

# AHP-based Susceptibility Analysis for Landslides in Fuman County, northwestern Iran

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Received: 07 February 2025 / Accepted: 17 April 2025 / Published: 28 April 2025

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**Abstract:** Landslides, multi-scale ground movements, significantly impact human lives and ecosystems, posing a major threat to rapidly growing regions. Effective sustainability planning is essential to mitigate these risks and support informed urban development and decision-making. This study focuses on assessing landslide hazards in Fuman County, Gilan Province, located in northwestern Iran. The research employs the Analytical Hierarchy Process (AHP) to classify landslide susceptibility, integrating various triggering factors such as topographic, geological, climatic, and anthropogenic variables. Data collection involved field surveys and analysis of remote sensing images, providing a comprehensive understanding of the region's risk profile. To ensure the accuracy of the results, the susceptibility map was validated using pixel-based assessments and remote sensing data fusion. These methods enhanced the precision of the hazard analysis, ensuring reliable identification of high-risk zones. Findings indicate that the most vulnerable areas are concentrated in the southern part of Fuman County, where the Alborz mountain range contributes to heightened susceptibility. This region's geological characteristics, combined with human activities and climatic conditions, exacerbate landslide risks. This study underscores the importance of hazard mapping and risk assessment in guiding sustainable development and disaster management strategies. The insights provided by this research can inform policymakers and urban planners in implementing effective mitigation measures to reduce potential damage and enhance resilience in landslide-prone areas.

**Keywords:** Landslide susceptibility, Geohazards, AHP, Fuman County, Iran.

## I. INTRODUCTION

Landslides are the downward and outward movement of materials along a slope, constituting one of the most significant natural hazards in mountainous regions globally (KC et al., 2022). These events encompass gradual to rapid displacement of materials on sloped surfaces, varying in scale and intensity, and are triggered by a combination of natural and

anthropogenic factors. Landslides rank among the most severe and destructive natural disasters. Iran, with its mountainous topography, high tectonic activity, seismicity, and diverse climatic and geological conditions, presents a high susceptibility to landslides. This hazard becomes particularly critical in areas near human settlements and infrastructure (Li et al., 2022).

Identifying and selecting the most influential factors contributing to landslides (known as triggering factors) is a foundational and crucial step in any analysis (Liu et al., 2023). Given the multifaceted nature of landslides, their occurrence can vary based on regional conditions, making it impossible to establish a universal standard for the selection of contributing factors (Chowdhury, 2023). However, most studies attribute landslides to natural causes and external triggering factors. Natural causes include geological conditions (lithology, geo-units, formations, hydrology, groundwater conditions, and their effects), slope geometry (slope angle, aspect, elevation, and curvature), and land cover (Nanehkaran et al., 2023). External triggers typically include rainfall, seismic activity, and human activities such as construction and agricultural practices in mountainous areas (Azarafza, et al., 2018). The mechanism of landslides often involves fine-grained formations (e.g., clay, marl, and shale) where water absorption disrupts the colloidal structure, detaching soil from the main mass and causing movement downslope under gravity (Van Westen et al., 2008). Importantly, landslides are among the disasters that can be mitigated through hazard assessment and the identification of high-risk areas (Pourghasemi et al., 2018). By predicting zones with significant landslide potential, proper planning and preventive measures can minimize the resulting economic and human losses (Asmare & Tesfa, 2022).

Several methods are available for this purpose, with landslide hazard zoning being among the most effective (KC et al., 2022). Hazard zoning involves mapping areas with similar probabilities of occurrence within a specific timeframe, dividing the terrain into zones of varying risk levels (ranging from very low to very high). Considering the substantial loss of life caused by landslides worldwide, predicting landslide-prone areas is essential (Hanifinia & Abakari, 2023).

Landslide susceptibility assessment plays a vital role in understanding and mitigating the risks associated with landslides. It involves identifying areas prone to landslides based on specific triggering factors and providing actionable insights for sustainable development and disaster management (Nanehkaran et al., 2023). Various methods are employed for such assessments, ranging from statistical approaches to machine learning and expert-based techniques, each offering unique strengths and challenges (Marjanović et al., 2011). Statistical models, including logistic regression, multivariate regression, and frequency ratio, are widely used for landslide susceptibility mapping (Reichenbach et al., 2018). These models analyze the relationships between landslide occurrences and their causal factors, such as slope angle, geology, rainfall, and vegetation cover (Hong et al., 2016).

The primary advantage of statistical methods lies in their ability to quantify the likelihood of landslides based on historical data, enabling more objective evaluations (Pourghasemi et al., 2012). Expert-based methods, such as the Analytical Hierarchy Process (AHP) and Fuzzy-AHP, rely on expert knowledge to rank and weigh contributing factors. These approaches are particularly effective when historical data is sparse or unavailable (Bahrami et al., 2021). AHP, for example, allows experts to systematically compare factors through pairwise comparisons, producing a weighted ranking that reflects the relative importance of each factor in landslide susceptibility (Zhao et al., 2017).

Conducting landslide susceptibility assessments is crucial for several reasons. First, it helps identify high-risk areas, allowing policymakers to prioritize regions for intervention (Saygin et al., 2023). Second, it provides a foundation for developing early warning systems, which can save lives and reduce property damage (Cengiz & Ercanoglu, 2022). Finally, susceptibility maps inform sustainable land-use planning, guiding infrastructure development and reducing environmental degradation (Reichenbach et al., 2018). The AHP method offers several distinct advantages for landslide susceptibility assessment. Its flexibility in integrating qualitative and quantitative data makes it suitable for diverse landscapes and scenarios (Okoli et al., 2023). By involving experts in the decision-making process, AHP ensures that local knowledge and experience are incorporated into the analysis, enhancing the reliability of the results (Marjanović et al., 2011).

A key strength of AHP lies in its systematic structure, which breaks down complex problems into smaller, more manageable components (Agrawal & Dixit, 2022). This hierarchical framework simplifies the process of evaluating multiple factors, such as slope, soil type, rainfall, and human activity, making it easier to assess their contributions to landslide risk (Akshaya et al., 2021). Moreover, AHP is relatively simple to implement compared to advanced statistical or machine learning models. It requires fewer computational resources and can be applied even in data-scarce regions (Abdi et al., 2021). This accessibility makes it a practical tool for decision-makers and researchers working in developing countries or areas with limited technological infrastructure (Reichenbach et al., 2018).

## II. AHP APPLICATION IN LANDSLIDE SUSCEPTIBILITY

The AHP is a decision-making tool that has gained significant traction in environmental and geohazard studies, particularly for landslide susceptibility assessment (Lyu et al., 2018). Developed by Thomas L. Saaty, AHP excels in systematically analyzing complex problems by structuring them into a hierarchy and assigning weights to criteria (Yoshimatsu & Abe, 2006). Its flexibility and precision make it ideal for evaluating landslide susceptibility, which involves multiple interrelated factors (Myronidis et al., 2016). One of the major strengths of AHP lies in its ability to integrate diverse data sources, such as geological, topographical, climatic, and anthropogenic factors. These variables often interact in nonlinear ways, contributing to landslide occurrences. AHP simplifies this complexity by allowing experts to assign weights to each criterion based on their relative importance, ensuring a robust prioritization process (Panchal & Shrivastava, 2022). This is particularly crucial in landslide-prone areas, where understanding triggering factors can significantly reduce risks (Reichenbach et al., 2018).

AHP's multi-criteria decision-making framework enhances its applicability in landslide susceptibility studies. In practice, a hierarchical structure is created, starting with the goal (landslide susceptibility assessment), followed by various criteria and sub-criteria such as slope, rainfall, land use, and soil type (Tyagi et al., 2022). This structure allows for systematic evaluation, ensuring no critical factor is overlooked. The pairwise comparison matrix, a core feature of AHP, further ensures that expert judgments are quantitatively incorporated into the analysis (Lyu et al., 2018). Field data collection and historical landslide records play a pivotal role in calibrating AHP models. By comparing real-world occurrences with model predictions, researchers can fine-tune the weightage assigned to different factors (Mandal & Mandal, 2018). This iterative process enhances the reliability of the susceptibility maps generated. Moreover, the integration of Geographic Information Systems (GIS) with AHP has revolutionized its application, enabling spatial representation of landslide-prone areas with high accuracy (Das et al., 2023).

The AHP is a highly versatile and effective method for landslide susceptibility analysis (Okoli et al., 2023). One of its primary advantages is its ability to integrate diverse and complex datasets into a structured decision-making framework. Landslide occurrences are often influenced by a combination of topographical, geological, climatic, and human-induced factors, each with varying levels of impact (Tyagi et al., 2022). AHP simplifies the assessment by assigning weights to these factors based on their relative importance, enabling researchers to prioritize critical variables accurately (Agrawal & Dixit, 2022). Another key advantage of AHP is its adaptability to different environmental contexts. Whether applied in mountainous regions dominated by steep slopes and fragile lithology or in urbanized settings where anthropogenic activities are prevalent, AHP can be tailored to reflect the specific conditions of a study area. This adaptability makes it a universally applicable tool for landslide susceptibility mapping, regardless of geographical or environmental variations (Abdi et al., 2021).

The integration of AHP with GIS significantly enhances its utility (Reichenbach et al., 2018). By combining the spatial analysis capabilities of GIS with the decision-making strength of

AHP, researchers can create detailed susceptibility maps that visualize high-risk zones effectively (Figure 1). These maps are invaluable for urban planners and policymakers in identifying areas that require immediate intervention, thereby supporting disaster risk reduction and sustainable development initiatives (El-Hamdouni et al., 2022). Despite its strengths, AHP has certain limitations. One notable drawback is its reliance on expert judgment for assigning weights to criteria, which can introduce subjectivity into the analysis (Pourghasemi et al., 2012). The accuracy of the results depends heavily on the expertise and perspectives of the individuals involved. While sensitivity analysis can partially address this issue, the inherent subjectivity remains a challenge, particularly in studies with limited access to multidisciplinary experts (KC et al., 2022). Another limitation is the potential for inconsistency in the pairwise comparison process, especially when dealing with a large number of criteria

and sub-criteria (Okoli et al., 2023). AHP requires consistency in judgments to produce reliable results. Inconsistencies can arise due to human error or biases, reducing the reliability of the final susceptibility map. While tools like consistency ratio checks are available, ensuring complete consistency can be challenging in complex studies (Das et al., 2023). Lastly, AHP may be less effective when dealing with datasets characterized by high uncertainty or variability (Marjanović et al., 2011). For instance, in regions where landslide triggers are poorly understood or data is scarce, AHP might struggle to provide accurate results. In such cases, combining AHP with machine learning or other quantitative methods can offer a more robust solution (Asmare & Tesfa, 2022). Despite these limitations, AHP remains a widely used and valuable tool in landslide susceptibility analysis due to its simplicity, flexibility, and practicality.

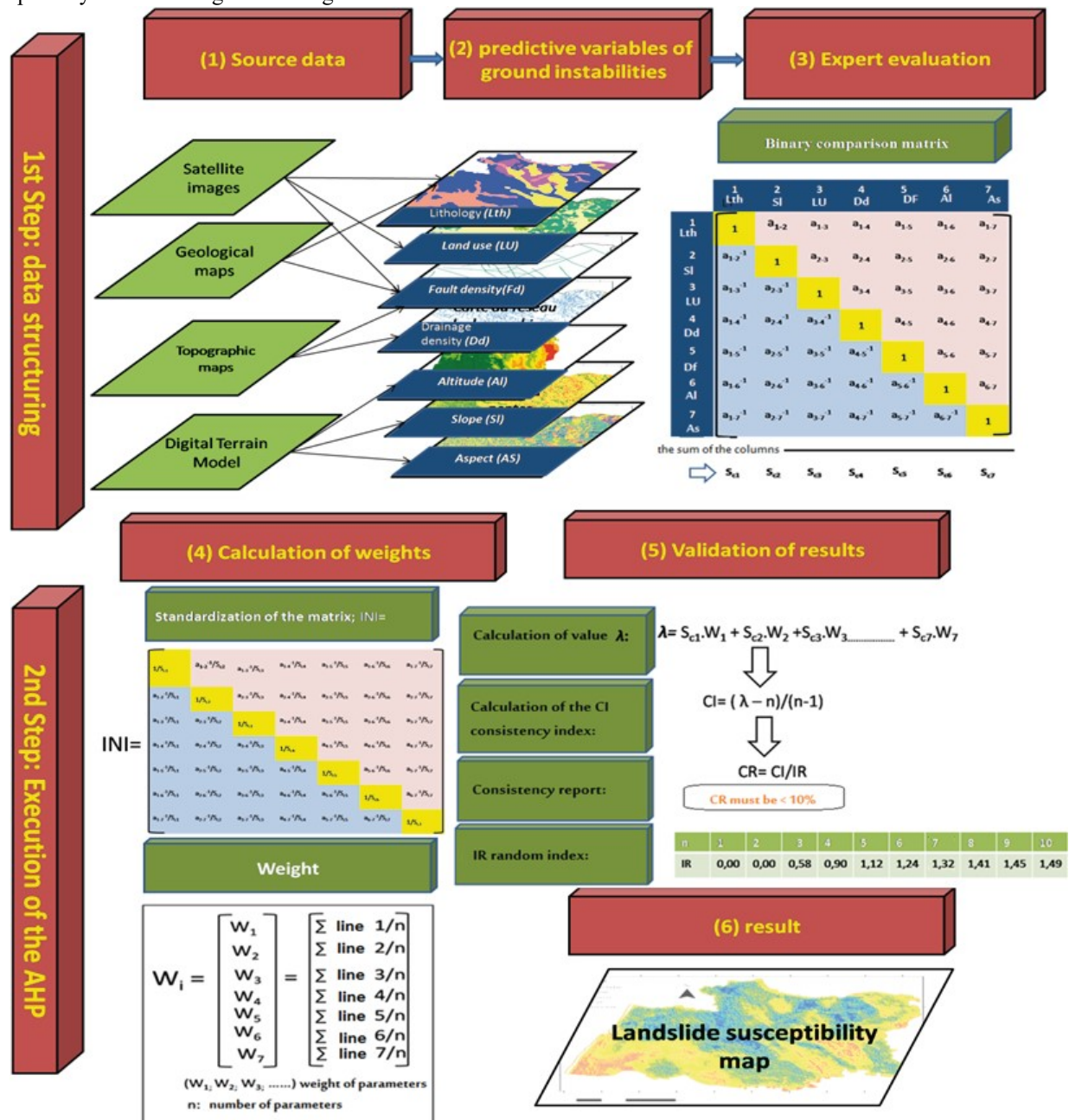


Fig. 1 The integration of AHP with GIS in landslide susceptibility mapping (El-Hamdouni et al., 2022)

### III. STUDIED LOCATION

Fuman County, located in the Gilan Province of northwestern Iran, is a region of considerable geographical and environmental significance. Figure 2 provides the location map of studied area. Known for its diverse landscapes, the county encompasses mountainous terrains, rolling hills, and flat plains, making it a microcosm of natural variety. Its location near the Alborz mountain range plays a pivotal role in shaping its geomorphological and climatic characteristics, as well as its susceptibility to various geohazards, including landslides (Nematollahi et al., 2018). The geomorphology of Fuman County is defined by its complex interplay of elevation gradients and natural drainage systems. The southern regions are dominated by rugged mountainous landscapes, primarily formed by the Alborz range (Razavi Pash et al., 2015). These areas exhibit steep slopes and deeply incised valleys, making them highly vulnerable to slope instability (Ardejani, 2019). The central and northern parts transition into gentler rolling hills and alluvial plains, which support agricultural activities. The diverse geomorphic settings not only dictate land use patterns but also influence the prevalence and distribution of natural hazards (Ardejani, 2015).

Fuman's climate is another critical factor contributing to its environmental dynamics (see Figure 3). The region experiences a humid subtropical climate, characterized by high annual precipitation levels, particularly during the fall and winter months. This significant rainfall, coupled with seasonal

snowmelt from the surrounding mountains, exerts pressure on the soil and slopes, heightening the risk of landslides (Jafari & Shahzeidi, 2018). Additionally, the region's warm summers and mild winters create a conducive environment for agriculture but also exacerbate soil erosion, a precursor to slope failures (Ardejani, 2015). Geologically, Fuman County lies within a tectonically active zone, influenced by the collision of the Arabian and Eurasian plates. This tectonic activity has resulted in diverse lithological formations, including sedimentary rocks such as sandstones, shales, and marls (Bahrami et al., 2021). Figure 4 is illustrated the geological map of studied area. The region's geology is further complicated by the presence of fault lines and seismic activity, which destabilize slopes and weaken rock structures over time. The combination of weak lithology, tectonic movements, and intense precipitation renders certain areas, particularly in the southern mountainous zones, highly susceptible to landslides (Sabouri et al., 2023). Geohazards are a pressing concern for Fuman County, with landslides being one of the most frequent and destructive phenomena. The high-risk zones are often located in regions where deforestation and agricultural expansion have disrupted the natural stability of slopes. Human activities, such as road construction and improper land use practices, further aggravate the problem, leading to increased landslide occurrences (Jafari & Shahzeidi, 2018). The southern areas, influenced by the Alborz range, are particularly prone to landslides due to their steep topography and unstable geological conditions (Nematollahi et al., 2018).

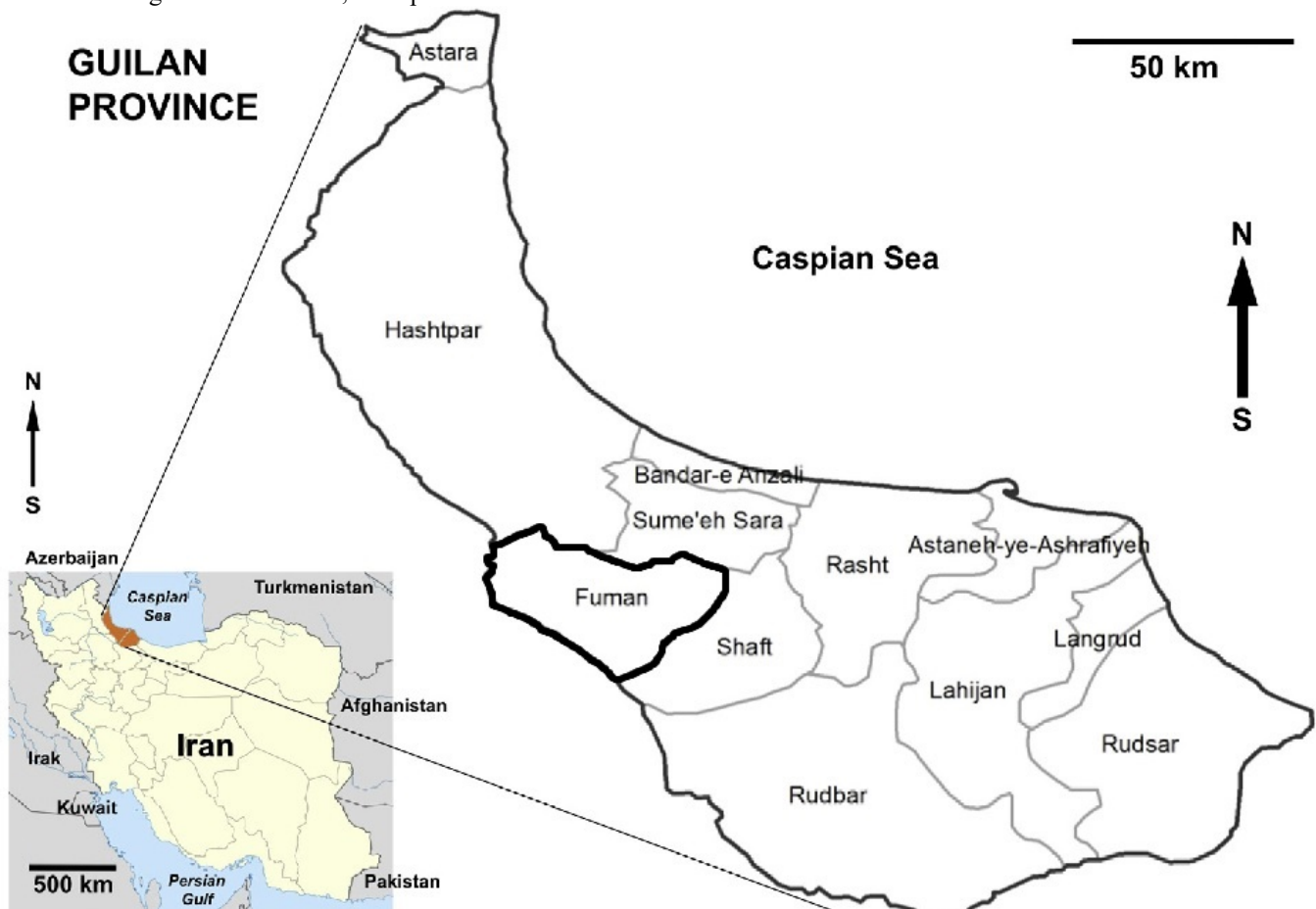


Fig. 2 Location of studied area based on Digital Elevation/Terrain Model (DEM) data (Ashrafi et al., 2015)

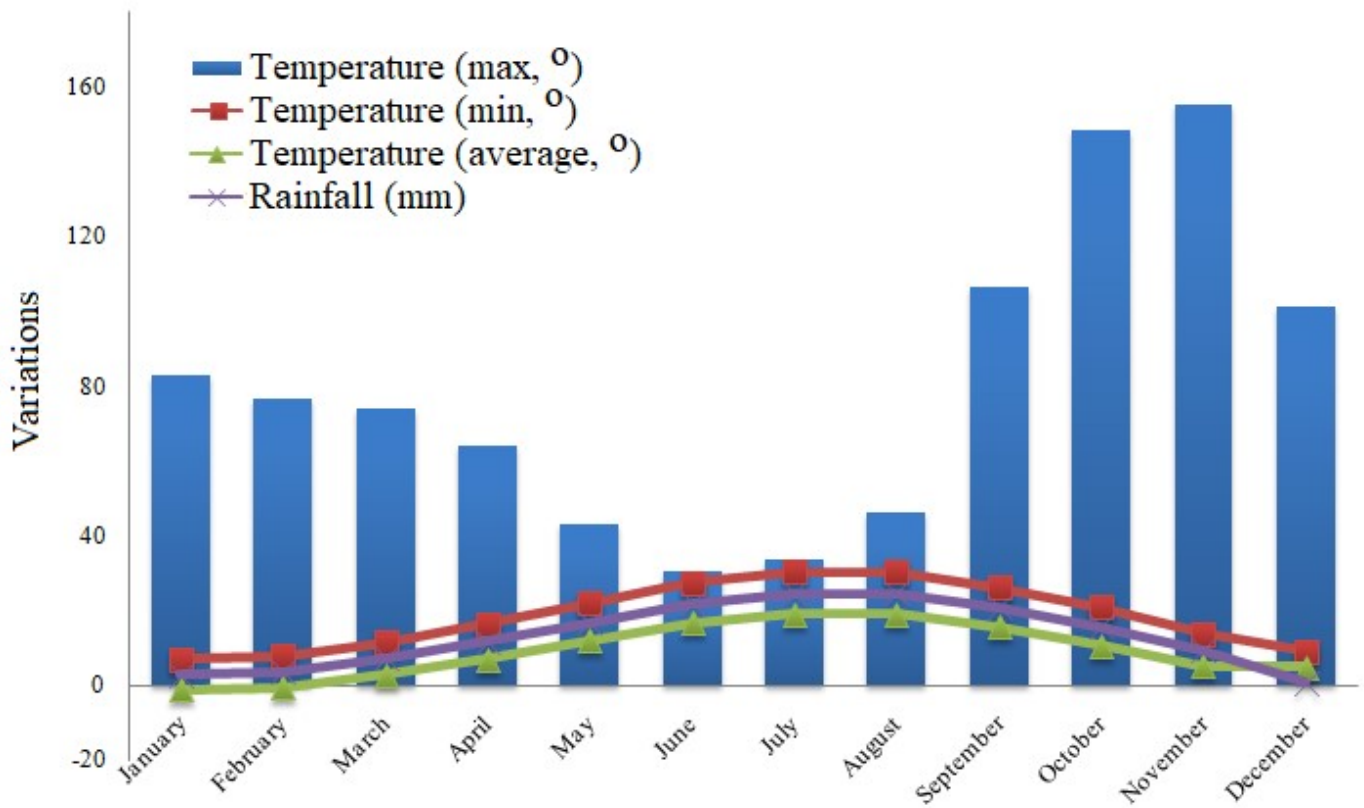


Fig. 3 Rainfall and temperature variations for studied area (Iran Meteorological Organization, 2023)

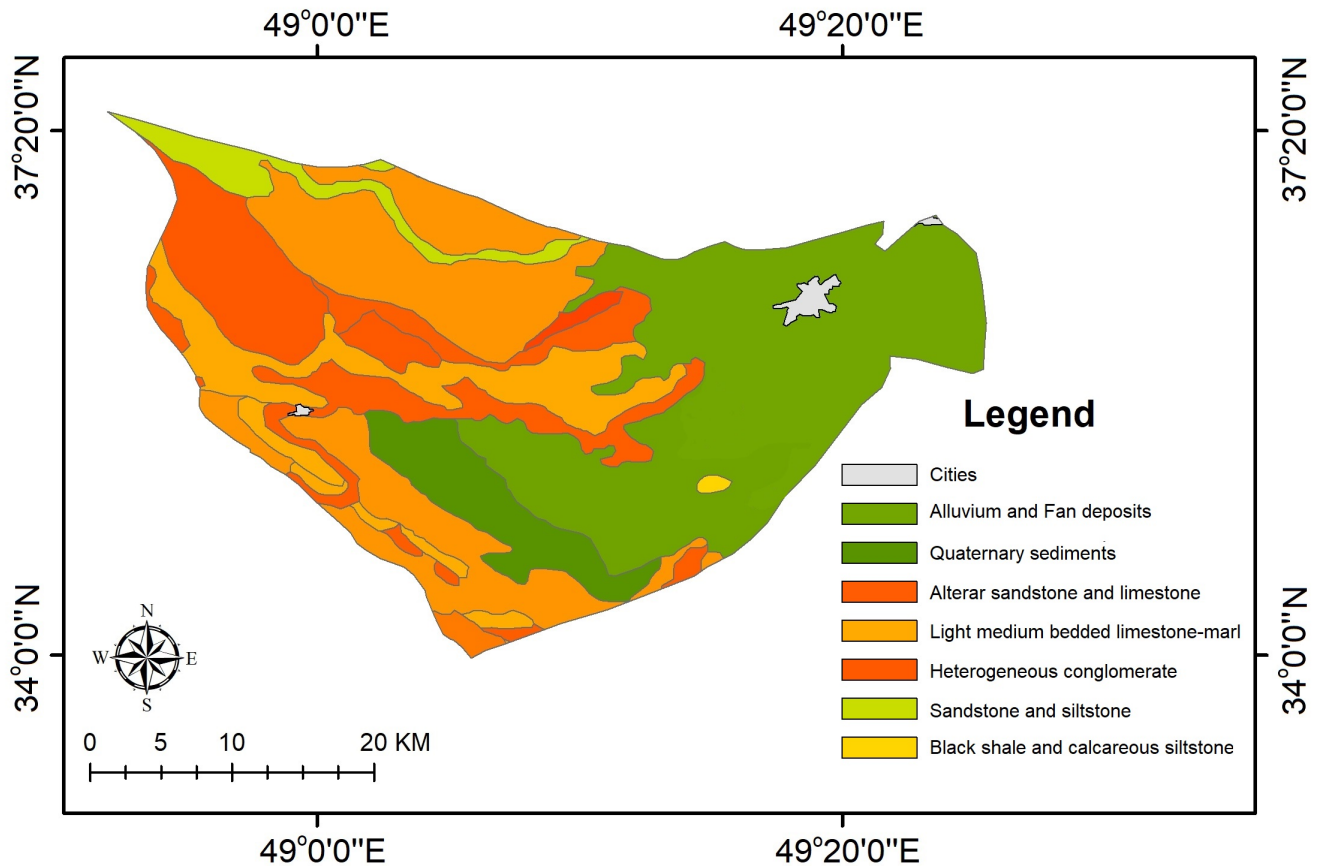
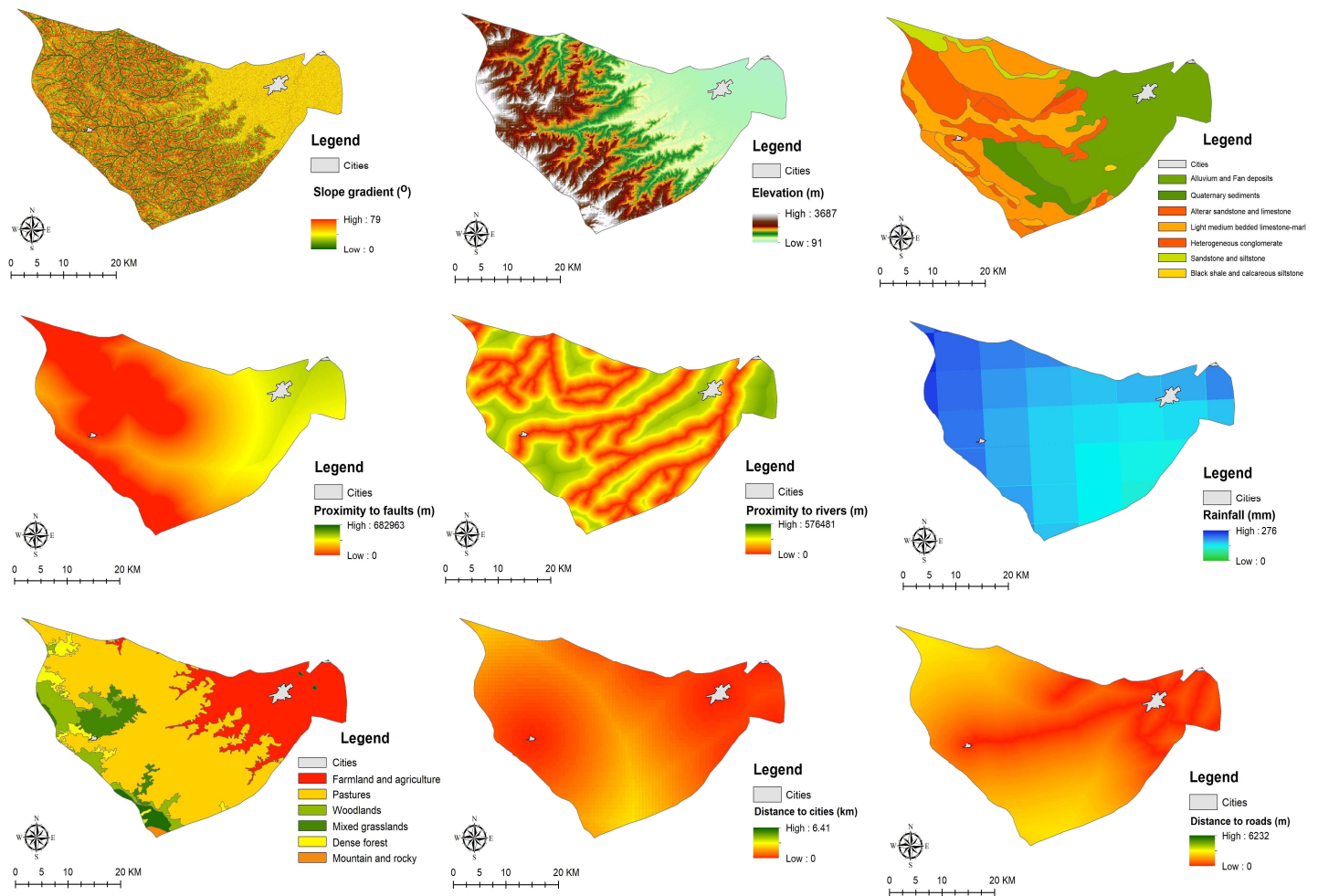


Fig. 4 Geological map for studied region (Geological Survey and Mineral Exploration of Iran, 2009)



**Fig. 5** Triggering factors utilized in this study: (a) slope gradient (b) elevation, (c) geology, (d) proximity to faults, (e) proximity to rivers, (f) rainfall, (g) land-use, (h) distance to cities, (i) distance to the roads

Landslides in Fuman County pose significant risks to both human settlements and the natural ecosystem. The transportation infrastructure is often disrupted by debris flows, while agricultural lands suffer from loss of fertile soil. In extreme cases, landslides have caused displacement of local communities, emphasizing the need for effective risk assessment and mitigation strategies. Historical records indicate that landslides in this region are triggered by a combination of natural factors, such as heavy rainfall, and anthropogenic influences, highlighting the complex interplay between human and environmental systems. Fuman County's unique combination of geomorphological, climatic, and geological characteristics creates a dynamic yet challenging environment. While the region's natural beauty and fertile lands offer economic opportunities, they also underscore the need for sustainable land management practices. Understanding the intricate relationship between the county's physical features and its susceptibility to geohazards is essential for ensuring the safety and resilience of its communities. Effective planning and intervention can mitigate the impact of landslides, safeguarding both the region's inhabitants and its ecosystems. Triggering factors for landslides are environmental and anthropogenic variables that contribute to slope instability (Azarafza et al., 2018). The selection of these factors is a critical step in landslide susceptibility studies to ensure accurate hazard

mapping (Ardejani, 2015). In this study, factors were chosen based on their relevance to the region's geomorphological, geological, and climatic characteristics, as well as their documented association with past landslides. The selection process involved a comprehensive review of literature, field surveys, and analysis of remote-sensing images in Fuman County. Priority was given to factors with significant spatial and temporal variability that could influence slope stability.

Topographic attributes, particularly slope gradient and elevation, are primary contributors to landslide susceptibility. The steep slopes in the southern regions of Fuman, influenced by the Alborz mountain range, are inherently unstable and prone to landslides. A steeper gradient increases gravitational stress on the soil and rocks, making them more susceptible to failure. Elevation also plays a role, as higher-altitude areas often experience intense weathering, snowmelt, and runoff, all of which exacerbate slope instability. These topographic features were analyzed using high-resolution DEMs to identify high-risk zones accurately. The geology of Fuman County, comprising sedimentary rocks, marls, and sandstones, significantly affects landslide susceptibility. Weak lithological formations are more prone to weathering and erosion, reducing their cohesion and stability (Geological Survey and Mineral Exploration of Iran, 2009). Additionally, the region's tectonic activity, characterized

by fault lines, further destabilizes slopes. Fault zones act as zones of weakness, where stress accumulation can trigger landslides. By integrating geological maps and field observations, the study identified areas with vulnerable lithology and proximity to active fault lines as critical contributors to landslide susceptibility.

Fuman's humid subtropical climate, marked by high annual rainfall, is a major driver of landslides. Intense precipitation saturates the soil, increasing pore-water pressure and reducing shear strength, which often leads to slope failure. Seasonal snowmelt adds to this instability, particularly in higher-altitude regions. Data from meteorological stations (Iran Meteorological Organization, 2023) were utilized to assess the spatial distribution of rainfall. The integration of climatic factors into the analysis provided insights into the temporal patterns of landslide occurrences.

Human activities, including deforestation (urban development), agricultural expansion, and infrastructure development, significantly influence landslide susceptibility in Fuman County. Deforestation reduces root reinforcement, which plays a vital role in stabilizing slopes. Agricultural practices, particularly in hilly terrains, disturb the natural soil structure, while road construction often involves cutting into slopes, creating artificial instabilities. Land-use, distance to cities and distance to the roads maps were analyzed alongside historical landslide data to determine the impact of anthropogenic factors on slope stability. Figure 5 is provided the triggering factors that used in this study for providing the susceptibility map for Fuman County. Each of these triggering factors was integrated into the AHP to create a comprehensive landslide susceptibility map. The weight of each factor was determined based on its relative importance and contribution to past landslide events. For example, steep slopes and high rainfall areas were assigned greater weights due to their predominant role in triggering landslides in Fuman County. This multi-faceted approach ensured a robust analysis, allowing for the identification of high-risk zones and providing valuable insights for disaster management and urban planning.

#### IV. METHODOLOGY AND MODEL IMPLICATIONS

The methodology for assessing landslide susceptibility in this study is rooted in the AHP, integrated within a GIS framework. This combination allows for a structured, multi-criteria decision-making approach, tailored to the unique geophysical and environmental characteristics of Fuman County, Gilan Province, Iran. The study focuses on integrating diverse datasets to produce a comprehensive landslide susceptibility map, essential for informed urban planning and disaster management. The first step in the methodology involves data collection and preprocessing. Data were gathered from multiple sources, including field surveys, and remote sensing technologies. These datasets provided crucial information on topographic, geological, climatic, and anthropogenic factors contributing to landslide occurrences. Each factor was standardized and converted into thematic layers to ensure compatibility within the GIS environment.

AHP was employed to assign weights to these factors based on their relative importance in triggering landslides. Experts

**Table 1** The parametric weights for applied triggering factors

| Triggering factors    | Weights | Normalizations |
|-----------------------|---------|----------------|
| Slope gradient        | 0.352   | 0.345          |
| Elevation             | 0.377   | 0.410          |
| Geology               | 0.163   | 0.210          |
| Proximity to faults   | 0.245   | 0.265          |
| Proximity to rivers   | 0.263   | 0.300          |
| Rainfall              | 0.310   | 0.315          |
| Land-use              | 0.252   | 0.250          |
| Distance to cities    | 0.169   | 0.185          |
| Distance to the roads | 0.188   | 0.185          |

were consulted to perform pairwise comparisons of the criteria, assessing their influence on landslide susceptibility. For instance, factors such as slope gradient, soil type, and precipitation levels were given higher weights due to their significant role in slope instability. Consistency checks were conducted to validate the reliability of these judgments, ensuring that the weight assignment reflected a logical and consistent decision-making process. Table 1 is provided the parametric weights for applied triggering factors. Once the weights were determined, a weighted overlay analysis was performed within the GIS framework. This process involved combining the thematic layers using the calculated weights to generate a composite susceptibility map. The map was divided into five classes: very low, low, moderate, high, and very high susceptibility. These classifications provided a spatial representation of landslide risk, highlighting vulnerable zones across Fuman County.

Validation of the susceptibility map was a critical component of the methodology. Pixel-based assessments and data fusion techniques using remote sensing were utilized to verify the accuracy of the results. Historical landslide locations were overlaid on the susceptibility map to assess its predictive capability. The alignment of high-risk zones with known landslide events demonstrated the model's effectiveness in identifying vulnerable areas. In addition to its practical applications, the methodology highlights the value of combining expert judgment with quantitative analysis. While AHP introduces subjectivity through expert input, its structured framework ensures that decisions are grounded in a logical and systematic process. The integration of GIS enhances this approach, enabling precise spatial analysis and visualization of risk factors.

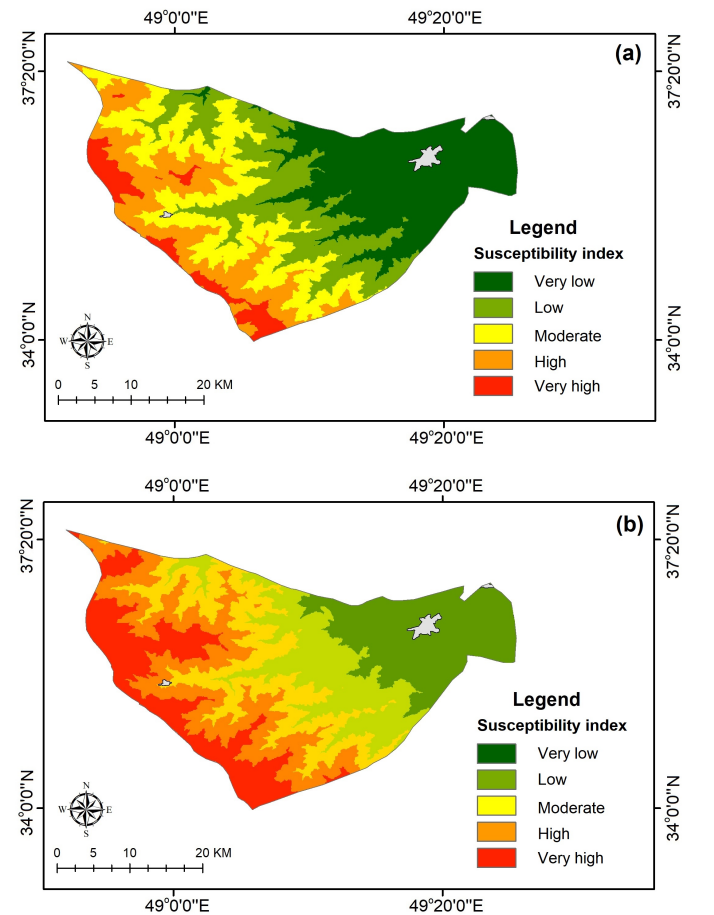
#### V. RESULTS AND DISCUSSION

The findings of the study revealed that the southern parts of Fuman County, particularly those influenced by the Alborz mountain range, exhibited the highest susceptibility. The region's steep slopes, fragile lithology, and intense precipitation, combined with anthropogenic activities such as deforestation and road construction, were identified as major contributors to landslide risks. These insights underline the importance of incorporating both natural and human-induced factors in hazard assessments. Figure 6 and Table 2 present the landslide susceptibility map and pixel-based validation results for this study. The methodological approach also has broader implications for landslide susceptibility studies in similar regions. The integration of AHP with GIS offers a replicable framework that can be adapted to various geographical contexts.

This adaptability makes the methodology suitable for regions with complex environmental settings and diverse landslide triggers, providing a scalable solution for hazard assessment. From a policy perspective, the results emphasize the need for targeted mitigation measures in high-risk areas. Urban planners and policymakers can use the susceptibility map to prioritize interventions such as slope stabilization, reforestation, and sustainable land use practices. The study's findings can also inform zoning regulations, ensuring that future developments are planned with an awareness of landslide risks. In conclusion, the methodology and model implications of this study showcase the effectiveness of combining AHP and GIS for landslide susceptibility analysis. The structured decision-making process, validated by comprehensive data integration and spatial analysis, provides valuable insights for sustainable development and disaster risk reduction. This approach not only addresses the immediate challenges of landslide hazards in Fuman County but also offers a robust framework for similar studies worldwide.

**Table 2** The Pixel-based verification for susceptibility analysis

| Susceptibility class | AHP-based assessment |            | Pixel-based verification |            |
|----------------------|----------------------|------------|--------------------------|------------|
|                      | Coverage             | Percentage | Coverage                 | Percentage |
| Very low             | 282                  | 2.38       | 120                      | 1.16       |
| Low                  | 870                  | 7.64       | 561                      | 3.25       |
| Moderate             | 1017                 | 10.47      | 1099                     | 15.21      |
| High                 | 1560                 | 23.59      | 1684                     | 29.80      |
| Very high            | 3687                 | 42.31      | 3687                     | 45.67      |



**Fig. 6** Landslide susceptibility map for Fuman County: (a) AHP, (b) Pixel-based

VI. CONCLUSION

This study highlights the critical need for comprehensive landslide susceptibility assessments to support sustainable urban development and disaster management strategies. By employing the AHP and integrating diverse factors such as topographic, geological, climatic, and anthropogenic variables, a detailed risk profile for Fuman County, Gilan Province, was established. The validation of the susceptibility map through pixel-based assessments and remote sensing data fusion ensured the reliability and accuracy of the findings, emphasizing the significance of advanced methodologies in hazard analysis. The results reveal that the southern regions of Fuman County, influenced by the geological complexities of the Alborz mountain range, are highly vulnerable to landslides. This vulnerability is further compounded by human activities and adverse climatic conditions, underscoring the pressing need for targeted mitigation strategies. The study provides actionable insights for policymakers and urban planners, enabling them to implement informed and effective measures to reduce landslide risks, protect human lives, and preserve ecosystems. Ultimately, the research underscores the importance of hazard mapping as a cornerstone for sustainable development in landslide-prone regions. By leveraging data-driven approaches and comprehensive analysis, this study contributes valuable knowledge to the field, fostering resilience and preparedness in vulnerable areas.

ACKNOWLEDGMENT

We extend our thanks to the reviewers for their meticulous attention to detail and constructive suggestions that greatly improved the quality of this manuscript. Your contributions have been instrumental in shaping this work.

AUTHORS' CONTRIBUTIONS

Alaleh Hamed and Sadeg Moharam Nejhad conducted the main data analysis, contributed to the data collection, preprocessing, and interpretation. Sadeg Moharam Nejhad was responsible for drafting the initial manuscript. Hassan Heydari Mofrad performed checks, supervision, conceptual guidance, and critical revision of the manuscript. All authors read and approved the final manuscript.

CONFLICT OF INTEREST

The authors have not disclosed any competing interests.

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