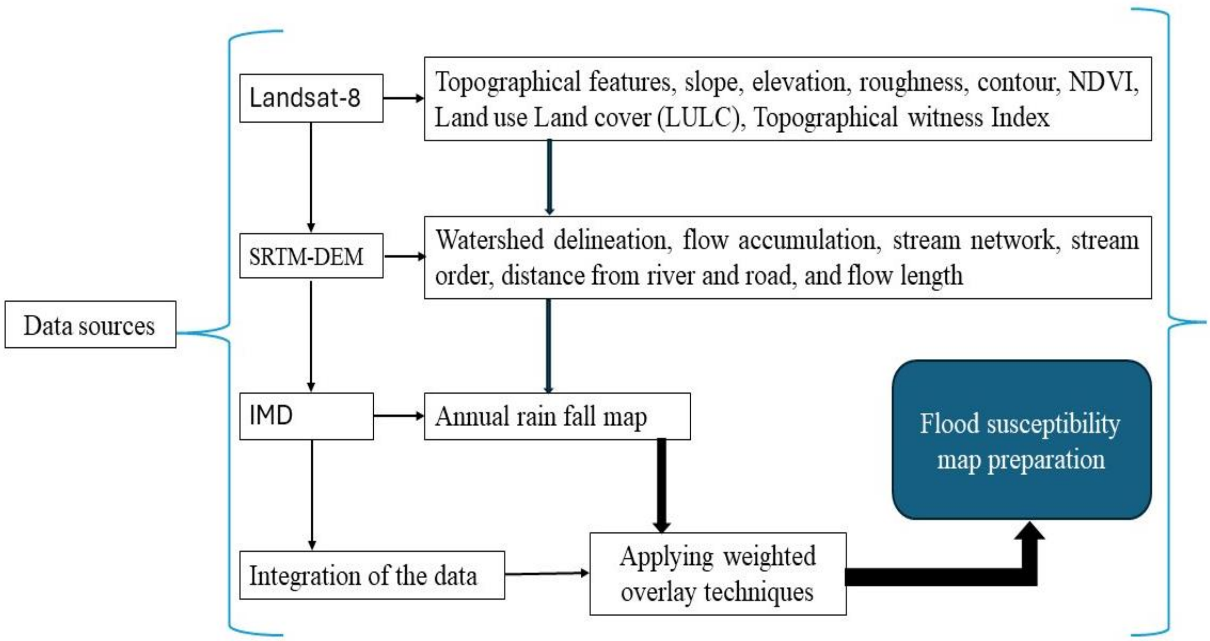

Fig. 2: Methodology chart for flood susceptibility assessment in Ferozepur district

Material and Methods

Data acquisition and processing were conducted using multiple sources to develop thematic maps for flood susceptibility assessment in Ferozepur district. Landsat-8 imagery from USGS website, SRTM-DEM data and rainfall data from IMD were collected. Landsat-8 data were utilized to generate thematic maps including elevation, slope, contour, roughness, drainage density, land use-land cover and lithology. SRTM-DEM data facilitated the delineation of watersheds, flow accumulation analysis, identification of stream networks, stream order, distances from rivers and roads and estimation of flow lengths.

By integrating these thematic maps, a comprehensive flood susceptibility map for Ferozepur district was created. The methodology flow chart, outlining the sequential steps of data collection, processing and integration, is presented in figure 2.

Topographical features of Ferozepur district: Flood susceptibility mapping in Ferozepur district, Punjab, is an integrated approach utilizing advanced techniques such as GIS and the AHP to meticulously assess vulnerable areas and develop effective mitigation strategies. The elevation analysis delineates the region into five distinct classes spanning from 0 to 250 meters, offering critical insights into flood-prone low-lying regions crucial for targeted intervention measures. Complementing this, the slope classification method categorizes terrain into five degrees, enabling the identification of areas characterized by steep gradients, which significantly influence surface runoff dynamics during flood events.

Moreover, aspect assessment further enriches the analysis by categorizing slope orientations (Fig. 3), thereby impacting sunlight exposure and water flow patterns, ultimately contributing to a comprehensive understanding of flood dynamics[10-13,26]. Incorporating roughness analysis, which incorporates maximum, minimum and mean values (Fig. 4), adds another layer of detail by highlighting surface irregularities that can profoundly affect floodwater flow patterns. Leveraging Landsat-8 imagery supplements this analysis by providing invaluable insights into land cover changes over time, offering a dynamic perspective crucial for accurate flood risk assessment.

Flow characterization: The provided input data offers crucial insights into various thematic maps essential for developing accurate flood susceptibility mapping in Ferozepur district, Punjab State. Findings reveal significant aspects such as the maximum basin area of 1939 sq. km, categorized into 5 groups with a maximum value of 530,000, highlighting potential flood-prone zones. Flow accumulation values vary, indicating areas susceptible to flooding. Flow direction is classified into 5 classes with values ranging from 1 to 130, aiding in identifying vulnerable areas[16,17]. The stream network map illustrates waterway interconnectedness, vital for predicting flood propagation routes. Annual rainfall distribution, with 70% occurring from July to September, provides crucial data for flood risk assessment. Line density, categorized into 5 groups, with the highest density observed at 1.23, offers insights into flow concentration. Stream density calculations reveal areas with higher concentrations of streams, indicating potential flood risk zones.

Considering Ferozepur's flat terrain and influence by the Sutlej river, these thematic maps are indispensable for delineating flood-prone areas accurately. Integrating local geographic and climatic factors including wind action and soil composition, is vital for comprehensive flood risk assessment. By leveraging these findings and accounting for nuances, effective flood susceptibility mapping can be conducted, enabling informed decision-making and robust risk mitigation strategies tailored to the district's specific vulnerabilities.

Understanding flood susceptibility involves a multifaceted approach, necessitating the development of various thematic maps to grasp the intricacies of the region's hydrology and terrain. Crucial thematic maps such as flow basin, flow accumulation, flow direction, stream network, annual rainfall map, line density and stream density are pivotal in this endeavour (Fig. 5)[14,15].

The flow basin delineates the extent of the area affected by flooding while flow accumulation maps provide insights into the volume of water accumulating in different areas, aiding in pinpointing high-risk zones. Flow direction maps categorize flow directions, guiding floodwater paths and potential inundation areas. Stream network maps depict the interconnectedness of waterways, aiding in understanding flood propagation routes.

Annual rainfall maps offer critical data on precipitation patterns, crucial for assessing flood risk. Line density and stream density maps provide quantitative measures of flow concentration, aiding in identifying areas prone to intense flooding.

Further underscoring the importance of comprehensive mapping techniques and understanding the climate dynamics including the distribution of rainfall and seasonal variations, are vital for accurate flood risk assessment. As the Satluj river traverses the district, delineating borders and influencing the region's hydrology, its behaviour and interaction with other water bodies must be thoroughly analysed.

Results and Discussion

Integrating Geospatial Parameters for Flood Susceptibility Mapping - Land Use Land Cover (LULC), NDVI and TWI: The LULC, normalized difference vegetation index (NDVI) and topographic wetness index (TWI) are essential geospatial parameters utilized in developing flood susceptibility mapping[18].

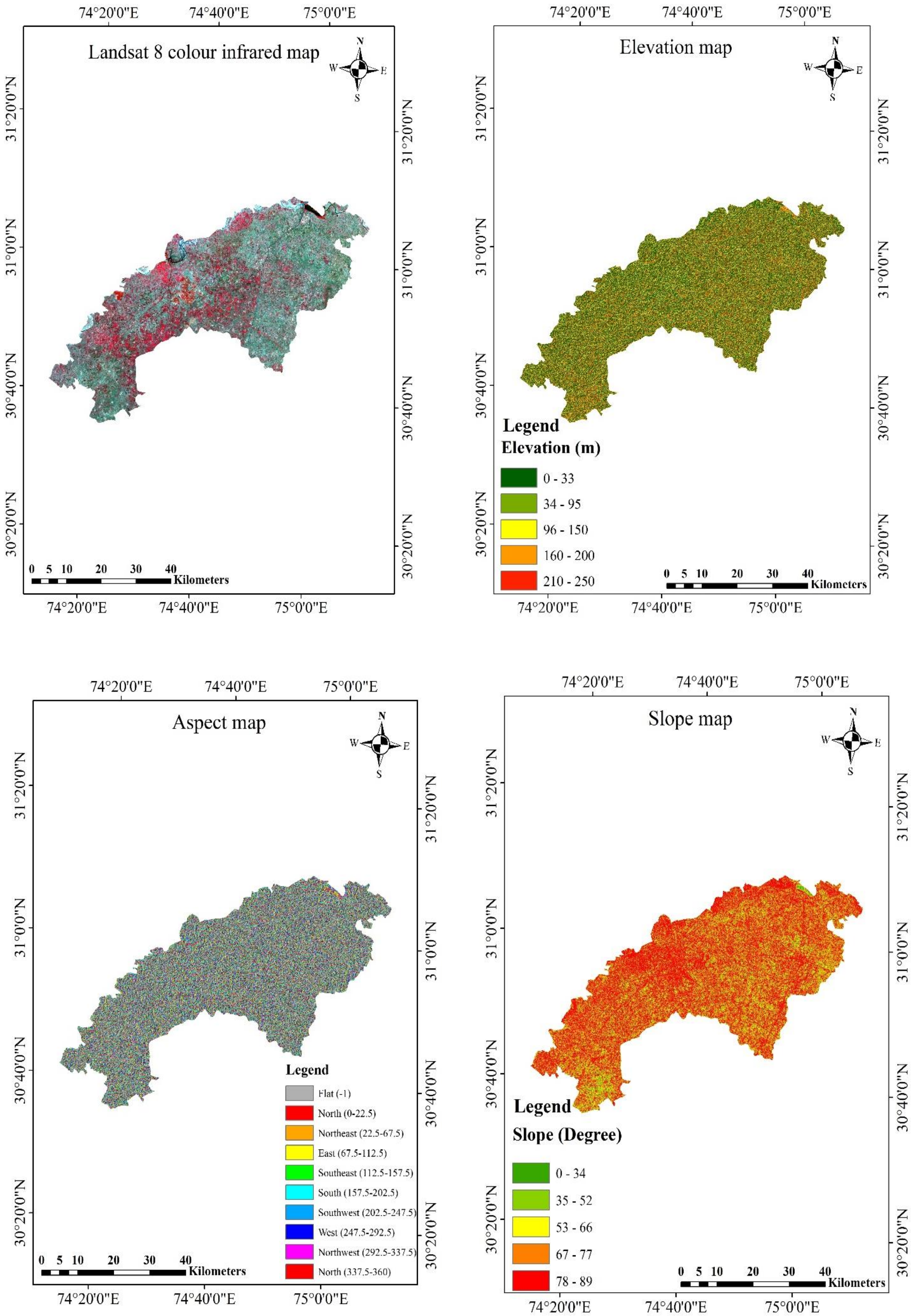

Fig. 3: Topographical features mapping of Ferozepur: Landsat 8, elevation, aspect and slope respectively.

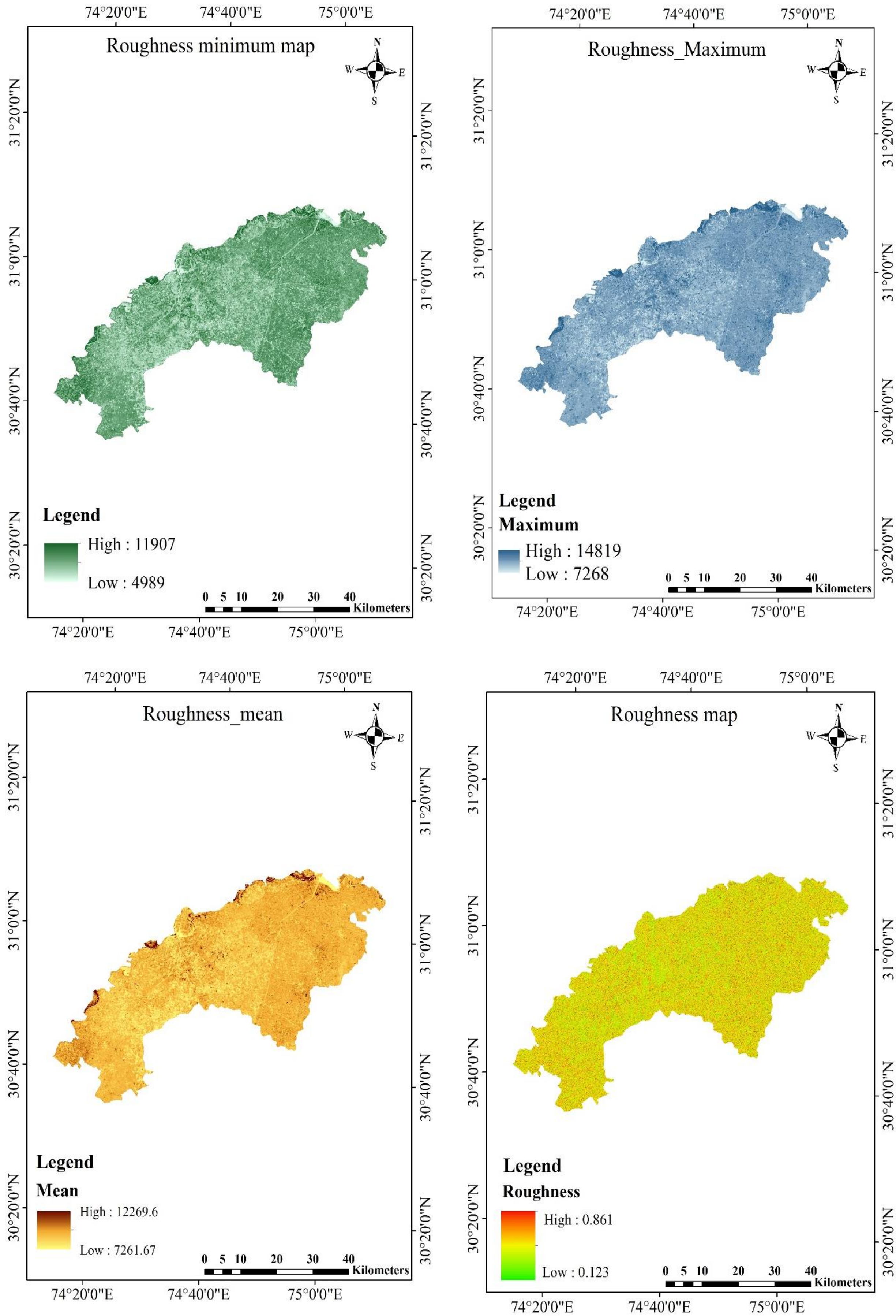

Fig. 4: Roughness mapping of the Ferozepur district, Punjab State

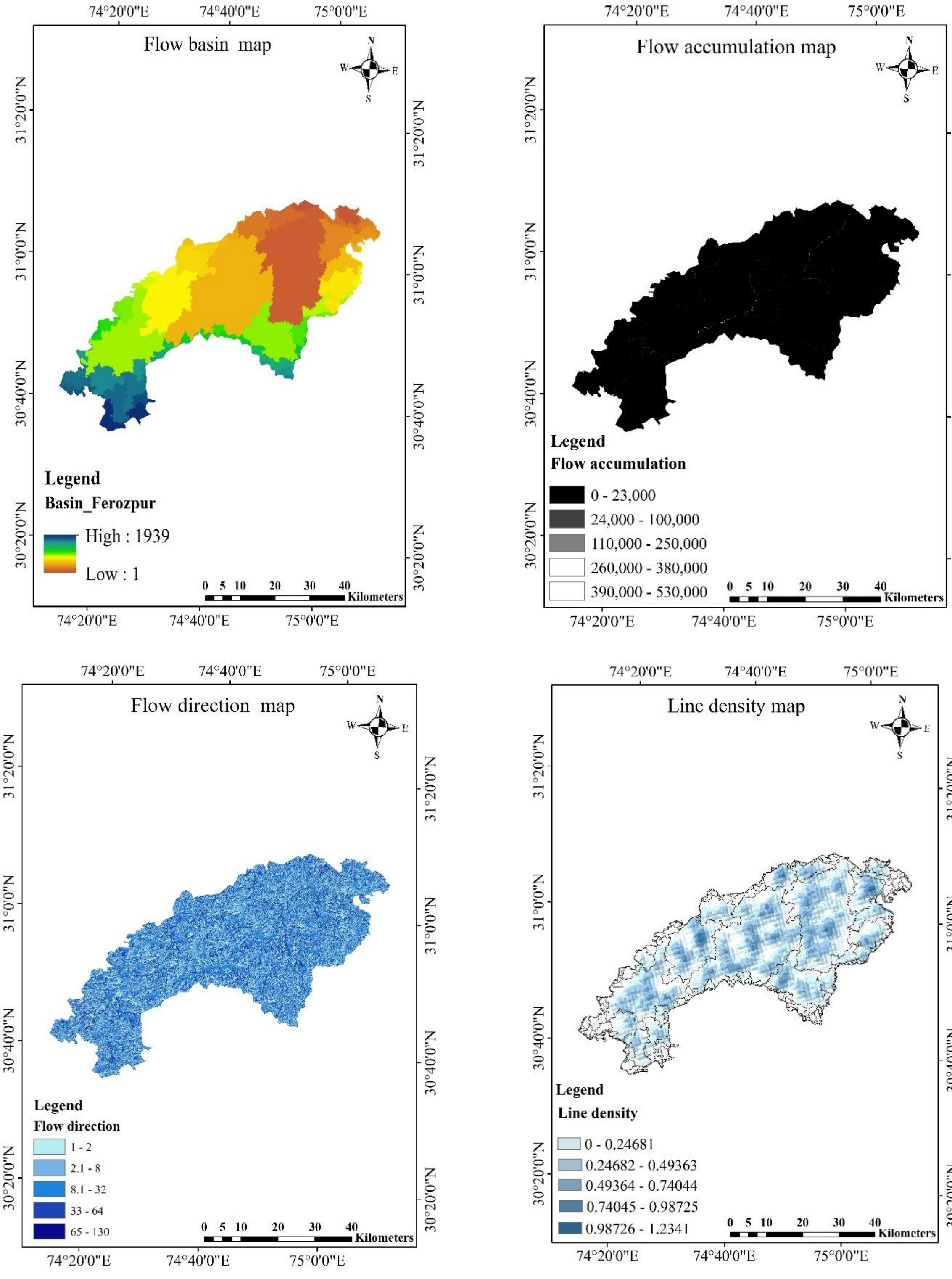

Fig. 5: Flow characteristics in term of basin, accumulation, flow direction and line density mapping

LULC data provides valuable information on the distribution of land cover types, aiding in identifying areas prone to flooding based on surface characteristics such as urbanization, agriculture, or natural vegetation. NDVI, derived from satellite imagery, measures vegetation density and health, offering insights into vegetation cover that influences water absorption and runoff, thus impacting flood susceptibility[22]. NDVI is calculated using the equation 1 where 'B' stands for band of the landsat-8 data.

$$NDVI = \frac{B5-B4}{B5+B4} \tag{1}$$

TWI, calculated from digital elevation models, assesses terrain wetness, highlighting areas with higher water accumulation potential, crucial for understanding flood dynamics[20,21] Integrating these parameters allows for a comprehensive assessment of flood susceptibility, considering both human-induced and natural factors, thereby enhancing the accuracy and effectiveness of flood risk mapping efforts. The TWI is a metric used to assess water flow accumulation and gravitational flow down slopes within drainage basins[21]. It is closely linked to soil moisture conditions as indicated by Gokceoglu et al[4]. TWI is calculated by combining area (a) and slope length (L) where slope angle (L) is determined using tangent.

$$TWI = Ln \frac{a}{tab\ (\beta)} \quad (2)$$

TWI serves as an environmental indicator, reflecting variations in soil properties such as organic matter, nutrients and texture. Different methods were used to estimate TWI, considering catchment area and slope[19,22].

Researchers have found that the choice of flow algorithm significantly affects the relationship between TWI and observed soil moisture. Consequently, sensitivity analyses were conducted using various flow algorithms and slope calculation methods[19].

In this investigation, a TWI map was created using ArcGIS and was classified into five categories based on the intensity of wetness. Through the interpretation of topographical data, various LULC have been discerned (Fig. 7). Human activities impact groundwater dynamics, evident in diverse land use patterns. Using GIS and Landsat-8 data, researchers mapped land use and cover changes influenced by local economics[33,34]. Categories include water bodies, vegetation, settlements etc. Each was prioritized based on water retention. Agricultural land and water bodies were prioritized while communities and uninhabited areas received lower priority. The thematic maps of distance from river, NDVI, TWI and annual rainfall map of the year 2022 are shown in figure 6.

Drainage density and distance from river mapping: The drainage pattern of a terrain, influenced by lithology and various factors like slope and rock resistance, reflects both surface and subsurface characteristics, crucial for understanding landform evolution[27-29]. Using GIS and DEM, a drainage density map was created for the Ferozepur district, categorized into five levels. Identifying flood-prone areas relies on proximity to rivers and surface water with overflow areas near rivers most vulnerable. ArcGIS tools, specifically buffering techniques are used to map flood potential zones, highlighting susceptible areas, especially around rivers and low-lying terrain.

ArcGIS also aids in calculating river length, essential for river geomorphology studies, helping understand river dynamics and management. River length, crucial for accurate assessments, is measured from the source to a specific point along the channel, derived from field data or vector-based topographic data.

Implementation of AHP techniques using GIS: Implementing AHP techniques within GIS offers a powerful approach for assessing flood susceptibility and devising effective risk management strategies. AHP serves as a structured decision-making tool, assigning relative weights to various spatial data layers based on their influences on flood susceptibility[21,30].

This is achieved through pairwise comparisons where each factor's importance is assessed relative to others, resulting in a hierarchical structure that reflects their respective impacts.

The significance of each factor is determined by evaluating pairwise comparisons, with criteria organized hierarchically and rated on a scale from 1 to 9 to denote varying degrees of importance (Table 1)[4,31]. 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) in equation 3.

$$A = \begin{bmatrix} a11 & a12 \ldots\ldots & a1n \\ a21 & a22 \ldots\ldots & a2n \\ an1 & an2 \ldots\ldots & ann \end{bmatrix}, a_{ii} = 1, a_{ij} = \frac{1}{a_{ij}}, a_{ij} \neq 0 \quad (3)$$

Despite inherent subjectivity in AHP's hierarchical structuring, its robustness makes it a widely recommended approach for regional studies. The process involves multiplying the weighted values of input raster by their corresponding cell values[32].

To facilitate weighted overlay analysis, all layers undergo reclassification, rasterization and resampling to ensure uniform pixel size and labelling. In this research, GIS was utilized employing the weighted overlay technique (WOT), with ten input layers utilized for overlay analysis using the mathematical equation provided as follows:

$$RI = \sum W_i R_j \quad (4)$$

In this context, 'W' represents the weight allocated to each layer and 'R' indicates the rank assigned to each theme within a layer. The variable 'i' denotes the number of layers while 'j' denotes the number of themes within each layer.

$$RI = W1 \times R1 + W2 \times R2 + W3 \times R3 + W4 \times R4 + W5 \times R5 + W6 \times R6 + W7 \times R7 + W8 \times R8 + W9 \times R9 + W10 \times R10 \quad (5)$$

where W1×R1, W2×R2 ………… W10×R10 are the weightage and ranking of LULC, elevation, TWI, slope, precipitation, NDVI, distance from river, aspect, drainage density+ and soil type respectively.

In the context of implementing AHP techniques using GIS, the AHP methodology, utilizing fundamental scales derived from Saaty[23] as illustrated in table 1, is employed to allocate weights to each vulnerability theme according to predefined standards. Specifically, the flood susceptibility map, illustrated in figure 7b, delineates vulnerability classes ranging from one to five where higher values denote lower susceptibility and vice versa.

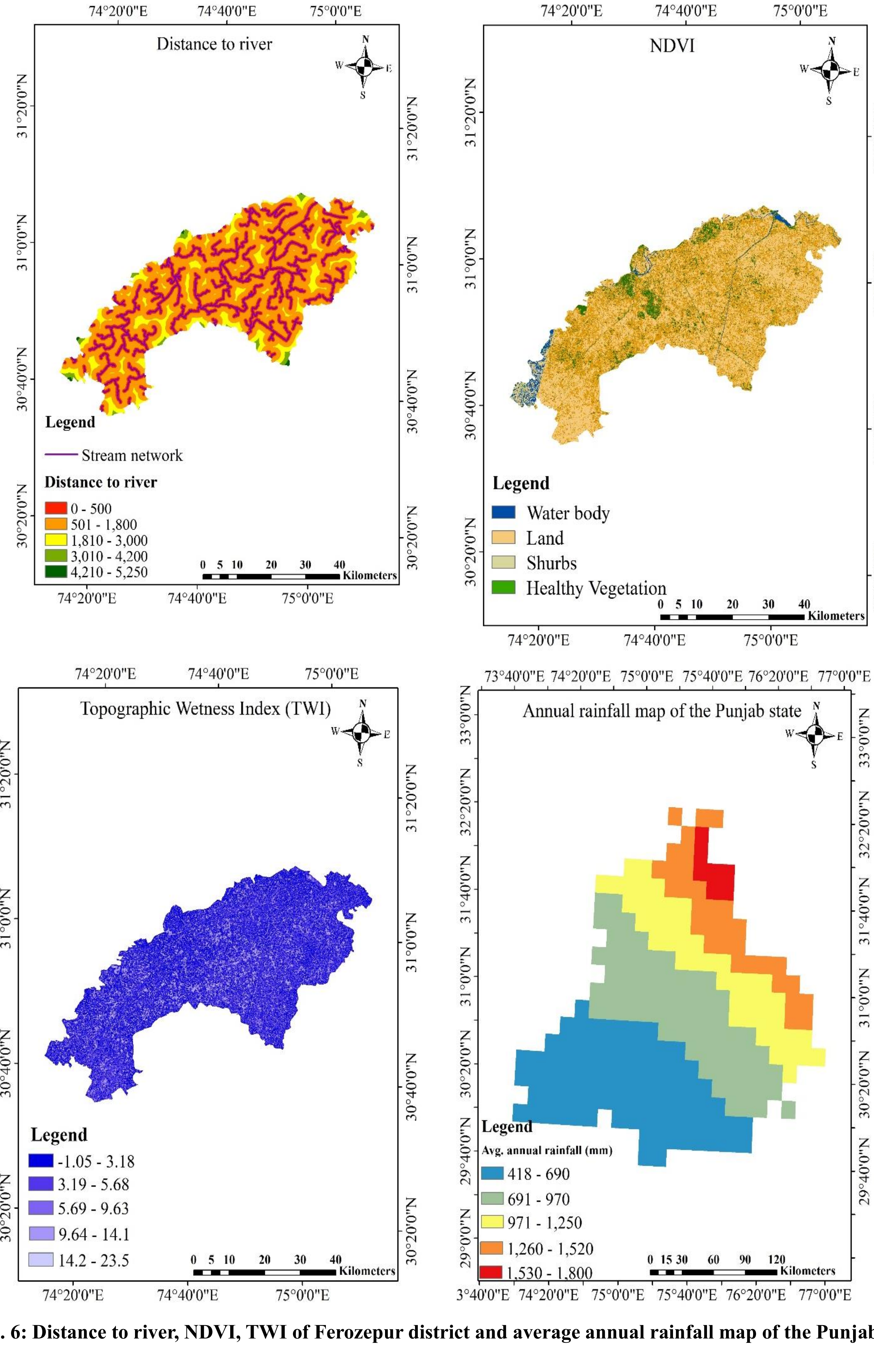

Fig. 6: Distance to river, NDVI, TWI of Ferozepur district and average annual rainfall map of the Punjab state

The allocated weights, outlined in table 2 provide insight into the percentage distribution across each vulnerability theme. This GIS-AHP approach for flood susceptibility analysis in Ferozepur district, Punjab state integrates drainage density, as discussed earlier, emphasizing a comprehensive approach that incorporates hydrological and spatial factors. By combining AHP-derived weights with GIS-based overlay methods, the mapping process gains depth, enabling a holistic comprehension of the region's vulnerability to potential flooding. Each factor underwent assessment based on its significance, receiving numerical ratings on a scale of 1 to 5. Subsequently, weights and ranks were assigned to each factor class, with higher values indicating a more substantial influence on flood occurrence, as detailed in Table 2.

Conclusion

This work aims to develop a flood susceptibility map for the Ferozepur district in Punjab State by employing GIS-AHP techniques. The initial phase involved gathering imagery, elevation data and rainfall information from pertinent sources. Thematic maps such as LULC and TWI played pivotal roles in flood susceptibility mapping, offering insights into land types and terrain characteristics respectively.

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		

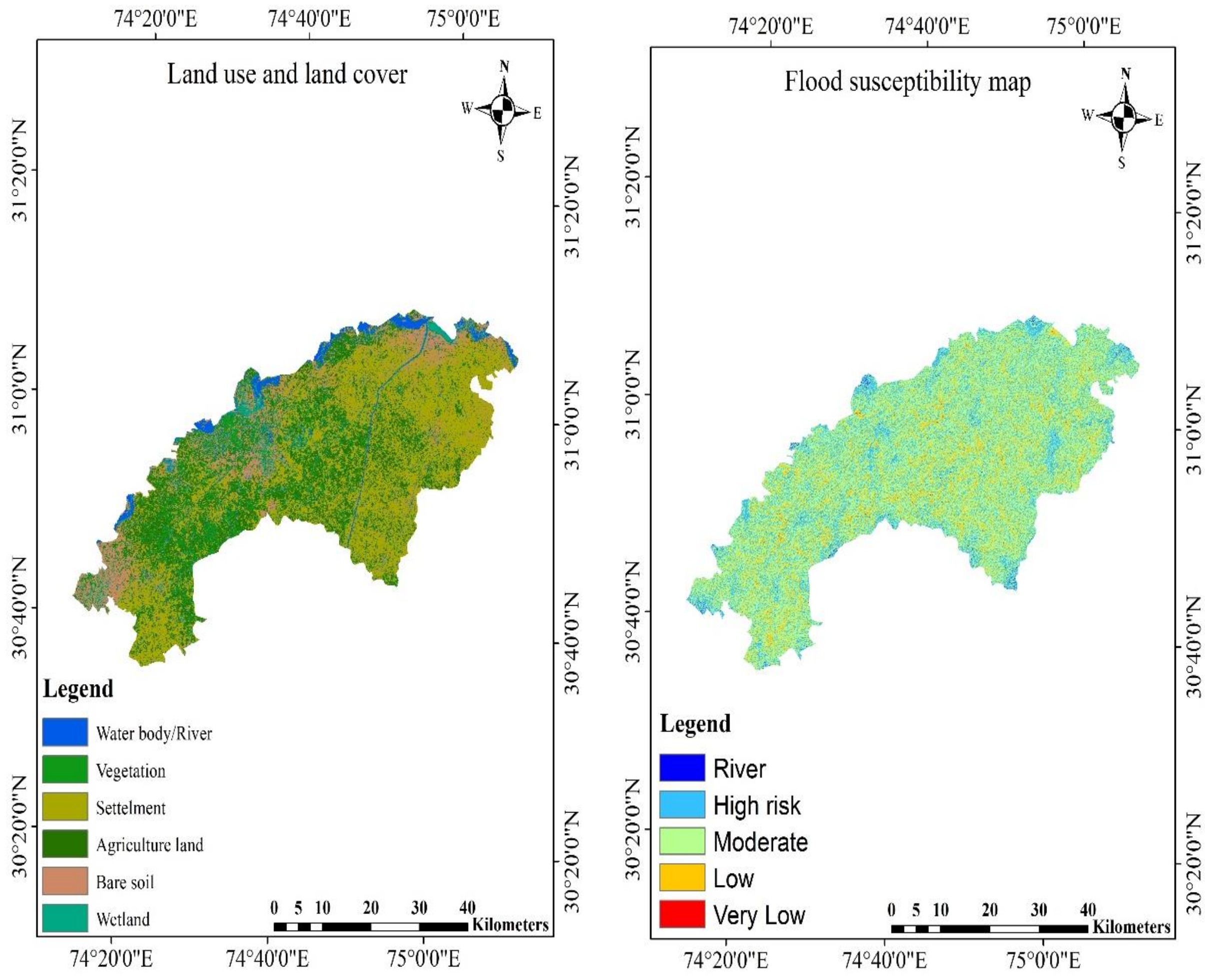

Fig. 7: a) LULC and b) flood susceptibility map of the Ferozepur district of Punjab State

Table 2
Ranking and weighting of susceptibility classes across various thematic maps.

Creation	Unit	Susceptibility class	Ratings	Weight (%)
LULC	Level	Very High	5	13
		High	4	
		Moderate	3	
		Low	2	
		Very Low	1	
Elevation	meters	Very High	5	12
		High	4	
		Moderate	3	
		Low	2	
		Very Low	1	
TWI	%	Very Low	1	12
		Low	2	
		Moderate	3	
		High	4	
		Very High	5	
Slope	degrees	Very High	5	11
		High	4	
		Moderate	3	
		Low	2	
		Very Low	1	
Precipitation	mm/year	Very Low	1	10
		Low	2	
		Moderate	3	
		High	4	
		Very High	5	
NDVI	Level	Very High	5	9
		High	4	
		Moderate	3	
		Low	2	
		Very Low	1	
Distance from River	meters	Very High	5	9
		High	4	
		Moderate	3	
		Low	2	
		Very Low	1	
		Low	2	
		Moderate	3	
		High	4	
		Very High	5	
Aspect	Level	Very High	1	8
		High	2	
		Moderate	3	
		Low	4	
		Very Low	5	
Drainage density	m/km	Very Low	1	8
		Low	2	
		Moderate	3	
		High	4	
		Very High	5	
Soil type	Level	Very High	5	8
		High	4	
		Moderate	3	
		Low	2	
		Very Low	1	

The AHP methodology was utilized to rank these thematic maps based on their significance and WOT was employed to assign weights to each map layer. The integration of these thematic maps culminated in the creation of a detailed flood susceptibility map for the district, delineating areas into low, moderate and high hazard zones. Vulnerable sites along the river Sutlej were identified including specific complexes and villages.

Furthermore, flood-prone areas in Zira Tehsil and Ferozepur Tehsil were accentuated, indicating the most sensitive villages in each region. In summary, the application of GIS-AHP techniques facilitated the development of a comprehensive flood susceptibility map, imperative for effective flood risk management and mitigation strategies in the Ferozepur district. Additionally, the identification of vulnerable sites and flood-prone areas offers valuable insights for disaster preparedness efforts.

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