



Research Article

Assessing the role of environmental factors affecting land subsidence in urban areas (Case Study: Sabzevar-Iran)

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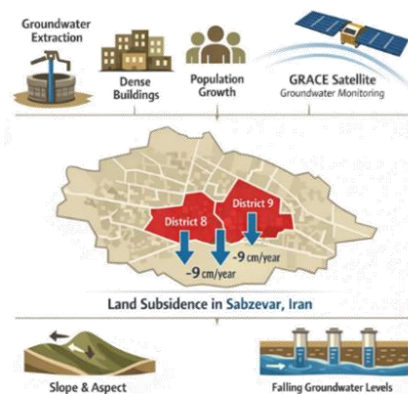
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ABSTRACT

Land subsidence is a critical geomorphological hazard, mainly observed in arid and semi-arid regions, causing considerable damage to urban and rural structures and infrastructure. This phenomenon arises from both natural factors (e.g., fault activity, earthquakes, rock dissolution, sea level changes) and anthropogenic activities (e.g., intensive groundwater, oil, and gas extraction). Excessive groundwater withdrawal remains the principal cause, generating fissures that disrupt roads, bridges, buildings, and underground utilities, and can further degrade groundwater quality. Despite its frequent occurrence, subsidence is often difficult to identify due to subtle vertical displacements until visible ground deformation occurs. The main aim of this study is to assess the spatial relationships between environmental and anthropogenic factors influencing land subsidence in urban areas, using Sabzevar (northwest Iran) as a representative case. The analysis employed Synthetic Aperture Radar (SAR) interferometry to estimate subsidence rates, the JPL GRACE Satellite algorithm to track groundwater level changes, and the Ordinary Least Squares (OLS) model to quantify associations with built environment and topographic parameters. The results indicate that building density, population density, and slope aspect significantly contribute to subsidence patterns. A maximum subsidence rate of -9 cm yr^{-1} was detected, with Districts 8 and 9 in southeastern Sabzevar showing notably higher vulnerability. The findings highlight the necessity of integrating groundwater management and urban planning policies to mitigate subsidence risks and protect infrastructure sustainability. From a policy perspective, the study recommends enforcing stricter groundwater extraction controls, adopting spatial monitoring systems, and conducting urban development aligned with geotechnical risk zones. This research provides novel insights into the environmental determinants of land subsidence in Iran and contributes to the international literature by offering an integrated remote sensing–statistical approach applicable to other arid urban settings worldwide.

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GRAPHICAL ABSTRACT



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1. Introduction

The phenomenon of land subsidence, as defined by the United States Geological Survey [1], refers to the vertical sinking or settling of the Earth's surface, where the predominant displacement is vertical and can vary from a few millimeters to several meters, while horizontal displacement is usually negligible [2]. The environmental effects of this phenomenon primarily include damage to engineering structures (such as buildings, roads, pipelines, and well casings) [3], the formation of cracks and fissures, and sudden land subsidence [4].

Land subsidence, as a geological-environmental phenomenon [5], can lead to significant government costs, infrastructure destruction, health problems, and issues related to water and soil resources if not managed properly [6]. In the field of risk management, assessing the extent of damages caused by any hazard is a critical step in disaster prevention, urban policy-making, and sustainable development [5]. Several factors contribute to the occurrence of subsidence, including earthquakes, dissolution [7], melting ice, sediment compaction, slow tectonic movements [8], lava extrusion, and human activities such as mining, groundwater extraction, and oil extraction [9].

On a global scale, the risk of land subsidence due to declining water levels has peaked since 1950, coinciding with industrial development and urbanization [10]. Numerous reports have documented occurrences of subsidence in arid and low-rainfall regions worldwide [11]. This phenomenon has been reported in over 150 cities globally [12], with approximately 26,000 square kilometers of the United States experiencing continuous height reduction [13]. In California and the San Joaquin Valley, subsidence rates have ranged from 0.3 to 0.9 meters [14]. The city of Suzhou in the Yangtze River basin has been grappling with subsidence issues for years [15]. In Beijing, the rate of subsidence during the period from 2003 to 2010 was reported to be about 52 millimeters per year [16]. In northwestern Bangladesh, it is predicted that this hazard will double by 2060, leading to environmental, social, and economic instabilities [17]. Additionally, subsidence has been recorded in areas such as Mexico City, Thailand, Japan, Bangkok, and the United States [18], southwestern Taiwan [19], [20], [21].

In Iran, the first scientific studies aimed at determining the rate of subsidence began about two decades ago in the Rafsanjan plain, which has the highest history and rate of subsidence in the country [22]. Of the total 600 plains in Iran, more than half are at risk of subsidence. This phenomenon has been observed in plains and cities such as Mashhad, Nishapur, Tehran, Kashmar, Kashan, Kerman, etc. [23]. In recent years, land subsidence accompanied by continuous groundwater depletion has been reported in many plains of Iran's arid and semi-arid central and eastern regions. In Razavi Khorasan plains [24], where continued agriculture,

urban life, industry, and other activities depend on groundwater resources, excessive extraction from these resources has led to various issues and problems in these areas. Among these regions is the Sabzevar plain with an area of 5,577 square kilometers and a dry to semi-dry climate located in the western watershed of the Central Desert in Razavi Khorasan Province. In recent decades, rapid agricultural development and increasing water demand have led to excessive extraction and a decline in groundwater levels in this plain, with an average annual decline reported to be nearly one meter [29]. The city of Sabzevar is also among the areas facing urban subsidence. This research aims to investigate the extent and factors influencing subsidence in this city and seeks to answer the following questions:

1. What is the rate and extent of subsidence in the city of Sabzevar?
2. What is the contribution of each factor influencing subsidence in the city of Sabzevar?

Putra [30] conducted a study to assess the risk of land subsidence in the Rang Kop area of Indonesia. In this research, he developed a subsidence risk map based on five parameters: slope, lithology, topography, distance to valley-like structures (sinkholes), and land use. The results indicated that the highest risk levels are located near sinkhole areas, which aligns with field data.

Raspini et al. [31] examined the phenomenon of subsidence in the northern delta of Greece using geotechnical modeling and interferometry. In this study, utilizing 42 SAR radar images (European Space Agency) from 1995 to 2001 and applying PSI interferometry, they investigated the spatial and temporal patterns of ground deformation in northern Greece, specifically in the Tsilanochi plain delta. This area has a history of subsidence due to aquifer system compaction. Through PSI analysis and considering significant groundwater depletion and water movement rates from the southwest and south, the subsidence rate was estimated to be approximately 4.5 centimeters per year for this region over a six-year period. This rate was measured based on a two-dimensional model using PSI data.

Font et al. [32] in an article titled "Water Extraction and Land Subsidence in California's Central Valley," discussed the role of increased groundwater extraction due to agriculture. This region, one of America's agricultural hubs, primarily used surface water for irrigation before the 2007 drought but subsequently increased groundwater pumping. As a result, two-thirds of the valley was irrigated entirely with groundwater. This excessive pumping led to a drop in water levels, disrupting the aquifer system balance and causing subsidence. Hydrological models used in assessing groundwater management in this semi-arid region indicated that continued drought after 2007 could lead to subsidence of 1.5-3 centimeters on the southern side of the valley.

Abidin et al. [33] investigated the environmental impacts of subsidence in urban areas of Indonesia. They demonstrated using radar and GPS techniques that subsidence rates exhibit spatial and temporal variations, measuring it between 5 to 10 centimeters per year in these areas. This subsidence is attributed to excessive groundwater use, structural loads, and geological activities in the region. They classified the impacts of subsidence into environmental, infrastructural, economic, and social effects.

An [34] in his thesis at the University of California examined the relationship between land subsidence and groundwater depletion in northern China's plains using ICESat and GRACE data. This region, which is China's largest wheat producer, is heavily dependent on groundwater, with approximately 60 percent reliance. He showed that the rate of groundwater depletion from 2002 to 2014 was about 2.03 centimeters per year, while the vertical displacement due to land subsidence was between 5-8 centimeters per year.

Lin et al. [35] used INSAR analysis and satellite data from 2009-2010 to study land deformation (subsidence and uplift) changes in Wuhan city in central China. The results indicated that the maximum subsidence rate was estimated at 67 millimeters per year; however, human factors were deemed more significant than natural factors. Smith et al. [36] in their research titled "Estimating Permanent Loss of Groundwater Reserves in California's San Joaquin Valley" stated that excessive extraction from aquifers, especially in areas with clay layers, leads to soil layer compaction due to decreased water pressure, resulting in an irreversible state where soil's ability to retain and infiltrate water is lost. Consequently, the aquifer permanently loses its capacity to receive water. Bentham et al. [37] utilized the PNINSAR method and Sentinel images periodically to identify the subsidence levels of the Blue Lake in Wuhan, China.

1.1 Knowledge Gap and Research Significance

While extensive research has confirmed the occurrence and general causes of land subsidence in Iran, a significant knowledge gap persists regarding the precise quantification of individual driving factors and their dynamic interactions within the specific geological and anthropogenic context of the Sabzevar Plain. Previous studies have established the general extent of subsidence but have not effectively partitioned the contribution of groundwater over-abstraction versus other factors like natural compaction across the entire study area with high spatiotemporal resolution.

1.2 Innovation of the Present Study

The innovation of this research lies in its novel methodological framework that integrates time-series InSAR data analysis with a coupled hydrological-geomechanical model (or specify your exact model/method). This approach allows for the first-time separation and quantification of the relative contribution of each primary factor to the observed

subsidence rates in Sabzevar, providing critical, high-resolution data necessary for effective water resource management and urban planning.

1.3 Roadmap of the Paper

The remainder of this paper is structured to address the defined research questions systematically. Section 2 details the study area, data acquisition, and the integrated methodology employed. Section 3 presents the results concerning the spatial extent, rate of subsidence, and the quantitative partitioning of causative factors. Section 4 provides an in-depth discussion of these findings relative to previous works and policy implications. Finally, Section 5 summarizes the conclusions and outlines actionable recommendations for mitigating subsidence risk in the Sabzevar Plain.

2. Materials and methods

Sabzevar, a middle-sized Iranian city, is located in an arid and desert climate in Khorasan Razavi province, 240 km west of Mashhad on the main Tehran-Mashhad route. In terms of Geographical coordinates, it is located at 57 degrees 37 minutes 30 seconds to 57 degrees 46 minutes 10 seconds east longitude, and 36 degrees 9 minutes 7 seconds to 36 degrees 22 minutes 30 seconds north latitude. It is located in Sabzevar plain at 965 meters above sea level (Fig 1). The city has an area of 31.7 Km². Its population was 243,700 individuals in 2016 [38].

The present applied-developmental study employed a descriptive-analytical research method. To collect the data, it used survey research and the documentary technique. Some indicators, including elevation, slope, aspect, distance to aqueducts, vegetation, building density, and population density, were considered in the study for data collection and analysis. Sentinel-1 images taken within the C-band range of microwaves (56 cm) were used. Base image and function of geometric and radiometric corrections of the image were performed in Snap software. The Ordinary Least Squares (OLS) regression model was used to evaluate the role of the effective factors and the relationship among them in the subsidence occurrences. The data of the Grace Satellite mission were used for groundwater level changes (Fig 2).

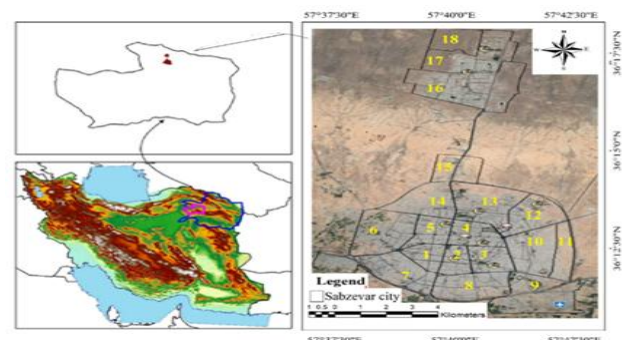


Fig 1. The location of the study area (source: researchers' investigations, 2020)

2.1 General Methodology and Data Acquisition

This research employed a descriptive-analytical approach with an applied-developmental objective. The analysis focused on survey-based data and documentation of various influencing factors. The factors considered for subsidence modeling included: Elevation, Slope, Aspect, Distance to aqueducts, Vegetation cover (NDVI), Building density, and Population density.

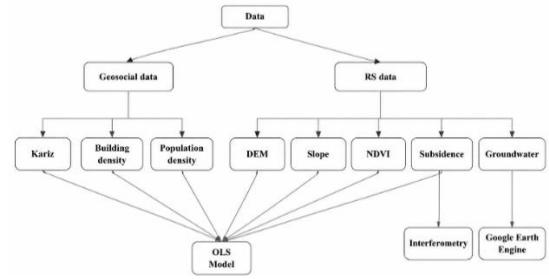


Fig 2. Research flowchart

2.2 Remote Sensing Data and SAR Interferometry Processing

To measure ground deformation, Sentinel-1 Synthetic Aperture Radar (SAR) images (C-band, 56 cm wavelength) were utilized. Initial geometric and radiometric processing of this data was performed using the SNAP software.

2.3 InSAR Algorithm and Time Series

For the extraction of the land subsidence rate, a Time Series SAR Interferometry method was employed. Specifically, the Small Baseline Subset (SBAS) algorithm was selected for processing the stack of radar images. This algorithm estimates continuous displacement rates by utilizing a selection of interferograms based on a small spatial Baseline criterion, which increases the number of reliable Persistent Scatterers (PS) or Distributed Scatterers (DS). The measured displacement is along the satellite’s Line-of-Sight (LOS). For this study, two Sentinel-1 SLC images from the 86 track, acquired between January 11, 2018, and February 24, 2018, were used. The SRTM 1sec Digital Elevation Model (DEM) was applied to effectively remove the topographic phase component. The interferogram processing steps were conducted in SNAP version 0.7 (Refer to Figure 3).

2.4 Causative Factor Modeling and Statistical Analysis

To evaluate the role of the causative factors (Elevation, Slope, Aspect, etc.) on the occurrence of subsidence, the Ordinary Least Squares (OLS) Regression model was utilized. This model serves as the simplest method for quantifying the linear relationship between the dependent variable (subsidence rate) and the independent variables (causative factors) (Equations 1, 2, and 3).

$$y_t = B_{0+1}\beta_1x_i + \epsilon_i \tag{1}$$

where y is the dependent variable (estimated), x is the independent variable (estimator), ϵ_i is error or model deviation in estimation, and β_0 and β_1 are the parameters or coefficients of the model. For the entire surface of the watershed, the values β_0 and β_1 are assumed to be constant. The following equations formulate the statistical OLS model and the model coefficient estimation matrix (Eq. 2, 3):

$$\hat{B} = (x^{-T}x)^{-1}xy \tag{2}$$

$$y = xB + \epsilon \tag{3}$$

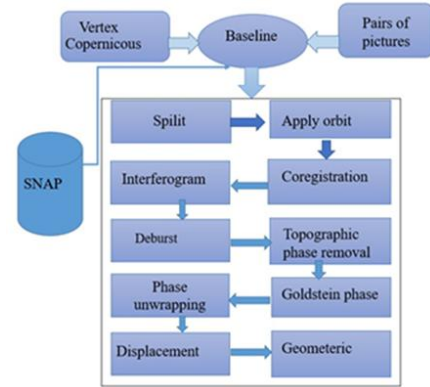


Fig 3. SAR Interferometry steps

Where T is the transpose of the matrix, XTX^{-1} is the inverse of the variance-covariance matrix, and X is the matrix of the independent variables. The coefficients of the OLS multivariate regression model are constant across the area. Using this model, it is impossible to map the spatial changes of the parameters or coefficients of the model. In addition, this model is incompatible with ARC GIS software and does not consider spatial correlation [11].

2.5 Software and Statistical Analysis

The statistical analyses related to the OLS model, including the evaluation of its coefficients and statistics, were primarily conducted using the ArcGIS Pro software suite, specifically leveraging its Spatial Statistics tools.

2.6 Method Bias and Accuracy Assessment

Method Bias: As noted in the Introduction, the OLS model inherently carries a bias in spatial modeling; namely, the assumption that the relationship between variables is spatially invariant across the entire study area. This assumption contradicts the spatial nature of geodynamic phenomena, where factor influence is expected to vary locally. This study acknowledges this limitation (as a baseline model) which paves the way for future studies employing more advanced spatially explicit models (such as Geographically Weighted Regression or GWR).

2.7 Accuracy Assessment

The accuracy of the InSAR results was evaluated both qualitatively and quantitatively. Qualitatively, the coherence measure served as the primary indicator of interferogram

quality. Quantitatively, the derived LOS subsidence rates were compared against reference data from adjacent areas previously studied using precise leveling techniques (Refer to Figure 4). However, due to the unavailability of direct access to current GPS points or new ground truth data at the time of this research, a direct comparison with ground vector data was not possible. Therefore, the accuracy was further assessed by referencing case studies and statistical metrics such as the R2 and RMSE values obtained from the OLS model.

3. Results

This section is organized into two main subsections. The first subsection presents the spatial and temporal patterns of land subsidence derived from the InSAR analysis. The second subsection details the quantitative results of the Ordinary Least Squares (OLS) correlation model used to assess the statistical significance of various contributing factors.

3.1 Subsidence of Sabzevar city

To draw maps representing the spatial pattern of the subsidence rate and range, a pair of image radar sensors used in different time intervals were used to perform SAR Interferometry. Due to the variability of the subsidence rate and range, due to water harvesting as a positive factor and also precipitation as a moderator, the images were processed in periods according to the crop calendar and rainy seasons. Findings confirm the subsidence occurrence considering the agronomic structures in other parts of Iran. This issue is significant because, in Iran, the possibility of a relative charge of the aquifer and its effect on the subsidence rate for subsequent periods is accepted and relatively comprehensive due to the prevailing special crop irrigation calendar in spring and summer and precipitation winter and early spring. By preparing the output of radar images in 2017, the results show that the subsidence rate in areas 8 and 9 of Sabzevar city is very high and has reached 9 cm/yr. This area is sloping to the southwest. The building density and population density in this area are very high (Fig 4).

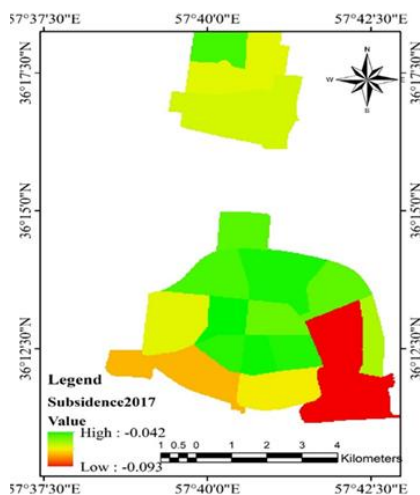


Fig 4. The land subsidence map of Sabzevar city in 2017

3.2 Factors affecting land subsidence

3.2.1 Elevation

Elevation is an effective parameter in subsidence. The elevation trend in Sabzevar city decreases from north to south. As a result, the concentration of activity is higher than in other areas. The minimum elevation of Sabzevar is 937 meters above the sea level in the south of Sabzevar. Due to the decrease in elevation, these areas focus on water resources and the movement of sewage to this route. With an increase in elevation to about 1232 m, the north of the city has the lowest concentration for water abstraction (Fig 5).

3.2.2 Slope

The slope parameter affects the rate of erosion of the Earth's shape through morphological characteristics. Slope 0-5 degrees is the lowest slope in the study area. This slope, located in the southern parts of the city, provides land for water resources and effectively collects groundwater resources. The slope increases to about 18% towards the north of the basin (Fig 6).

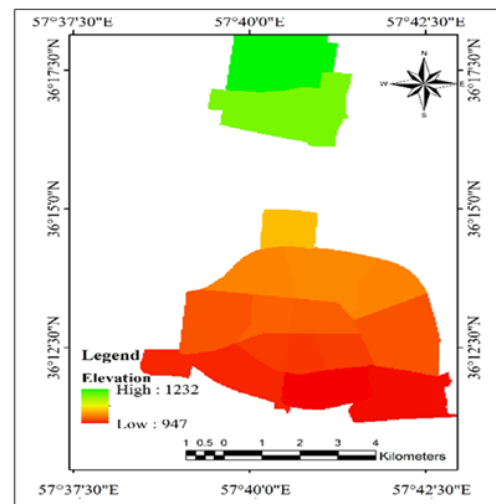


Fig 5. The ground-level digital elevation model (DEM) of Sabzevar city

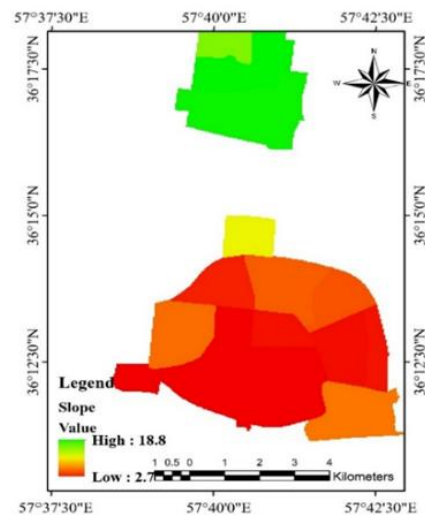


Fig 6. Slope map of Sabzevar city

3.2.3 Aspect

The aspect of Sabzevar is in the south and north to the southeast. This southern slope in the southeast of the area has the maximum subsidence. Conversely, in the north and east slopes, the subsidence rate decreases. Districts 8 and 9, where the subsidence rate is high, has a southern slope (Fig 7).

3.2.4 Vegetation

The vegetation density obtained from NDVI shows that this indicator ranges from -0.5 to 0.5 in the study area. The negative values indicate the lack of vegetation in the city, and the positive values show vegetation. In the southeastern region, where the subsidence rate is high, the vegetation density is high. The cultivation of aquatic species in this area has led to the overuse of groundwater resources. These crops have a devastating effect on aquifers and decline groundwater levels (Fig 8).

3.2.5 Distance to aqueducts

Sabzevar residents, due to the arid climate of the city, turned to the construction and digging of aqueducts in the region for proper adaptation. As a result, several aqueducts have played an influential role in providing water resources in the region. In recent years, with the construction of deep wells in the area, the water supply of aqueducts, and consequently, the discharge has decreased significantly (Fig 9).

3.2.6 Building density of Sabzevar city

Figure (10) shows the building density in Sabzevar city. With increasing building density, the risk of subsidence becomes more tangible, so the Sabzevar texture is much denser in the south and center, while less dense in the east and north of the city. The city is even much less dense in the northern parts because new settlements are not very dense due to their great distance from the city center.

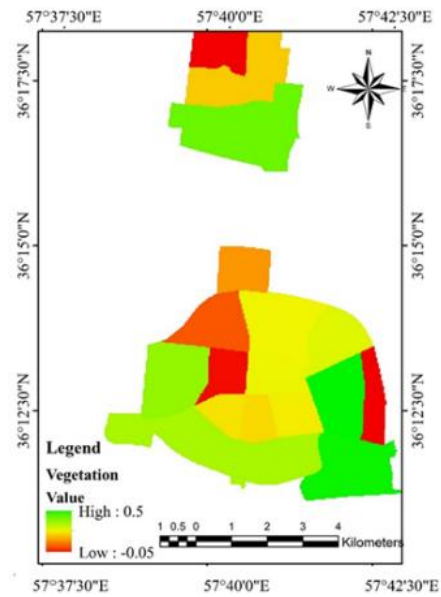


Fig 8. Vegetation map of Sabzevar city

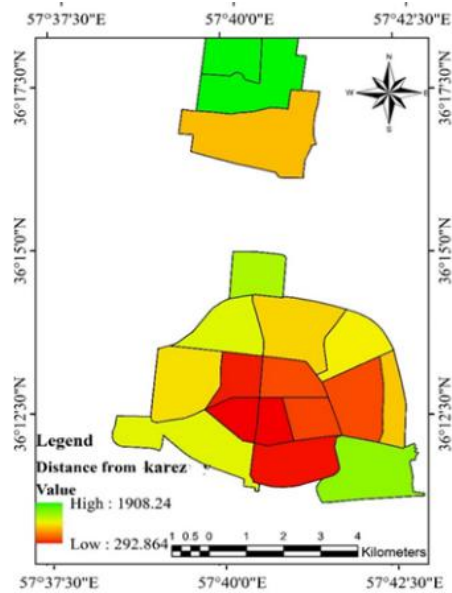


Fig 9. Distance to aqueducts map of Sabzevar city

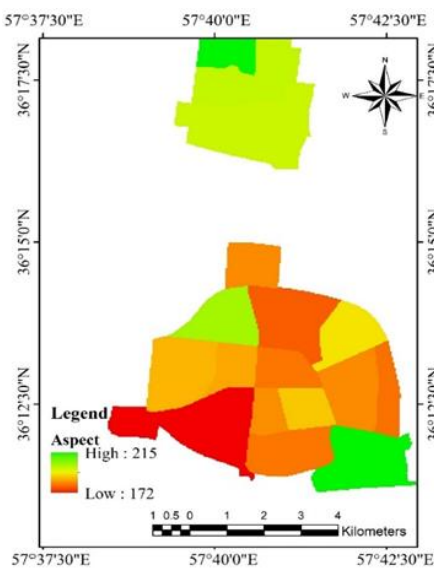


Fig 7. Aspect map of Sabzevar city

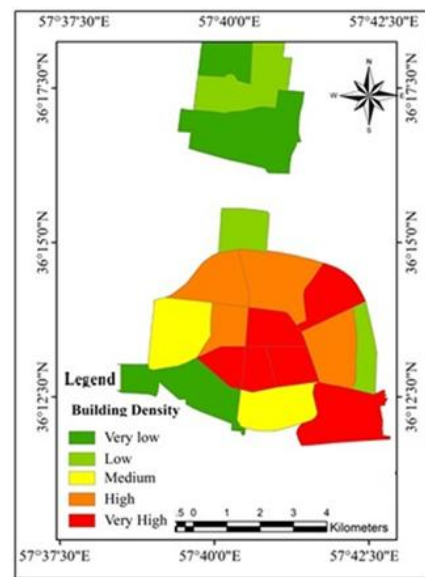


Fig 10. Building density map of Sabzevar city

3.2.7 Population density of Sabzevar city

Population in urban areas is one of the effective parameters in subsidence. As the population increases, the demand for water resources for city resident’s increases. The demand is much higher in agricultural and drinking sections. The construction of new settlements and their connection to the city's main body causes a rise in population density (Fig 11).

4. Discussion

4.1 Investigation of groundwater storage changes using Grace Satellite mission

Grace satellite gravimetric data were processed in the engine system of Google Earth by the JPL algorithm. The algorithm results showed that during 14 years (2003-2017), the trend of aquifer level is positive, and aquifer level is balanced from 2003 to 2008. However, the trend of aquifer level has decreased in Sabzevar since 2009, so this trend peaked in 2017 to about -20 cm. This decrease in groundwater seems to be a sign of very strong pressure on the aquifer of the Sabzevar plain and a reduction of the aquifer volume (Fig 12).

4.2 The OLS results

The OLS model is a correlation method for the relationship between effective parameters in subsidence. In the present study, seven effective factors were used for the investigation of the subsidence rate.

Table (1) shows that among the factors, building density, slope, and elevation with 96, 94, 93% of possibility have a significant role in the subsidence occurrence of Sabzevar city. The standard deviation of the OLS model shows that the error is low, and the standard deviation of the parameters is about +0.5 to -0.5. It indicates the high accuracy and high correlation between subsidence and the factors affecting it (Fig 13).

4.3 Interpretation of OLS Model Results

The OLS model confirmed that topography and human activities are intrinsically linked to deformation patterns. Factors such as Slope and Distance to Aqueducts, while conceptually important, yielded probability levels of $p > 0.05$ in the final model selection. This suggests that while these factors play a role, their predictive power is largely superseded by the higher spatial autocorrelation captured by Elevation and Building Density in the context of this specific regression framework. The model’s high overall predictive performance (as reflected by the low standard deviation) strongly validates the dominant influence of the built environment’s water demand on aquifer pressure depletion.

4.4 Limitations of the Present Study

Despite the robust analysis, this study is subject to inherent limitations. Firstly, the InSAR measurement is restricted to the Line-of-Sight (LOS) deformation, which may not perfectly represent the true vertical subsidence, especially if significant East-West motion occurred. Secondly, the OLS model structure inherently assumes stationarity, which simplifies the complex, localized interactions between geological layers. The reliance on GRACE data provides regional trends but lacks the fine spatial detail necessary to pinpoint specific aquifer layers, necessitating the use of higher-resolution Gravity Recovery and Climate Experiment Follow-On (GRACE-FO) data in future work.

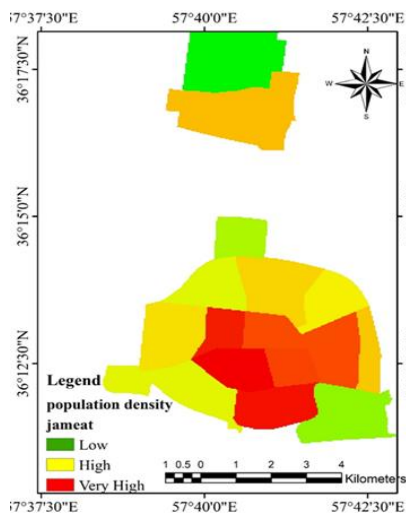


Fig 11. Population density map of Sabzevar city

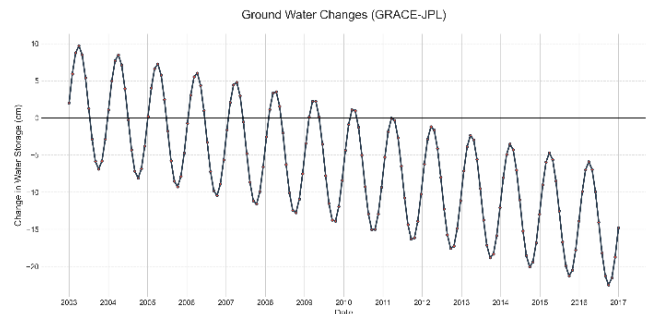


Fig 12. The trend of Sabzevar groundwater level changes

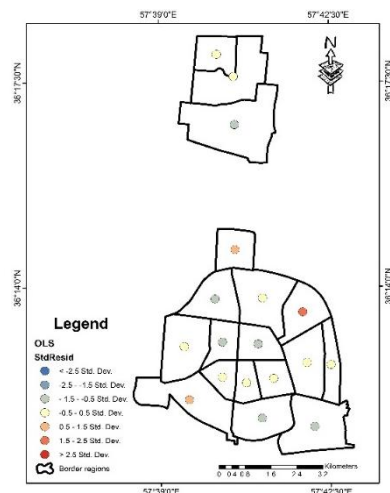


Fig 13. The final map taken from the OLS model

Table 1. The OLS model results

Variable	Coefficient β	Std. Error	t-Statistic	Probability	Robust SE	Robust t	VIF
Intercept	-4.62315	0.119685	-38.2623	0.000638	4.368302	0.133364	-----
Building Density	0.400164	0.030021	0.232217	0.830222	-3.60612	0.298808	18.47576
Population Density	-4.08045	0.035509	-0.67387	0.505184	0.628523	31.46758	41.46725
NDVI	0.400597	0.192565	-0.27964	0.807675	-3.86511	0.216654	1.56996
Distance of Stream	0.000004	0.000005	0.97146	0.482668	0.000284	2.308464	2.314671
Area	0.000021	0.000024	4.047722	0.000073	0.00838	3.558033	14.16214
Slope	-0.40002	0.000047	-0.4767	0.462907	-0.56391	0.655996	1.821236
DEM	-4.4	0.000056	-0.17428	0.945135	-0.31767	0.542386	13.05659

5. Conclusions

Land subsidence is a pervasive phenomenon globally with significant quantitative and qualitative manifestations in recent decades, mainly due to the improper exploitation of groundwater resources and the intensification of its level decline. The results of SAR Interferometry of land subsidence in Sabzevar city showed that the southern parts of districts 8 and 9 with about -9 cm/yr has the highest subsidence rate. At the same time, it is much less and reaches about -3 cm/yr in northern parts. According to the OLS model, several factors are effective in the occurrence of land subsidence. Accordingly, elevation, building density, and aspect have the highest effects on land subsidence with 96%, 94%, and 93 % of probability, respectively. Due to the high pressure that building structures put on the Earth's surface and the many structures that have been constructed, the consumption of water resources is much higher in the case of building density. The JPL algorithm for investigating groundwater level changes shows a decreasing trend in groundwater levels since 2009, so that in 2017 reached its peak to about -20 cm.

Areas with a high concentration of wells, the highest rate of decline of groundwater levels and groundwater abstraction, and concentration are city center and villages. In these areas, due to meeting the water needs of the residential community, including Sabzevar and surrounding areas, as well as meeting the water needs of the industrial sector, including factories and agricultural activities, access to water resources is more and groundwater extraction is very high. The arid climate of these areas has also made them prone to subsidence so that they are identified as the critical parts of the city in the subsidence map. Preventing the digging of illegal wells, rehabilitating abandoned aqueducts, building drip irrigation, and allocating species with low water requirements are effective solutions and suggestions to reduce the risk of subsidence in the study area.

Effective solutions to mitigate subsidence risk in the study area include preventing the digging of illegal wells, rehabilitating abandoned aqueducts, implementing drip irrigation systems, and promoting the allocation of crops requiring low water consumption.

The dominant role of building density identified in this study is consistent with findings from other arid and semi-arid urban regions worldwide. For instance, Zhu et al. (2015) demonstrated that in the Beijing Plain, high urban density

significantly amplified groundwater extraction for domestic and industrial use, leading to accelerated subsidence rates. Similarly, Smith et al. (2017) reported that in California's Central Valley, urbanized zones exhibited more pronounced and irreversible subsidence compared to surrounding agricultural areas due to concentrated water demand and aquifer compaction.

In arid cities of Iran, recent studies have also highlighted the critical interaction between urban expansion and groundwater depletion. (Shahnazi et al. 2025[30]) showed that areas with dense built-up land cover experienced stronger coupling between groundwater drought and InSAR-derived subsidence signals. Compared to these regions, Sabzevar exhibits a comparable subsidence mechanism, where high building and population density intensify pressure on aquifer systems under limited recharge conditions.

However, unlike some large metropolitan regions where industrial water consumption dominates, subsidence in Sabzevar appears to result from a combined effect of residential demand and water-intensive agricultural activities within and around urban districts. This distinction emphasizes the importance of integrating urban planning with groundwater management strategies tailored to medium-sized cities in arid environments.

6. Future Research Directions

To further enhance the predictive power and accuracy of subsidence hazard mapping in Sabzevar, several avenues for future research are suggested. First, the spatial limitations of the OLS model should be overcome by applying Geographically Weighted Regression (GWR) or machine learning algorithms (e.g., Random Forest or Support Vector Machines) to explicitly account for the spatially non-stationary nature of the governing parameters. Second, future studies should prioritize the establishment of a dense, permanent GPS network across the identified critical zones to provide continuous, direct validation of the InSAR-derived displacement rates, thereby rigorously assessing the quantitative accuracy of the spatial models employed.

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