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A GIS-Based Multi-Criteria Decision Analysis for Land Subsidence Susceptibility Mapping and Risk Assessment of Water and Wastewater Networks in Tabriz City

Sajjad Ahadzadeh

Research Center of GeoSpatial Sensors and Unmanned Platforms (GeoSUP), College of Engineering, University of Tehran, Tehran, Iran - sajjad.ahadzadeh@gmail.com

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Abstract

Land subsidence in contemporary megacities, driven by the overexploitation of groundwater resources, is akin to a silent bomb on the verge of detonation. It poses the potential for irreversible disasters affecting urban infrastructure, buildings, and the lives of thousands of people. This creeping phenomenon directly threatens the security, economy, and health of city residents with increasing severity. The metropolis of Tabriz has likewise experienced a growing trend of land subsidence over recent decades, and the present study investigates the spatial potential of subsidence across its urban extent. To this end, an integrated GIS–MCDA approach, combined with remote sensing data, was employed. Specifically, environmental layers influencing subsidence risk were first weighted and integrated using the WLC multi-criteria technique. Subsequently, the resulting hazard zoning map was validated against COSMO-SkyMed satellite imagery. According to the findings, the adopted methodology produced accurate results, with 93.3% of high-risk zones overlapping with areas of actual subsidence in the region. The outcomes of this research underscore the critical importance of addressing land subsidence hazards within the study area and demonstrate that the application of an integrated RS–GIS approach can provide a comprehensive and reliable model for decision-makers and urban planners in managing environmental risks.

1. Introduction

Land subsidence is a critical environmental hazard characterized by the gradual downward displacement of the Earth's surface due to a combination of natural geological processes and human-induced activities (Biancini et al., 2019). Over recent decades, it has emerged as one of the most significant geohazards threatening the sustainability of urban environments and the safety of human societies worldwide (Minh et al., 2019). The phenomenon is particularly severe in densely populated urban regions, where intensive groundwater extraction, rapid urbanization, and excessive land loading exacerbate the rate and extent of ground deformation (Dang et al., 2014). Prolonged and spatially uneven subsidence can lead to irreversible damage to buildings, transportation corridors, and subsurface utilities such as water, gas, and sewage pipelines (Karimzadeh and Matsouka, 2020). Moreover, even minor differential settlement or localized tilting can critically undermine the stability of engineering structures that depend on precise alignment and gravitational equilibrium (Holzer and Johnson, 1985).

Historically, the understanding of land subsidence evolved from foundational geomechanical theories—notably those of Terzaghi and Biot, who elucidated the relationship between effective stress, pore pressure, and aquifer compaction—to contemporary satellite-based observation systems. The advent of Interferometric Synthetic Aperture Radar (InSAR) has revolutionized subsidence research by enabling high-resolution, spatially continuous, and temporally dense measurements of surface deformation across extensive urban landscapes. This technological advancement has allowed researchers to quantify not only the magnitude and spatial variability of subsidence but also its direct impacts on urban infrastructure and risk propagation mechanisms.

In this regard, the modeling contributions of Gambolati and Teatini (2015) have been seminal in demonstrating how differential settlement induces severe tensile and compressive stresses in foundation systems, often culminating in widespread cracking and structural deterioration. Likewise, empirical investigations in rapidly sinking megacities such as Jakarta and Bangkok have documented extensive damage to linear infrastructures, including distorted railway alignments, fractured road pavements, and ruptured underground pipelines—leading to chronic service interruptions and substantial maintenance expenditures (Abidin et al., 2011). Furthermore, the compound hazard posed by land subsidence and sea-level rise has become a prominent research frontier. Studies by Shirzaei and Bürgmann (2018) have shown that localized subsidence dramatically amplifies flood risk in low-lying coastal cities, reducing the effectiveness of flood defenses and drainage systems, and contributing to the permanent inundation of vulnerable urban districts.

Collectively, these findings underscore a paradigm shift in the understanding of land subsidence—from being viewed as a localized geological issue to being recognized as a multi-hazard phenomenon with systemic implications for urban resilience, infrastructure integrity, and environmental sustainability. The growing body of research converges on the consensus that addressing land subsidence requires integrated risk management approaches that combine scientific monitoring, spatial analysis, and proactive policy interventions.

Among various infrastructure systems, urban water supply and wastewater networks are particularly susceptible to subsidence-induced damage. Deformation of buried pipelines can disrupt essential water services, cause leakage or contamination, and impose substantial financial burdens for repair and reconstruction (Garajeh et al., 2024). The resulting infrastructure failures not only threaten urban service continuity but also pose public health and environmental risks, making the assessment of these networks' vulnerability a central concern in modern urban hazard management.

Effective planning and mitigation of land subsidence impacts necessitate a comprehensive understanding of its spatial distribution, temporal dynamics, and associated risks. One of the most practical and widely applied tools in this context is hazard zoning, which identifies and prioritizes high-risk areas for targeted interventions (Ghorbanzadeh et al., 2018). Advances in Geographic Information Systems (GIS) and remote sensing have enabled the integration of multiple spatial datasets, facilitating detailed modeling and visualization of subsidence patterns. When combined with Multi-Criteria Decision Analysis (MCDA), GIS becomes a powerful decision-support platform for synthesizing diverse environmental, geological, and anthropogenic factors to produce reliable hazard and vulnerability maps (Feizizadeh et al., 2020).

However, a key limitation in current research lies in the predominance of static hazard assessments, which often fail to account for future risk evolution under changing hydrogeological and anthropogenic conditions. There remains a pressing need to transition from descriptive mapping toward dynamic and predictive risk modeling that integrates real-time monitoring data, groundwater abstraction rates, and scenario-based forecasting. Such approaches are essential for identifying emerging subsidence hotspots and implementing preventive management measures before critical thresholds are reached.
In light of these considerations, the present study aims to develop an integrated GIS–MCDA framework to (1) delineate the land subsidence hazard zones in Tabriz with high spatial precision, and (2) assess the vulnerability of urban water and wastewater networks to subsidence-induced deformation. By combining remote sensing observations, spatial modeling, and multi-criteria analysis, this research seeks to provide a scientifically grounded, operational tool for supporting risk-informed urban planning and infrastructure management in subsidence-prone regions.

2. Study Area

The study area encompasses the city of Tabriz, the capital of East Azerbaijan Province, located in northwestern Iran (Figure 1). Geographically, Tabriz is situated on the northern foothills of the Sahand volcanic mountain range, approximately 1350–1600 meters above sea level. The city extends across the Tabriz Plain, which forms part of the Urmia Lake Basin, one of the most important endorheic basins in Iran. Geographically, it lies between latitudes 38°00′–38°12′ N and longitudes 46°10′–46°25′ E.
Tabriz serves as one of Iran's principal industrial, commercial, cultural, and educational hubs, and it is the largest urban center in northwestern Iran. The city has undergone rapid urban expansion and population growth over the past few decades, with a current population exceeding 1.8 million inhabitants. This demographic and industrial development has led to a substantial increase in water demand for domestic, agricultural, and industrial purposes.
The region hosts several key industrial and infrastructural facilities, including the Tabriz Thermal Power Plant, a petrochemical refinery, and the Tabriz–Miandoab water transmission network. Additionally, more than 40 deep wells have been drilled across the urban and peri-urban areas to supply groundwater for irrigation and industrial operations. However, unsustainable groundwater extraction has become a major environmental concern. According to Karimzadeh (2015), the annual groundwater withdrawal in the Tabriz Plain is estimated at approximately 5 million cubic meters, significantly exceeding the permissible limit of about 3 million cubic meters per year.
This overexploitation of groundwater has triggered land subsidence, posing serious risks to the city's infrastructure, including buildings, roads, railways, and pipelines. The phenomenon has been identified as one of the most critical geohazards affecting the region. Based on satellite interferometric analyses, the magnitude of surface deformation within the urban area of Tabriz ranges from approximately –394.7 mm to +201 mm, with maximum subsidence rates reaching up to 39.47 cm per year in localized zones. These deformation patterns correlate strongly with areas of intensive groundwater extraction and compressible alluvial deposits, highlighting the urgent need for effective groundwater management and continuous geotechnical monitoring.

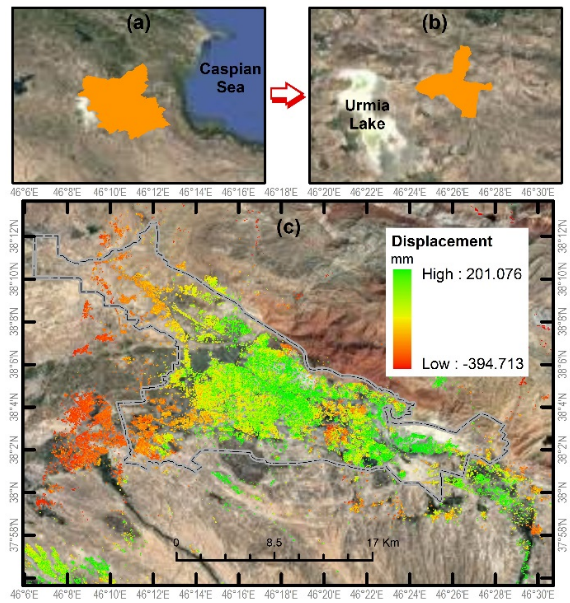

Figure 1. Study Area: (a) East Azerbaijan Province, (b) Tabriz County, (c) Surface deformation map of Tabriz city.

3. Material and Method

3.1 Methodology

The methodology of this study is structured into two principal phases: (1) hazard zoning and (2) validation.
In the first phase, the spatial distribution of land subsidence potential within the study area was determined by integrating multiple datasets and criteria. Following data collection and preprocessing, a GIS-based multi-criteria decision analysis (MCDA) framework was implemented to carry out the spatial modeling. Specifically, the Weighted Linear Combination (WLC) method—one of the most commonly applied MCDA techniques—was employed to combine the selected criteria and generate the hazard zoning map.
The second phase concentrated on evaluating the vulnerability of the urban water and wastewater infrastructure to land subsidence, thereby serving as a validation of the hazard zoning results. To this purpose, COSMO-SkyMed satellite imagery was employed to detect and analyze subsidence patterns (Figure 1-c).
The overarching objective of the proposed methodology is to assess the effectiveness of integrated remote sensing (RS) and GIS techniques for spatial modeling of land subsidence hazards in urban environments. This approach highlights the potential of RS–GIS integration as a robust framework for hazard assessment and infrastructure vulnerability analysis.

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3.2 Input Data and Sources

In this study, eight environmental factors influencing land subsidence within the study area were systematically analyzed. As shown in Figure 2, these factors comprise elevation, slope, land use, drainage density, soil texture, lithology, distance from faults, and groundwater depth. Each factor contributes uniquely to the occurrence and spatial variability of subsidence. To integrate these datasets within a GIS framework, spatial layers were generated, classified, and assigned numeric codes ranging from 1 to 5. Raster layers were subsequently produced to support the analytical processes. Table 1 provides a summary of the input data and their corresponding sources.

A Digital Elevation Model (DEM) with a 30 m spatial resolution, obtained from the Shuttle Radar Topography Mission (SRTM) of the U.S. Geological Survey, was used to derive the elevation, slope, and drainage density layers. Land use information was extracted from a Landsat-8 OLI image acquired in the summer of 2024, also with a 30 m resolution. In addition, urban water and wastewater network data were provided by the East Azerbaijan Province Water and Wastewater Company and processed following quality corrections.

To further assess land subsidence hazards, a high-resolution Level-1c X-band image from the COSMO-SkyMed satellite was employed. Operated by the Italian Space Agency and the Ministry of Defense, COSMO-SkyMed integrates Small Baseline Subset (SBAS) interferometric techniques, representing a state-of-the-art advancement in InSAR data processing for enhancing ground displacement measurements (Cigna et al., 2014). The first satellite of the COSMO-SkyMed constellation was launched on June 8, 2007, into a sun-synchronous orbit at approximately 619 km altitude, with a 97-minute repeat cycle. Its relatively short revisit time makes it highly suitable for continuous monitoring of surface deformation. As an X-band radar system, it operates at a shorter wavelength, enabling the generation of high-resolution interferograms with reduced temporal decorrelation (Hong, 2024). These attributes highlight the significant advantages of COSMO-SkyMed imagery in studying and monitoring surface processes, particularly land subsidence.

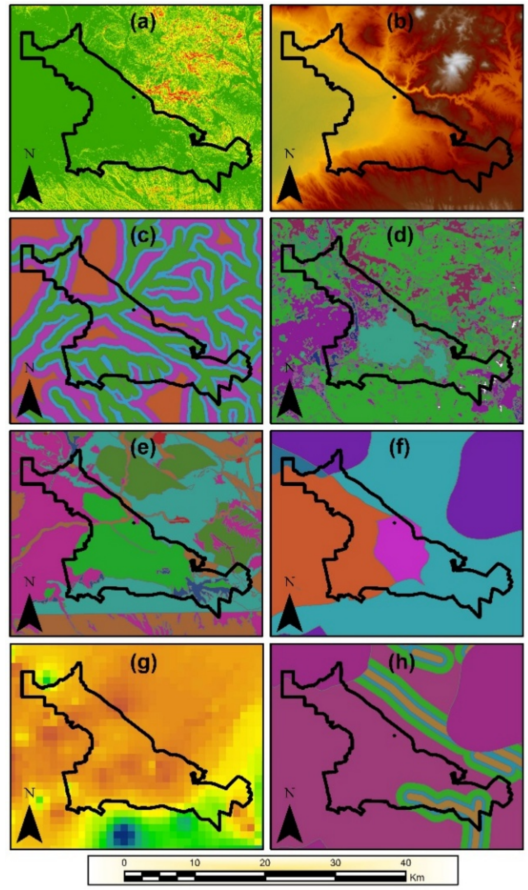

Figure 2. Criteria considered for land subsidence hazard potential: (a) slope, (b) elevation, (c) drainage density, (d) land use, (e) lithology, (f) soil texture, (g) groundwater depth, (h) distance from faults.

Input data	Source
Elevation	SRTM DEM 30m
Slope	
Drainage Density	
Land Use	Landsat 8 OLI 30m
Lithology	1:100000 Geological Map
Fault Lines	
Soil Texture	Natural Resources and Watershed Management Organization
Groundwater Depth	
Urban Water Network	Water and Sewage Company of East Azerbaijan Province
Urban Wastewater Network	
Land Subsidence	COSMO-SkyMed ESA Archive

Table 1. Input Data Layers and Their Sources

3.3 Weighted Linear Combination (WLC) Technique

The Weighted Linear Combination (WLC) technique, also referred to as the Weighted Sum method, is one of the most fundamental and widely applied GIS–MCDA techniques. WLC is based on the simple yet powerful principle that the final judgment or decision is obtained through the linear combination of all contributing criteria, each weighted by its relative

importance. This method explicitly accepts the concept of "trade-off" among criteria, meaning that deficiencies in one criterion may be compensated for by strengths in another. Owing to this feature, WLC is considered a compensatory method.
As expressed in Equation (1), this technique is essentially a map-combination process in which a set of criterion weights is associated with alternatives and aggregated accordingly:

$$V(A_i) = \sum_{k=1}^{n} Wk^{V(a_{ik})} \quad (1)$$

where $V(A_i)$ represents the overall value of alternative i on the map, and $V(a_{ik})$ denotes the value of alternative i with respect to factor k, as measured using a value function. The alternative with the highest $V(A_i)$ is considered the most preferable option (Malczewski and Rinner, 2015). In this study, several key steps were followed in applying the WLC technique:

1. Preparation of raster maps for the criteria (alternatives);
2. Reclassification of the criteria maps into five classes;
3. Standardization of the criteria maps using numerical values;
4. Overlay of the standardized maps using the Weighted Overlay function in GIS.

Accordingly, WLC can be regarded as a fully spatial GIS–MCDA technique, employed in this research to produce a spatial zoning of land subsidence potential across the study area.

3.4 Assessment of Land Subsidence Hazard Potential

The hazard zoning map of land subsidence potential for Tabriz city is presented in Figure 3. As shown, the level of subsidence hazard in the study area can be categorized into four distinct classes: (1) very low hazard, (2) relatively low hazard, (3) relatively high hazard, and (4) very high hazard. The analysis reveals that a significant portion of the study area—particularly in its western parts marked in red—is characterized by a very high potential for land subsidence. In contrast, only a small fraction of the area is classified as having very low potential. Overall, the majority of Tabriz city falls into the medium-to-high hazard categories.
More precisely, as indicated in Table 2, approximately 2.7 hectares of the total area fall within the very low hazard zone, 1298 hectares in the relatively low hazard zone, 17971.4 hectares in the relatively high hazard zone, and 5748.8 hectares in the very high hazard zone. The multi-criteria zoning results therefore demonstrate that 5.19% of the total area is classified as low-to-moderate risk, while 94.81% falls into the moderate-to-high risk categories. These findings highlight that Tabriz city possesses a very high potential for land subsidence occurrence.
From a spatial perspective, the evaluation indicates that high-risk zones for subsidence predominantly correspond to flat plains within the western half of Tabriz, which also host most of the city's industrial and agricultural activities. Conversely, the eastern half of the city—characterized by more mountainous topography and lower levels of industrial and agricultural activity—falls largely within the lower-risk categories.

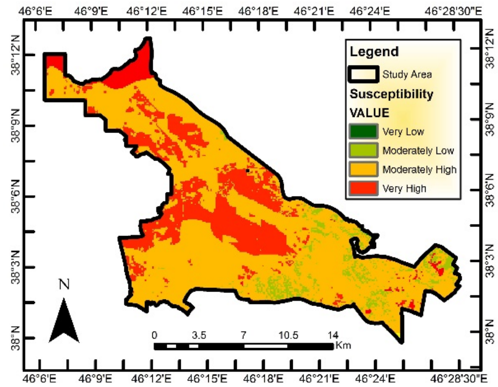

Figure 3. Land subsidence hazard potential zoning map of Tabriz city.

Hazard Level	Area (hectares)	Percentage (%)
Very low	2.7	0.01
Relatively low	1298	5.18
Relatively high	17971.4	71.8
Very high	5748.8	23.01
Total	25021	100

Table 2. Area of land subsidence hazard potential zoning

3.5 Assessment of the Vulnerability of Urban Water and Wastewater Networks

The spatial assessment of vulnerability to land subsidence hazards across the city of Tabriz constitutes a central component of this study. Urban water and wastewater infrastructures are critical to the functionality and resilience of any city, and in Tabriz, they play a pivotal role in satisfying the essential needs of the population. The potable water distribution system of Tabriz primarily comprises two components: qanat channels and water transmission pipelines. These systems rely on gravitational flow sourced from surrounding well fields, as well as from both traditional and modern qanats. The city's drinking water is supplied through the treatment and conveyance of water from the Nahand and Zarrineh Rud rivers. The wastewater network of Tabriz has been operational since 2001, conveying sewage by gravity to a treatment facility located approximately four kilometres west of the urban center. Figure 4 presents the spatial distribution of Tabriz's potable water (a) and wastewater (b) networks.

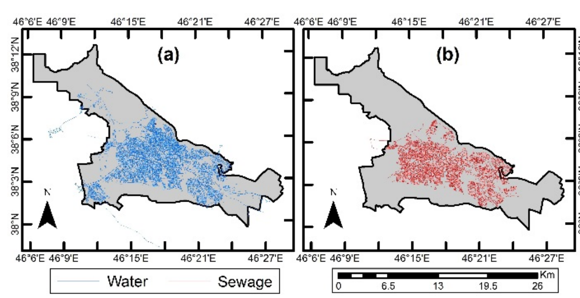

Figure 4. Infrastructure network maps of potable water and wastewater in Tabriz: (a) potable water, (b) wastewater

Subsequently, the spatial vulnerability of the water and wastewater infrastructures across the study area was analysed. To achieve this, the Spatial Join function in the GIS environment was used to spatially overlay the land subsidence hazard zoning map with the water and wastewater network maps. Similar to the hazard zoning map, the resulting vulnerability map was classified into four categories, as shown in Figure 5. As illustrated, a significant portion of Tabriz's water and wastewater networks, highlighted in red, lies within the "very high vulnerability" zone, indicating that land subsidence has the potential to cause severe damage to these infrastructures. According to the evaluation, approximately 33.8% of the water network and 32.9% of the wastewater network of Tabriz fall within the very high vulnerability zone to land subsidence. In contrast, only 2.35% of the water network and 1.08% of the wastewater network fall within the very low vulnerability zone. These findings highlight that the vulnerability of the region's water and wastewater infrastructures to land subsidence hazards must be taken seriously, necessitating preventive and engineering measures to mitigate potential future damages.

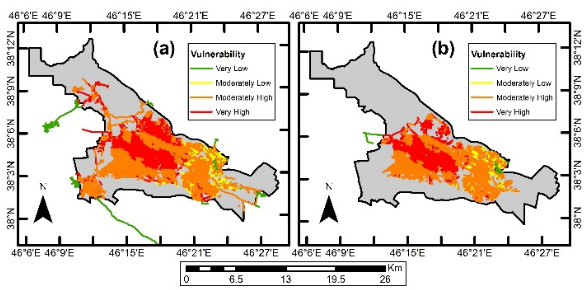

Figure 5. Vulnerability map of water and wastewater networks to land subsidence hazards: (a) potable water, (b) wastewater

The hazard zoning results were validated against observed land subsidence in Tabriz using COSMO-SkyMed satellite imagery. Figure 6 illustrates the spatial overlay of observed subsidence and its potential occurrence as predicted by the hazard model. The analysis indicates that land subsidence has affected approximately 4148.2 hectares, corresponding to 16.5% of the total urban area. Maximum subsidence reached 39.47 cm in certain locations. Overlay analysis further revealed that around 3873 hectares are at risk of land subsidence. The GIS–MCDA-derived hazard zoning exhibited a spatial agreement of 93.3% with the subsidence map obtained from COSMO-SkyMed imagery, demonstrating strong concordance despite variations in subsidence intensity across different urban sectors.
Consistent with the hazard zoning results, which identified the western half of Tabriz as highly susceptible, most observed subsidence events were concentrated in this region. Key hotspots include Tabriz Airport, the railway corridor, agricultural lands, and the western industrial zone. The primary driver of subsidence is excessive groundwater extraction from deep and semi-deep wells. Intensive withdrawal for agricultural and industrial purposes has led to a pronounced decline in the groundwater table in western Tabriz. The lack of permanent rivers and modern irrigation infrastructure has exacerbated dependence on groundwater resources. Consequently, this has resulted in the development of deep ground fissures, damage to agricultural lands, structural cracking of buildings, and threats to critical infrastructure, including roads, railways, and water and wastewater networks.

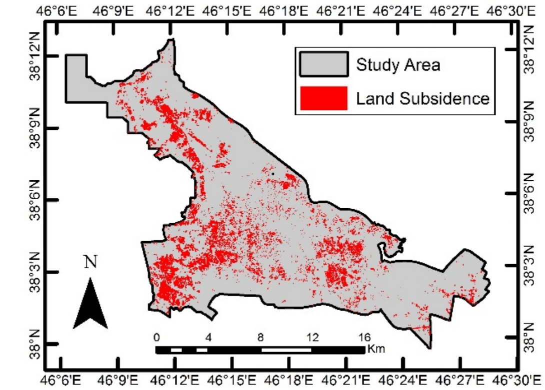

Figure 6. Spatial overlay map of observed land subsidence and its potential occurrence in Tabriz city

4. Discussion

This study provides a comprehensive assessment of land subsidence hazards and infrastructure vulnerability in Tabriz, revealing a critical geohazard situation across the metropolitan area. The analysis indicates that approximately 94.81% of the urban extent falls within moderate-to-high risk categories, with the western plains emerging as the most prominent subsidence hotspot. This spatial pattern is consistent with global observations, particularly those reported by Abidin et al. (2011) in Jakarta and Gambolati et al. (2015) in their theoretical modeling of subsidence mechanisms, both of which associate severe subsidence with flat, alluvial plains subjected to excessive groundwater withdrawal for industrial and agricultural purposes. The hydrogeological and geomorphological parallels between these regions reinforce the inference that anthropogenic overexploitation of aquifers, coupled with the compressible nature of alluvial sediments, is the dominant driver of ground deformation in Tabriz.
The strong spatial correspondence (93.3%) between the multi-criteria GIS-based hazard model and InSAR-derived subsidence data from COSMO-SkyMed imagery provides a high level of methodological confidence. This agreement not only validates the integrated modeling framework but also demonstrates the synergistic potential of remote sensing and GIS-based multi-criteria evaluation for predictive subsidence risk mapping in rapidly urbanizing regions. The model's robustness suggests it can be replicated or adapted for other subsidence-prone basins characterized by limited ground-based monitoring infrastructure.
Beyond delineating hazard zones, this research advances the discussion by incorporating a critical vulnerability assessment of urban infrastructure, which reveals that nearly one-third of Tabriz's essential water and wastewater networks are situated within areas classified as "very high vulnerability." This finding has profound implications, as it mirrors the outcomes observed by Shirzaei and Bürgmann (2018), who documented that persistent ground displacement can rupture underground utility lines, disrupt service continuity, and escalate maintenance costs. The clustering of subsidence near critical facilities—including the airport, railway corridor, and industrial estates—further emphasizes the compounded risks to urban functionality, transportation safety, and socio-economic resilience.
These results collectively underscore that land subsidence in Tabriz is not an isolated geological issue but a multi-dimensional urban hazard with direct consequences for public safety, infrastructure sustainability, and spatial planning. Consequently, the study highlights an urgent need for policy

and management interventions, including the regulation of groundwater abstraction, promotion of aquifer recharge initiatives, and the implementation of engineering measures to safeguard lifeline infrastructures. Integrating these strategies into urban planning and environmental governance frameworks will be crucial for enhancing the long-term resilience of Tabriz against subsidence-induced risks.

5. Conclusion

Land subsidence, often driven by excessive groundwater extraction, represents a creeping and irreversible crisis that is exacerbated by population growth and increasing pressure on water resources. In urban areas, due to high population density and concentrated infrastructures, this phenomenon causes considerable damage and directly threatens water and wastewater transmission networks, gas pipelines, roads, railways, and building foundations. Therefore, comprehensive studies and continuous monitoring through integrated and precise approaches are of critical importance for achieving a sound understanding of its extent and magnitude. Such investigations provide the essential foundation for safe urban planning, sustainable water resource management, and the protection of national assets against irreparable financial and human losses.

In this context, the present study conducted a land subsidence hazard assessment in Tabriz, one of the key population and industrial center of northwestern Iran, by adopting an integrated approach and leveraging the capabilities of RS–GIS to analyze the spatial dimensions of this hazard. The study constitutes a significant step toward zoning the potential of land subsidence occurrence in the metropolis of Tabriz. The findings, which indicate a high subsidence potential across substantial portions of the urban area and a strong spatial correspondence between the hazard potential map and observed data, clearly demonstrate the effectiveness of integrated RS–GIS approaches in producing accurate hazard models and validations.

The key innovation of this research lies in the integration of influential environmental layers (such as groundwater depth, drainage density, fault density, and land use) with satellite-based surface deformation monitoring data as empirical evidence, thereby providing a comprehensive and reliable model for decision-makers and urban planners. As a recommended pathway for future studies, the development of a dynamic, machine learning–based model is proposed. Such a model, integrating LIDAR data, three-dimensional subsurface modeling, and InSAR time-series datasets, could zone land subsidence potential while also predicting its magnitude and rate of change under various climate change and water resource management scenarios. This transition from static to dynamic modeling would mark a fundamental advancement in the management of this critical hazard.

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