


Geosystem–ecosystem interactions and land use dynamics in western Tehran: A fuzzy logic–based geospatial assessment

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ABSTRACT

The accelerated urban growth of Tehran has introduced significant modifications to its underlying geosystems, with cascading effects on ecological patterns and land use dynamics. This research investigated the dynamic relationship between Tehran's geological evolution and its ecological conditions, focusing on how geosystems influenced the ecological dynamics of western Tehran, particularly regarding land use patterns. The novelty of this work lies in integrating geosystem variables (lithology [L], river proximity [R], and fault distribution [F]) into a fuzzy logic–based a land use (LU) change index, empirically validated through a network of control points. The research was conducted in the foothills of the Alborz Mountains and along the Vardij River. Data collection involved geological mapping, remote sensing, and field studies. The findings emphasized the critical role of geosystems in shaping ecosystems, revealing that significant land use changes occurred within a susceptible LU index range of 4.02 to 4.90, contrary to the belief that high LU indexes predominantly drive urban development. This transformation was influenced by the rugged topography and the optimization and vulnerability of the studied variables, highlighting the need for effective environmental management and conservation strategies in the face of increasing urbanization pressures. Ultimately, this study underscored that understanding the relationships between geosystems and ecosystems was essential for preserving the ecological integrity of western Tehran. By integrating geological factors into land use planning, stakeholders could better manage natural resources and protect the region's ecological heritage.

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1. Introduction

Urban ecosystems are increasingly shaped by the interplay between natural geosystem components and rapid anthropogenic pressures. While urban expansion has long been studied through socio-economic and environmental perspectives, recent research emphasizes the critical role of geological systems in guiding ecological dynamics and land use trajectories. These systems include lithology, river networks, and fault structures (Mandarino et al., 2023; Zhang et al., 2023). These variables define both opportunities and constraints for urban development, particularly in transitional landscapes where natural susceptibility interacts with human-induced change. Tehran, the capital

of Iran, exemplifies such dynamics. Its western sector, located along the foothills of the Alborz Mountains, has experienced unprecedented urban expansion over the past decades. Nonetheless, despite this rapid urbanization, few studies have systematically incorporated geosystem parameters into models of land use change and ecosystem vulnerability. Existing approaches often assume that urban development primarily occurs in zones of maximum suitability, overlooking the ecological importance of moderately susceptible areas where both resilience and fragility coexist. Tehran has been experiencing accelerated patterns of urban growth, while its location at the



confluence of significant geological and ecological systems renders the city particularly sensitive to environmental and tectonic dynamics.

Its distinctive geography, situated along the southern foothills of the Alborz Mountains and in close proximity to active fault lines, makes it particularly susceptible to geological changes, including tectonic movements and seismic events. Simultaneously, the swift pace of urbanization and industrial growth has exacerbated ecological challenges such as air and water pollution, land degradation, and a decline in biodiversity. A comprehensive understanding of the interaction between geological changes and ecological dynamics is vital for effective urban planning, risk management, and the promotion of sustainable development. Western Tehran, characterized by its diverse topography and rich geological history, presents a unique opportunity to study the interplay between geosystems and ecosystems. The Alborz Mountain range significantly influences geological formations and sedimentary basins in the region. A significant body of research has investigated the changes in ecosystems within the Tehran region from multiple perspectives.

In recent studies, various researchers have examined the ecological impacts and environmental changes as well as the changes in ecosystems within the Tehran region from multiple perspectives. [Tavallai and Sasanpour \(2009\)](#) quantified the city's ecological footprint, revealing significant ecological impacts. [Zenouzi et al. \(2022\)](#) reported a notable decrease in vegetation density, while [Ansari et al. \(2023\)](#) highlighted threats to wildlife in Iran's biomes, particularly due to habitat degradation in Tehran. Furthermore, [Shamsipour et al. \(2024\)](#) emphasized the low ecological resilience in Tehran's central districts, attributing this to high population density. [Sobhani \(2024\)](#) explored the relationship between urban development and its environmental consequences, particularly concerning protected areas. In a related study, [Hoseini et al. \(2024\)](#) concluded that urban expansion has significantly undermined green spaces within the city. The distinct climatic variations across different regions of Tehran, particularly the urban heat island (UHI) effect, have been extensively studied. [Zargari et al. \(2025\)](#) highlighted the significant temperature disparities caused by urbanization, while [Nasr](#)

[et al. \(2025\)](#) illustrated the impact of land use changes and the decline of urban green infrastructures on the environment. Collectively, these studies highlight the urgent necessity for sustainable urban planning and conservation initiatives, as well as the environmental challenges confronting Tehran. Despite the existence of numerous studies, there is a noticeable gap in research focused on the direct effects of geosystem components on regional ecosystems. [Ahadnejad et al. \(2016\)](#) examined how the geomorphological characteristics of Tehran impact its climatic conditions and urban development patterns. Similarly, [Shamsipour et al. \(2024\)](#) explored ecological risks within the city, highlighting concerns such as geological instability and air pollution. Tectonic activities, including faulting and folding, have played a pivotal role in shaping the landscape, while variations in lithology are vital for promoting soil diversity and influencing habitat availability. The geological attributes of Tehran, particularly its distinct geomorphology and aquifer systems, have a profound impact on the city's ecosystem. Key factors, including urban expansion, air pollution, and geological instability, are fundamental to understanding the environmental challenges and resilience of the city.

This study examines the dynamic relationship between Tehran's geological evolution and its ecological conditions, with an emphasis on the influence of geosystems in shaping the ecological dynamics of western Tehran. Particular attention is given to biodiversity patterns, soil characteristics, and habitat distribution. By synthesizing existing studies with case-specific analyses, the research provides a comprehensive assessment of the geological and ecological factors driving the city's environmental landscape, offering insights that can support metropolitan policy-making aimed at resilience and environmental stewardship. Given that land use changes are critical factors influencing ecosystem transformations within a region ([Cao and Song, 2022](#)), this study employed a land use change index derived from three geosystem variables analyzed through fuzzy logic: Lithology (*L*), River (*R*), and Fault (*F*). Therefore, the present study develops a fuzzy logic-based Land Use (LU) index that integrates lithology, river proximity, and fault distribution. By validating the index against a network of control points

and conducting geospatial analysis, this study identifies essential interactions between geosystems and ecosystems that elucidate the concentration of significant land use changes within a particular range of the LU index. Beyond advancing methodological innovation, this work provides a decision-support tool for sustainable land use planning and ecological management in western Tehran and other rapidly urbanizing peri-urban regions.

2. Material and methods

2.1. Study area

The Alborz Mountain range, situated in northern Iran, extends for more than 277 kilometers in length and over 877 kilometers in

width. This region represents an area of active geological deformation along the southern perimeter of the Caspian Sea. The Alborz Mountain Range is situated in a collision zone between the Arabian and Eurasian plates, leading to extensive crustal deformation and shortening (Sodoudi et al., 2009). The ongoing deformation within the Alborz Mountain Range is primarily attributed to the convergence and collision of the Arabian Plate with the southern Eurasian landmass, in conjunction with the movement of the South Caspian Plate towards the Central Iranian Plate. The research area includes western Tehran, covering the foothills of the western Alborz mountains and the nearby plains, as well as the Vardij River and the North Tehran Fault (NTF) (Fig. 1).

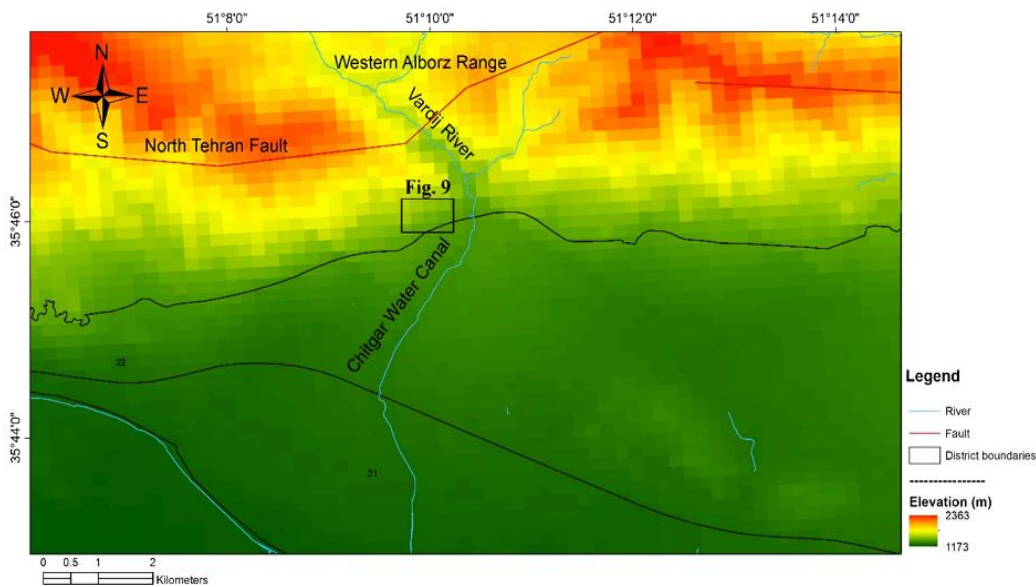


Fig. 1. The study area, illustrating the locations of various parameters employed to evaluate the influence of the geosystem on the urban ecosystem. Key morphological features, including the river and fault, are highlighted. A 30-meter resolution DEM derived from Landsat 8 imagery (Datum: WGS_1984) was used for spatial analyses. Lithological diversity and other relevant variables pertinent to the study are presented in the results section.

Based on consecutive fault displacements and associated microseismic activity, five principal seismically active fault zones that were either unknown or less well-documented have been identified in the Tehran region. The seismic activity associated with these faults suggests an ongoing and dynamic structural evolution. Evidence of active faulting is prevalent, with significant historical earthquakes, such as the 1990 Manjil-Rudbar earthquake, highlighting the region's seismic activity (Javidfakhr and Ahmadian, 2018). The active faults of Tehran are typically classified into three distinct deep-seated zones: northern, central, and southern. One of the key geographical features of western

Tehran is its rivers, which exhibit a high sensitivity to tectonic activity. These rivers serve as significant natural indicators for assessing the active tectonics of the area. Paleostress analyses indicate multiple deformation phases, including compressional and transpressional events, which have shaped the current geological landscape (Safari and Yassaghi, 2023).

2.2. Methodology

The process of data collection for this study was conducted in three distinct phases.

1. Geological mapping: Geological maps at a scale of 1:100,000 were obtained from the Iranian Geological Survey report published in 2021. These maps provided detailed information on lithological units, stratigraphic sequences, and tectonic structures such as major and minor faults. The geological base maps were subsequently digitized and georeferenced within a GIS environment to facilitate integration with other spatial datasets. Particular attention was paid to lithological variations in the foothills of the Alborz Mountains, as these units strongly influence both slope stability and land use dynamics.

2. Remote sensing: Multi-temporal satellite imagery (Landsat 8 OLI and Sentinel-2) and high-resolution aerial photographs were analyzed to detect land use and land cover changes over time. Landsat 8 OLI was selected for its long-term, freely available archive and 30 m spatial resolution, which make it highly suitable for multi-decadal analysis of regional land use dynamics. Sentinel-2 imagery, with its finer spatial resolution (10 m in visible bands) and higher temporal frequency (5-day revisit), was incorporated to enhance the level of detail in urban-periurban assessments. This combination ensured both historical continuity and high-resolution coverage for the study area. Standard preprocessing steps, including atmospheric correction, geometric rectification, and mosaicking, were applied to ensure data accuracy. Supervised and unsupervised classification techniques were employed to delineate ecological zones, vegetation cover, urban expansion, and hydrological features. Remote sensing analysis not only captured temporal changes but also enabled the identification

of areas most affected by anthropogenic activities, particularly in the vicinity of the Vardij River and the urban fringe of western Tehran.

3. Field studies and sampling: Extensive field surveys were conducted during the spring and summer seasons to validate and ground-truth the remote sensing and geological mapping results. Fieldwork included direct observation of lithological contacts, structural features (fault scarps, folds, and fractures), and geomorphological indicators of active tectonics. Photographic documentation, GPS-based geolocation, and limited sampling of lithological units were carried out to verify classification accuracy. In addition, land use categories identified through satellite imagery (e.g., agricultural land, built-up areas, rangeland, and bare surfaces) were cross-checked on-site to improve the reliability of the LU index analysis.

By integrating these methods, geologists can effectively measure and analyze the relationship between geological changes and ecosystem dynamics, leading to a better understanding of environmental resilience and adaptation. The spatial analysis and fuzzy membership functions were implemented using Geographic Information System (GIS) software integrated with custom Python scripts for data processing and modeling, enabling efficient handling of geographical data and precise computation of membership values.

Our fuzzy approach analyzing geological elements' roles in urban land use changes, defining fuzzy variables involves quantifying uncertainties and gradational influences of parameters like lithology, river proximity, and fault locations. The basics of defining these variables are as described in Table 1.

Table 1. Overview of the fundamental definitions of the variables utilized in this study.

Variable	Membership Degree	Basis	Logic	Ref.
Lithology (<i>L</i>)	(0-1)	Based on rock type suitability for urbanization	Limestone or sandstone (stable foundations) → higher membership for "urbanizable" Clay-rich or fractured formations (prone to subsidence) → lower membership	(Huang and Siller, 1997; Maghsoudi et al., 2016)
River (<i>R</i>)	(0-1)	Based on water access and limited access	Model zones of influence using trapezoidal or Gaussian curves.	(Cieślak and Górecka, 2021; Biłozor et al., 2024)
Fault (<i>F</i>)	(0-1)	Based on risk gradients via linear or sigmoidal functions	Integrating fault activity rates as buffer zones	(Huang and Siller, 1997; Maghsoudi et al., 2016)

L as a fuzzy variable represents the degree to which rock types facilitate or hinder urbanization, quantified via membership values. This captures gradational transitions between lithological units and their mechanical/geochemical properties. The linear or sigmoidal functions were used to model gradational boundaries between lithologies (e.g., 100m buffers around mapped contacts) as follows (Eq. 1):

$$\mu_{\bar{a}}(x) = \begin{cases} 0 & \text{if } d > 500\text{m} \\ \frac{x}{500} & \text{if } 0 \leq x \leq 500\text{m} \end{cases} \quad (1)$$

where x is proximity to limestone outcrops and d is distance. The Eq. 1 is rooted in fuzzy set theory (Lotfi Zadeh, 1965), where membership

functions—often linear or sigmoidal—quantify the degree of association to a particular set, here representing lithological proximity.

R as a fuzzy variable is not simply *near* or *far*, but rather a continuum where each location has a degree of membership (between 0 and 1) to the set *close* to river. This reflects the reality that flood risk and river-related influences decrease gradually with distance, not abruptly (Parhizgar et al., 2017; Sonmez and Bizimana, 2020). The fuzzy small or fuzzy MS small membership functions was typically used. These assign higher membership values to locations closer to the river and lower values as distance increases. Membership function for R was designed according to Table 2.

Table 2. General design of the membership function for the variable R .

Distance from River (m)	Fuzzy Membership (Risk/Influence)
0–50	1.0 (Very High)
50–100	0.8 (High)
100–250	0.6 (Moderate)
250–500	0.3 (Low)
500–1000	0.1 (Very Low)
>1000	0.0 (Negligible)

F is a critical factor in urban land use planning due to its direct relationship with seismic hazard and landslide risk, especially in arid and tectonically active regions (Poursharifi et al., 2020; Abdelkarim et al., 2024; Habibi et al., 2024). In this study, fault proximity is best

represented as a *continuous variable* that expresses the degree of risk or unsuitability for urban development based on distance from active faults. Membership function for F was designed according to Table 3.

Table 3. General design of the membership function for the variable F .

Distance from Fault (m)	Fuzzy Membership (Risk/Unsuitability)
0–200	1.0 (Very High)
200–500	0.7 (High)
500–1000	0.3 (Moderate)
>1000	0.0 (Negligible)

L was defined for urbanization suitability based on stability, erosion resistance, and geotechnical properties according to Table 4. Validation in this study includes compare fuzzy outputs with slope failure incidents to calibrate membership thresholds.

4. Results and discussion

One of the key evaluators of the ecosystem change index related to land use alterations is the geological characteristics of an area. The Tehran region is particularly significant in this regard, as it is one of the most seismically active and hazardous zones within the context of Iran's geodynamic scale. Situated atop ten active

faults, the region includes notable examples such as the NTF, which extends approximately 108 kilometers, the Mosha Fault at around 200 kilometers, and the South Rey Fault measuring about 20 kilometers. Given this context, geological characteristics were identified as the primary variable in the fuzzy logic function. In addition, the region's drainage system is directly influenced by the tectonic dynamics of the NTF, located in the Western Alborz. Field studies revealed that the NTF was distinguished by intricate tectonic processes, particularly characterized by reverse faulting and dextral strike-slip movements. Situated in the southern region of the Central Alborz, the TNF extends from Lashkarek and Sohanak to Farahzad and Hesarak, continuing westward towards Valian,

which lies to the west of Karaj. This fault, along with its associated secondary faults, predominantly causes disruptions and

displacements within the Tertiary and Quaternary sedimentary sequences along its strike.

Table 4. General design of the membership function for the variable *L*.

Geological formation	Lithology	Geomechanical properties	Ref.	Fuzzy Membership (Risk/Unsuitability)
Qt2	Quaternary Low level piedment fan and vally terrace deposits	Unconsolidated sediments with high erosion/flood risks and poor foundation support	(Hansen et al., 1982)	1.0 (Very High)
Eka	Middle-Eocene Calcareous shale with subordinate tuff (Asara Shale)	Swelling clays and dissolution susceptibility in carbonate-rich layers create instability	(Hansen et al., 1982; Aseraei et al., 2021)	0.8 (High)
Etliv	Eocene Andesitic volcanic tuff	Friable pyroclastic deposits with variable permeability and fracture risks	(Vittecoq et al., 2019; Lucero et al., 2025)	0.6 (Moderate)
Ek	Well bedded green tuff and tuffaceous shale (KARAJ FM)	Moderate stability in layered volcanoclastics but prone to weathering in shale intervals	(Li et al., 2018; Lucero et al., 2025)	0.3 (Low)
Qplc	Pliocene-Quaternary Fluvial conglomerate, Piedmont conglomerate and sandstone	Well-cemented sedimentary units provide stable foundations but require assessment of cementation quality	(Hansen et al., 1982)	0.1 (Very Low)
Eviv	Middle-Eocene Andesitic volcanics	Dense, competent igneous rock with high load-bearing capacity and erosion resistance	(Vittecoq et al., 2019)	0.0 (Negligible)

The analysis conducted for the ecosystem change index utilized a weighting system grounded in three primary inputs. This included a field approximation derived from the current study, alongside supplementary data from earlier research. Systematic sampling was executed in linear regions, specifically along adjacent river courses, following the relationship $k = N/n$. In addition, both transverse and longitudinal surveys facilitated cluster sampling in areas surrounding the rivers. Following data collection, a partial weighting of potential items was performed through the application of multivariate problem-solving techniques, employing fuzzy weighting methods. Key variables crucial to the assessment of the ecosystem change index, particularly in relation to land use changes, comprised *L*, *R*, and *F*. In this context, the classical set with Crisp relations was not employed due to the interdependence of the variables; instead, the variables were

categorized as structural variables. The fuzzy function was directly conditioned based on the membership degree as established in Eq. 1. Consequently, for each visitation route, a three-variable system was designated to quantify the ecosystem change index. The land use index (LU_index) is a component of the ecosystem change index and is used to quantitatively assess Ecosystem Suitability (ES). More specifically, it represents a subset of Urban Ecosystem Viability (UEV). Therefore, the results of this study aim to determine the ability of an ecosystem to support various functions and services, particularly in urban development contexts.

The three-dimensional representation of the fuzzy system diagrams for this index, derived from equation (1), are illustrated in Figs 2, 3, and 4. In this context, the rule definitions derived from the input variable matrix [3 3 2] are illustrated in a three-dimensional format, as depicted in Fig. 5.

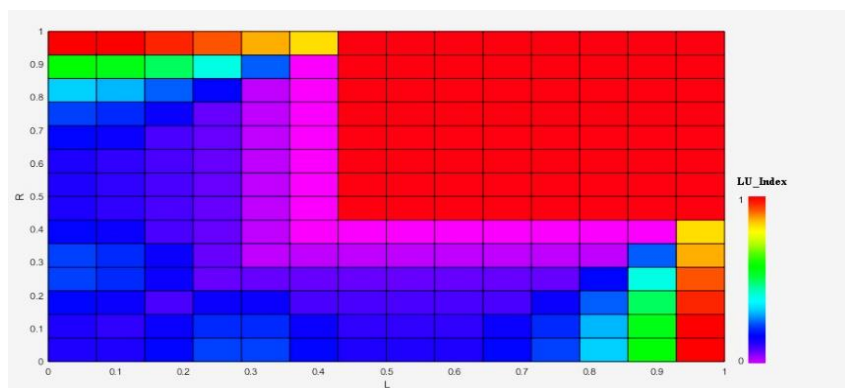


Fig. 2. Fuzzy UEV system defined for ES based on the land use index (LU_index) in L-R plane.

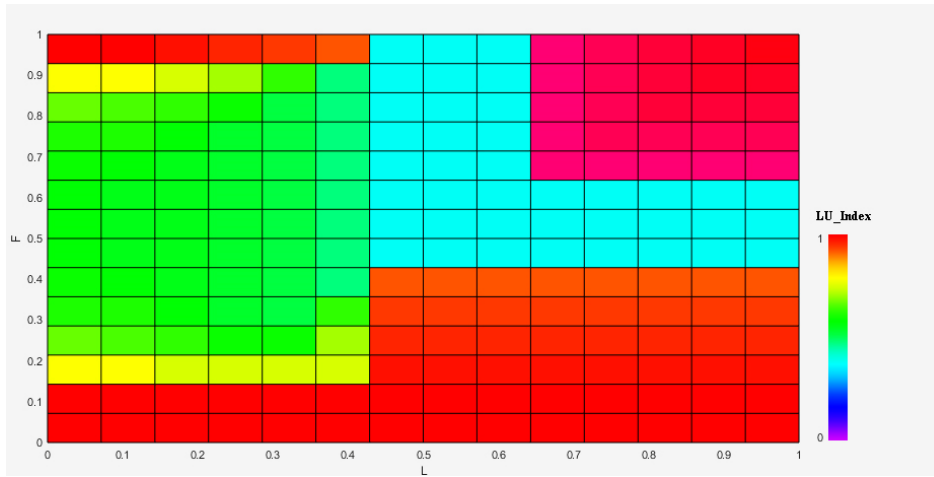


Fig. 3. Fuzzy UEV system defined for ES based on the land use index (LU_index) in L-F plane.

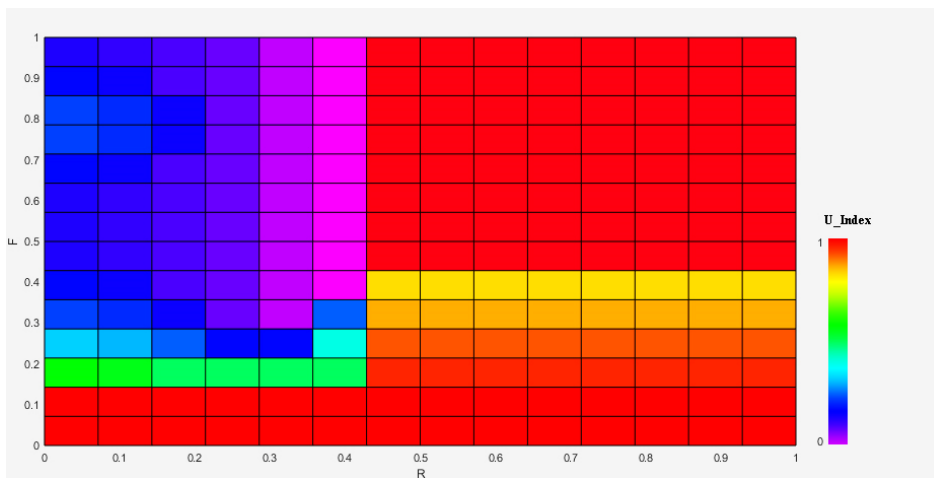


Fig. 4. Fuzzy UEV system defined for ES based on the land use index (LU_index) in R-F plane.

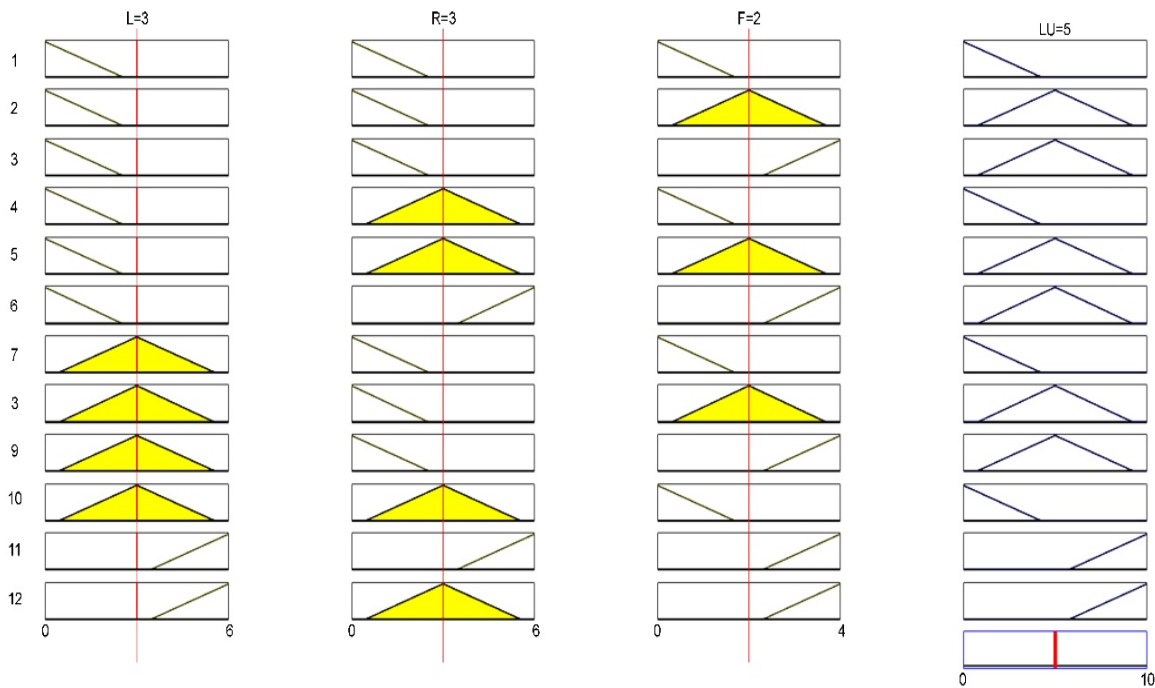


Fig. 5. Sensitivity plots corresponding to the fuzzy UEV system based on the input variable matrix [3 3 2]. The first three subplots display the membership sensitivity for individual input variables L, R, and F within their specified fuzzy sets. The rightmost subplot depicts the final aggregated output response derived from the combination of the three input variables, shown over the output range. This visualization highlights the influence of each variable on the system's response and the resulting fuzzy rule-based inference.

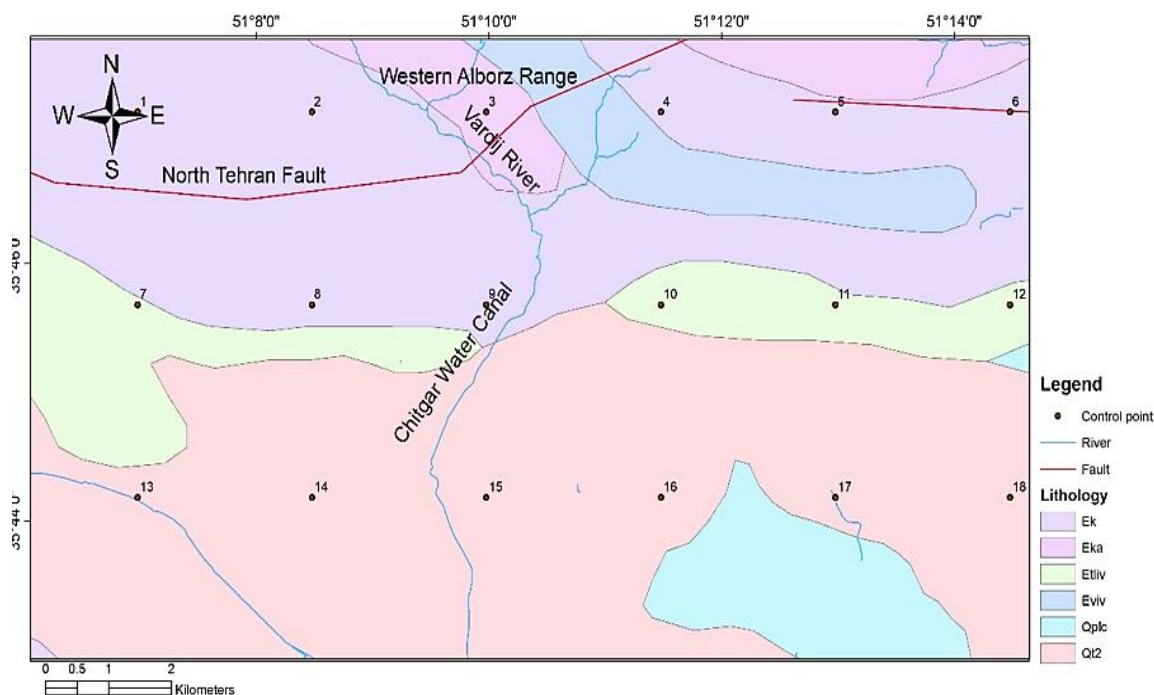


Fig. 6. Initial configuration of the control point network based on the geosystem variables of the study area. These control points (n=18) form the input for subsequent LU index calculations, the results of which are analyzed and presented in Fig. 7. For further details regarding lithology, please consult Table 4.

Based on this foundation, a network of control points was developed utilizing the mapped evaluation variables, including variables *L*, *R*, and *F*, as illustrated in Fig. 6. Based on the variable matrix [2 3 3], the LU index is established within the range of 2.03 to 13. In this context, the variables *L*, *R*, and *F* were

computed in accordance with the fuzzy rules outlined in Fig. 5, utilizing data from Tables 2, 3, and 4. These calculations were applied to 18 control points illustrated in Fig. 6, resulting in the LU index zoning for the ecosystem impacted by geosystem changes, as depicted in Fig. 7.

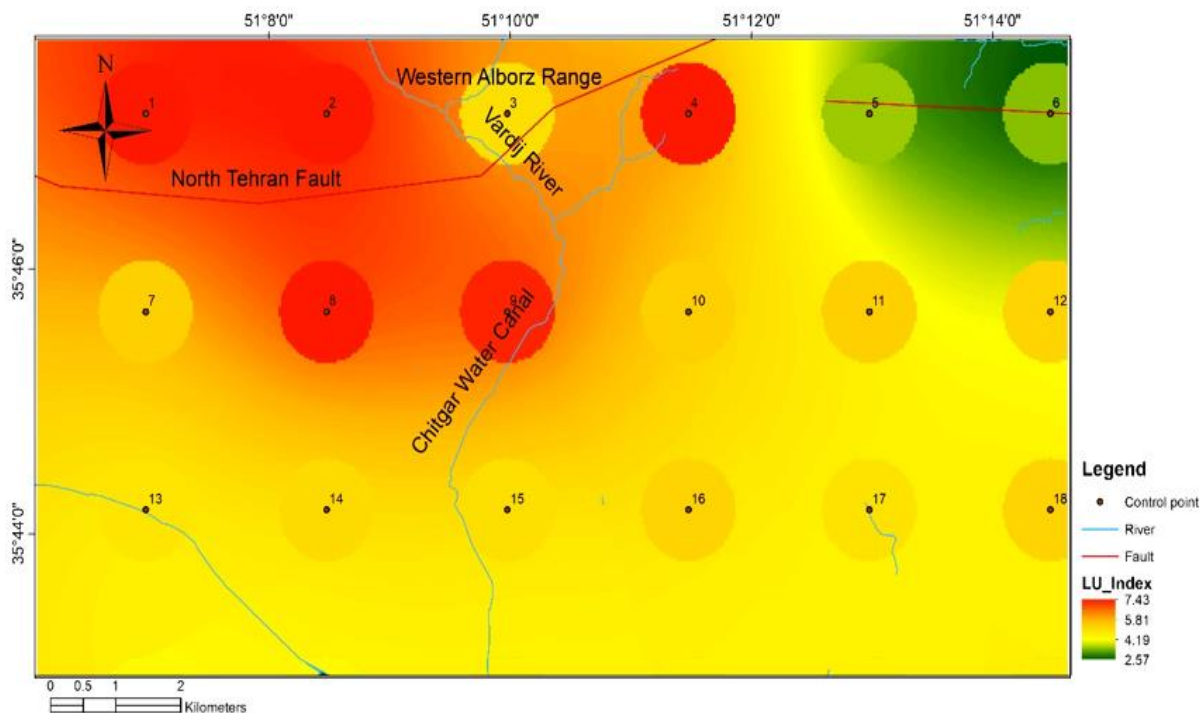


Fig. 7. Zoning of the LU index reflecting the ES and UEV status influenced by regional geosystems. The zoning was derived from the 18 control points illustrated in Fig. 6, and is presented in two formats: general zoning (spectra) and detailed zoning for each control point (circles).

Fig. 7 illustrates the LU index zoning derived from the 18 control points configured in Fig. 6, highlighting spatial variations in ES and UEV influenced by regional geosystems. Notably, the highest LU index values are observed in areas located farther from NTF and rivers, which contrasts with common expectations that areas proximal to key geosystem features would exhibit higher land use intensity. A detailed comparison with the distribution of land uses presented in Fig. 8 reveals a strong correlation between LU index zoning and actual urban development patterns. This finding indicates that the majority of urban land use changes, which serve as key indicators of

ecosystem alteration, are influenced by the combined effects of lithology, river proximity, and fault density. Such an analysis underscores the critical role of geosystem variables in modulating the spatial dynamics of land use change. By linking the control points of Fig. 6 to the zoning in Fig. 7, the study provides a clear framework for identifying sensitive regions where ecosystem impacts are most likely to occur. The dual presentation of general zoning (color spectra) and point-specific details (circles) allows for both a regional overview and fine-scale assessment, supporting targeted environmental management strategies.

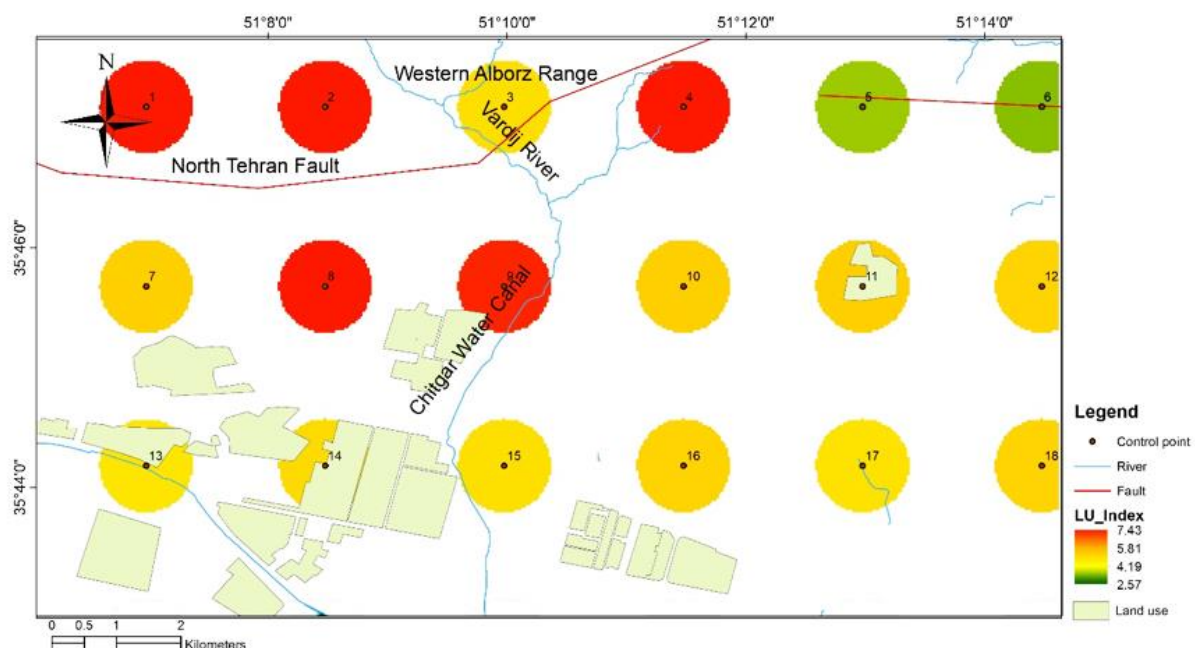


Fig. 8. Comparative map illustrating the LU index zoning for each control point (circles) impacted by changes in the region's geosystem as a result of urban land use.

Fig. 8 provides a comparative representation of the LU index zoning for each control point (as shown by circles), directly linking geosystem variables to observed land use patterns. The analysis reveals that control points with intermediate LU index values correspond to areas undergoing the most pronounced urban expansion, particularly near the urban fringe of western Tehran. This correlation highlights the sensitivity of transitional zones, where ecological stability is constrained by both natural and anthropogenic pressures. Furthermore, the zoning in Fig. 8 demonstrates that areas with intermediate LU index values (e.g., 4.02 to 4.90) are particularly susceptible to geosystem-driven land use transformations. This observation challenges the assumption that only high LU index areas drive urban

expansion, emphasizing the interplay between geomorphological constraints and regional geosystem characteristics.

This finding challenges the conventional assumption that urban growth predominantly occurs in areas with the highest suitability or LU index values. Instead, it suggests that transitional zones—where ecological stability is influenced by both natural and anthropogenic pressures—are more vulnerable to land use changes. Similar observations have been reported in studies of urban fringe dynamics, where areas with moderate ecological resistance tend to experience rapid and often unplanned development (Seto et al., 2012; Liu and Xu, 2024).

The comparative approach demonstrates that land use changes are not evenly distributed

across the geosystem framework but are concentrated in zones where lithological characteristics, proximity to rivers, and fault density collectively create favorable yet vulnerable conditions for development. Importantly, this comparison supports the conclusion that LU index zoning is not merely a theoretical construct but has strong explanatory power in identifying where urban growth is most likely to alter ecosystem dynamics.

The clustering of land use changes in zones characterized by specific lithological features, river proximity, and fault density underscores the multifactorial nature of urban expansion. Our findings resonate with those of Zhang et al. (2023), who demonstrated that geological and hydrological factors significantly shape urban growth patterns, especially in seismically active and geomorphologically complex regions. The LU index zoning, therefore, provides a robust framework that integrates these geosystem variables, offering explanatory power beyond socio-economic or purely land cover-based models (Wang and Nanekaran, 2024).

By integrating LU zoning with observed land use changes, Fig. 8 validates the applicability of the proposed methodology as a decision-support tool for urban planning and environmental management. When considered alongside Fig. 7 and Fig. 9, this comparative analysis reinforces the role of geosystem variables as key drivers of ecological vulnerability in rapidly urbanizing landscapes. Furthermore, integrating LU zoning with observed land use changes validates the methodology as a valuable decision-support tool for urban planners and environmental managers. Fig. 9 illustrates the alignment between land use changes and geosystem variables, reinforcing the potential to guide sustainable urban expansion while minimizing ecological disruption. This aligns with the findings of Marker et al. (2003), who emphasized the importance of incorporating geophysical constraints into urban planning models to enhance ecological resilience.

While urban development and changes in land use typically have adverse effects on regional ecosystems, in areas that are designated for development, a greater alignment between land use change patterns and ES can lead to more manageable ecological outcomes within the framework of urban planning. For instance, as a means of validation, Fig. 9 illustrates the

alignment of land use changes in urban development with the variables examined in this study. As a means of validation, Fig. 9 illustrates the alignment of land use changes in urban development with the geosystem variables examined in this study, and this evidence, when considered alongside the preceding findings, highlights the importance of incorporating geosystem considerations into urban planning to achieve more sustainable and ecologically manageable outcomes.

The novelty of this study lies in its fuzzy logic-based LU index, which accounts for uncertainties and gradational influences of geosystem factors. Unlike traditional deterministic models, this approach reflects the complex and often ambiguous interactions between lithology, hydrology, and tectonics in shaping urban land use dynamics. The unexpected finding that areas with moderate LU index values are most susceptible to change aligns with recent work by Lin et al. (2020), who argued that transitional zones act as ecological "hotspots" where development pressures and environmental vulnerabilities converge.

The findings of this study advance the current understanding of urban ecosystem dynamics by introducing a novel integration of geosystem variables into land use change analysis. Unlike conventional approaches that primarily emphasize socio-economic or land cover drivers, our framework incorporates lithology, river proximity, and fault distribution into a fuzzy logic-based LU index. This methodological innovation accounts for uncertainties and gradational influences of geosystem factors, providing a more nuanced representation of urban expansion processes. The unexpected identification of the most significant land use changes within a moderate susceptibility range (LU index 4.02–4.90) challenges prevailing assumptions that urban development is largely confined to highly suitable zones. This counterintuitive result highlights the vulnerability of transitional geosystem areas, where natural and anthropogenic pressures converge. Furthermore, by validating the model through geological mapping, remote sensing, and field observations, this research provides both conceptual novelty and empirical robustness. Beyond the case of western Tehran, the methodological framework developed here offers a transferable decision-support tool for

sustainable land use planning and ecological resilience in geologically complex urban–periurban settings.

Moreover, the validation of the model through geological mapping, remote sensing, and field observations ensures empirical robustness and practical applicability. This multi-method approach strengthens the credibility of the findings and supports their transferability to other geologically complex urban–periurban

regions (Zhuang et al., 2023). In summary, this study advances urban ecosystem research by integrating geosystem variables into land use change analysis. It highlights the importance of considering geological and geomorphological factors alongside socio-economic drivers, ultimately offering a more holistic and sustainable framework for urban planning and ecological management.



Fig. 9. A perspective on verifying the alignment of land use changes in urban development with the variables examined in this study, specifically within the Mahsan and Moalem residential complexes in western Tehran.

4. Conclusions

This research demonstrated that geosystems exert a decisive influence on the ecological dynamics and land use patterns of western Tehran. By integrating lithology, river proximity, and fault distribution into a fuzzy logic–based LU index, and validating the results through a network of 18 control points, the study successfully identified ecologically sensitive zones. The zoning analysis revealed that the most significant land use changes occurred within the susceptible LU index range of 4.02 to 4.90, challenging the prevailing assumption that urban development primarily takes place in zones with the highest LU values. This transformation was largely driven by rugged topography and the interplay of geosystem variables, emphasizing the vulnerability of transitional zones within the

study area. While urban development and land use changes often negatively impact regional ecosystems, a better alignment between land use patterns and ES in designated development areas can result in more sustainable ecological outcomes. The comparative zoning map (Fig. 8) further illustrated that urban expansion is concentrated in geosystem-sensitive zones, particularly along the urban fringe, where both anthropogenic and natural pressures converge. The consistency of these patterns with Fig. 9, which validated the alignment between observed land use changes and geosystem variables, underscores the robustness of the proposed methodology. These findings not only provide empirical evidence for the critical role of geosystems in shaping ecosystems but also highlight the value of integrating geological parameters into land use planning and biodiversity conservation. The methodological

framework developed here offers a decision-support tool for sustainable urban planning and environmental management in rapidly urbanizing landscapes. Future studies should expand this framework by establishing a denser control point network and incorporating additional variables such as geological contacts, while also accounting for long-term interactions under climate change scenarios. Ultimately, a geosystem-informed approach can enhance the ecological resilience of western Tehran and similar urban-periurban regions facing escalating development pressures.

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