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Assessment of Land Surface Displacement Along the Hamadan–Sanandaj Railway Corridor and Its Relationship with Groundwater Level Changes

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Original Article

Abstract

INTRODUCTION: Land subsidence is a geomorphological process that can have environmental, social, and economic consequences. In Iran, this phenomenon is associated with factors such as unsustainable groundwater extraction, climate variability, and increasing water demand. This study aimed to assess land surface displacement along the Hamadan–Sanandaj railway corridor, focusing on the Dehgolan–Qorveh and Hamadan–Bahar sections, and to examine its relationship with groundwater level changes.

METHODS: An integrated approach based on literature review and field studies was adopted. Sentinel-1 time-series images were processed using Interferometric Synthetic Aperture Radar (InSAR), and the resulting displacement estimates were compared with groundwater level data recorded by regional piezometers.

FINDINGS: Analysis of Sentinel-1 radar imagery showed that the maximum negative displacement along the satellite Line of Sight (LOS) during the periods 2019–2020, 2020–2021, and 2021–2022 was 0.17, 1.10, and 1.50 cm, respectively. Higher displacement values were mainly concentrated in the Dehgolan–Qorveh area. Piezometric data were used to assess the relationship between groundwater level changes and land surface displacement.

CONCLUSION: Given the nature of radar measurements, the reported values represent displacement along the satellite LOS and should not be interpreted as direct measurements of vertical land subsidence without separating the displacement components. Continued land surface deformation may have implications for the stability of railway and road infrastructure. Therefore, continuous monitoring and integrated management of groundwater resources are essential.

Keywords: Land subsidence; Land surface displacement; Interferometric Synthetic aperture radar; Hamadan–Sanandaj railway; Groundwater.

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Introduction

Land subsidence is the gradual settling or sudden sinking of the Earth's surface caused by the movement of subsurface materials. It is a major geohazard affecting settlements and infrastructure worldwide (1). Subsidence differs from landslides, which involve substantial downslope movement, and from sudden collapses or localized settlement in anthropogenic fill (2–5). In Iran, a predominantly warm and arid climate and the country's geological and geomorphological setting make land subsidence a particular concern (6-9). Over recent decades, drought linked to climate change, together with rapid and poorly planned agricultural expansion, has sharply increased water demand and undermined the sustainability once provided by traditional water management systems.

Iran is divided into 609 plains and groundwater study areas. According to Noori et al. (2023), approximately 422 of these plains were classified as critical or prohibited areas due to groundwater depletion and unsustainable groundwater use (10). These classifications indicate restrictions on groundwater abstraction and do not necessarily confirm the occurrence of

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land subsidence in all the affected plains. The Hamadan–Bahar and Qorveh–Dehgolan plains in western Iran are among the regions where land subsidence has been documented. Previous studies have investigated land subsidence in the Hamadan–Bahar plain using the SBAS time-series method (11), in the Qorveh and Chahardoli plains using the PS-InSAR technique (12), and have examined the effects of groundwater decline on land subsidence in the Dehgolan plain (13).

Both plains are designated as groundwater-prohibited areas. In addition, urban expansion and the development of critical infrastructure, including electricity and gas transmission lines, highways, railway networks, and large buildings, may increase pressure on land and water resources and contribute to the intensification of subsidence-related risks. These issues highlight the importance of monitoring land surface displacement, particularly along critical infrastructure corridors such as the Hamadan–Sanandaj railway.

Small-baseline InSAR time-series methods, such as SBAS, are widely used to detect and monitor ground-surface deformation over extensive geographical areas (14). In Iran, different InSAR approaches, including SBAS, PS-InSAR, and differential InSAR, have been applied to investigate land deformation in several plains, including the Hamadan–Bahar, Qorveh–Chahardoli, Khanmirza, and Qahavand plains (11,12,15,16).

Previous studies have examined the relationship between groundwater-level decline and land subsidence in the Dehgolan plain (13). In the Ajabshir plain, Nouri-Sangarab et al. (17) combined the ALPRIFT-based subsidence susceptibility assessment with Sentinel-1 observations and estimated 2.4 cm of subsidence during 2020–2021. They reported a statistically significant association between the detected subsidence, groundwater levels during the 2020–2021 water year, and the subsidence potential index. In the Semnan plain, Helali et al. (18) identified a maximum displacement of 6 cm between 2014 and 2021, concentrated in two zones. Analysis of groundwater-level records from 23 piezometric wells revealed declines ranging from 0.15 to 8.4 m over the same seven-year period. Similarly, Choubin et al. (19) applied radar interferometry and ensemble soft-computing models to assess land subsidence in the Urmia plain. Using 52 radar-image pairs acquired between 2014 and 2019, they estimated subsidence values ranging from 0 to 59 cm. Their InSAR estimates showed strong agreement with measurements from a permanent geodynamic station (R^2=0.99; RMSE=0.008). Collectively, these studies demonstrate the usefulness of InSAR for mapping regional land surface displacement and examining its association with groundwater-level variations.

Railways are critical linear infrastructure systems whose safe operation depends on the stability of the supporting ground, the condition of associated engineering structures, and the maintenance of acceptable track geometry. Differential ground settlement and localized deformation along railway corridors may alter track geometry, affect subgrade stability, and increase maintenance requirements. Under severe conditions, such deformation may lead to operational restrictions or temporary service closures (20-23). Therefore, monitoring land surface displacement along railway corridors is important for identifying potentially unstable sections, assessing infrastructure conditions, and supporting railway safety and risk management.

In recent years, InSAR has been increasingly applied to monitor land surface displacement along railway corridors in different geographical settings. Shi et al. (20) investigated differential subsidence along the Beijing–Tianjin Intercity Railway in China using multiband synthetic aperture radar data and examined its potential implications for railway operation. Chang et al. (21) integrated Sentinel-1 InSAR and laser-scanning data to identify unstable railway sections and distinguish railway tracks, embankments, and surrounding infrastructure along the Betuwe freight corridor in the Netherlands. Their results showed good agreement with in-situ railway track survey measurements. Xue et al. (22) applied PS-InSAR to monitor and predict regional subsidence along the Taiyuan South–Taigu East high-speed railway in China. More recently, Carlvik et al. (23) investigated the relationship between InSAR-derived land surface displacement, geological conditions, and track geometry irregularities along Sweden's Iron Ore Line. These studies demonstrate the potential of InSAR for monitoring deformation along railway infrastructure. However, the combined assessment of railway-corridor deformation and groundwater-level variations in groundwater-restricted plains remains an important area for further investigation, particularly in western Iran.

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Against this background, the Hamadan–Sanandaj railway corridor provides an important case for investigating land surface displacement in relation to groundwater-level changes. Although InSAR has been widely applied to monitor subsidence in Iranian plains, the Hamadan–Sanandaj railway corridor has received limited attention, and the relationship between land surface displacement along the railway and groundwater-level fluctuations in the surrounding plains has not been sufficiently investigated. Therefore, this study uses multi-temporal interferometric analysis of Sentinel-1 satellite imagery acquired between 2019 and 2022 to quantify land surface displacement along different sections of the Hamadan–Sanandaj railway and examine its spatial and temporal relationship with groundwater-level variations in the Hamadan–Bahar and Qorveh–Dehgolan plains, based on available piezometric-well records.

Table 1. Piezometric stations used in this study

Station name	Longitude	Latitude	Mean annual precipitation (mm)
Dehgolan	47.25	35.17	286.84
Hassan Khan	47.41	35.26	316.60
Khosrowabad	47.56	35.31	323.70
Aliabad	46.57	35.03	530.58
Hosseinabad Qeshlaq	47.07	35.33	418.71
Sarab Qamish	46.56	35.26	367.97
Qorveh	47.47	35.10	251.12
Salavatabad	47.14	35.33	276.75
Grizeh	47.08	35.20	437.62
Qeshlaq	47.00	35.25	554.50
Pir Salman	47.27	34.43	427.55
Sanandaj Airport	47.02	35.15	399.45
Ramesht Tunnel	46.58	35.01	413.00
Gavoshan	46.59	34.58	344.05
Asefabad	47.45	35.05	360.77
Central Ramesht	47.12	35.04	357.94
Sonqor-e Kolyai	47.47	34.58	390.17
Sonqor	47.35	34.46	396.38
Do-Sar Qorveh	48.01	35.05	279.96
Solan	48.27	34.50	390.69
Salehabad	48.20	34.55	336.30
Bahadorbeg	48.49	34.57	311.14
Kushkabad	48.34	34.02	247.38
Ekbatan Dam	48.36	34.46	350.52
Bujin	48.03	34.48	418.50
Ali Sadr Cave	48.18	35.18	286.00
Damaq	48.38	35.32	307.99
Qahavand	48.08	34.51	256.27
Geyto	48.10	35.19	340.19

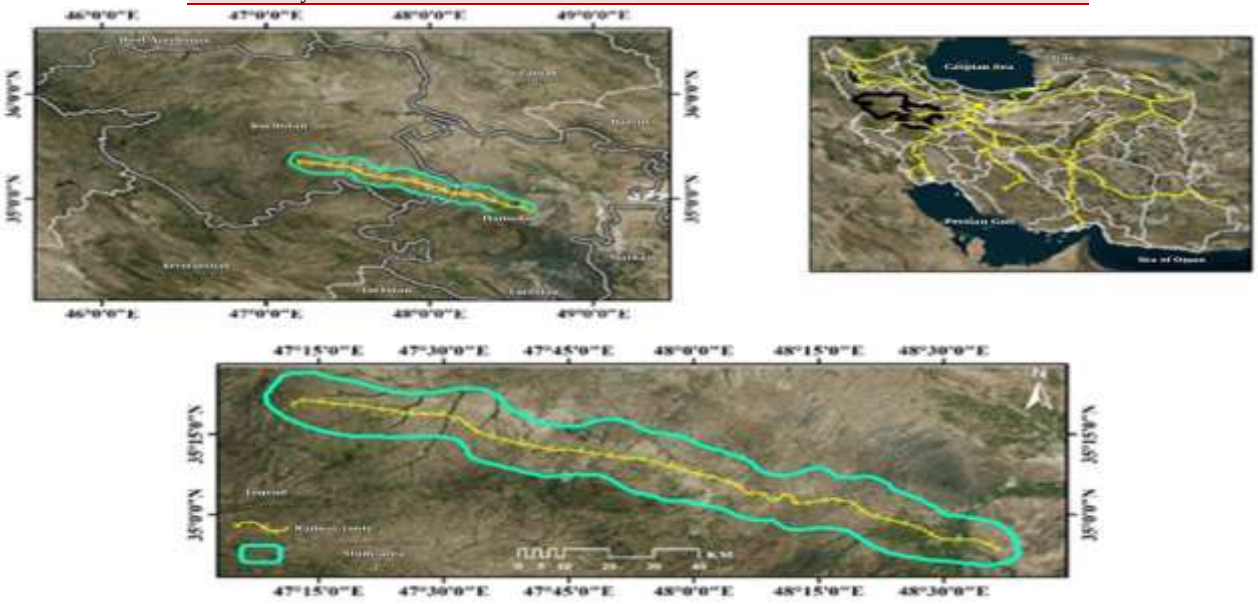


Figure 1. Location map of the study area

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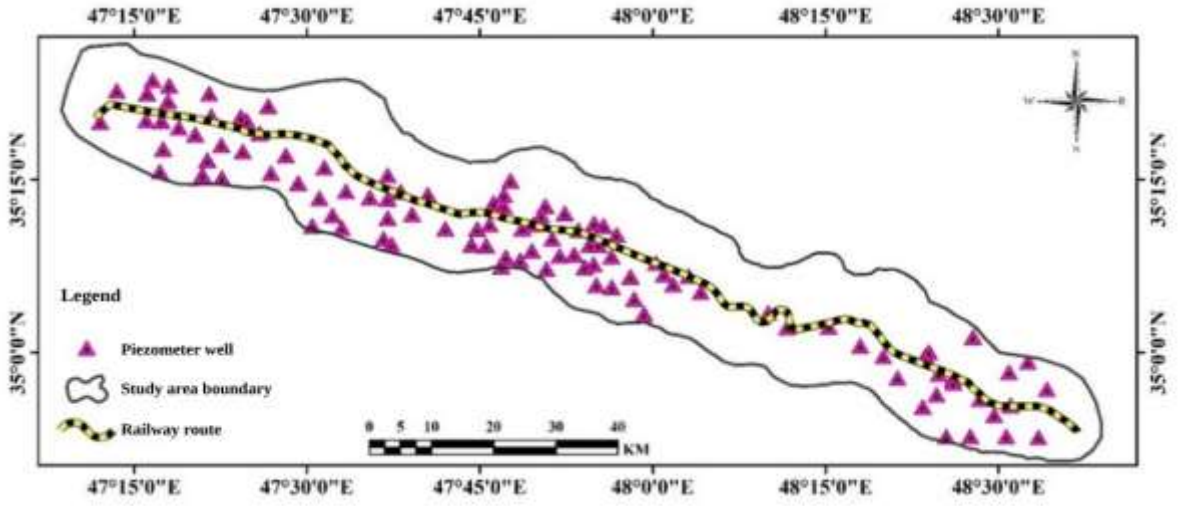


Figure 2. Location map of the piezometric stations

Study area

The study area comprises the Hamadan–Sanandaj railway corridor, located in western Iran within the geographical boundaries of Hamadan and Kurdistan provinces. The Hamadan–Sanandaj railway forms an extension of the Tehran–Hamadan railway line and extends in a southeast–northwest direction, approximately parallel to the existing Hamadan–Sanandaj highway. Along its route, the railway traverses the Hamadan–Bahar plain in Hamadan province and the Qorveh–Chahardoli and Dehgolan plains in Kurdistan province (Figure 1).

Table 2. Characteristics of satellite imagery used in this study

Parameter	Specification
Acquisition years	2019, 2020, 2021, 2022
Satellite	Sentinel-1
Polarization	HH–HV

Satellite data and piezometric stations

Sentinel-1 satellite imagery from three annual periods (2019–2020, 2020–2021, and 2021–2022), together with groundwater piezometric data from the study area, was used in this study. Figure 2 and Table 1 show the locations and characteristics of the piezometric stations, while Table 2 summarizes the Sentinel-1 imagery used in the analysis.

Methods

Land surface displacement was estimated using Interferometric Synthetic Aperture Radar (InSAR) applied to Sentinel-1 satellite imagery. Eight C-band Sentinel-1 Single Look Complex (SLC) images acquired between 2019 and 2022 were used, each covering about 100 × 100 km². Image pairs were processed in the Sentinel Application Platform (SNAP) software to identify areas of land surface displacement and to examine its temporal variations. The displacement values represent changes along the satellite Line Of Sight (LOS); hereafter, they are referred to as LOS displacement.

Interferometric Synthetic Aperture Radar (InSAR) was used to analyze Sentinel-1 satellite imagery. Pairs of images were processed in the Sentinel Application Platform (SNAP) software to identify areas of land surface displacement and examine temporal variations in surface displacement. A schematic representation of the processing workflow is provided in Figure 3, while Figure 4 illustrates the fundamental concepts of the method. Eight C-band Sentinel-1 Single Look Complex (SLC) images acquired between 2019 and 2022 were used. Each image covered about 100×100 km².

Image pairs covering the study corridor were selected for the annual observation periods. Five independent interferograms were generated from image pairs with temporal baselines of one year or less.

The displacement values derived from Sentinel-1 imagery represent measured changes in the satellite LOS direction. Because LOS measurements are affected by both vertical and horizontal components of ground motion, these values cannot be directly interpreted as vertical displacement or actual land subsidence. Independent estimation of the vertical component requires suitable observation geometries, such as

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measurements acquired from ascending and descending satellite orbits, or the use of complementary geodetic data.

The accuracy of InSAR results is affected by several factors, including spatial and temporal coherence, atmospheric conditions, changes in surface cover, orbital errors, and the quality of the processing steps. Displacement measurements must thus be interpreted in consideration of the methodological limitations and the quality of the available data.

Land surface displacement along the railway corridor was assessed using deformation maps and field observations. The reported displacement values were treated as Sentinel-1 measurements in the satellite LOS direction; the vertical component was not independently estimated.

C-band Sentinel-1 SLC images were processed in SNAP to generate interferograms and estimate land surface displacement from interferometric phase measurements. Topographic, atmospheric, orbital, and noise components were then addressed during processing. Since Sentinel-1 directly measures displacement in the satellite LOS direction, the reported deformation values represent LOS displacement rather than independently derived vertical displacement.

Spatial and temporal decorrelation can reduce the reliability of interferometric measurements, particularly in areas where vegetation, atmospheric conditions, or changes in surface scatterers affect image coherence.

InSAR processing and land surface displacement analysis

InSAR processing was applied to Sentinel-1 satellite imagery using SNAP software to identify areas affected by land surface displacement and examine temporal variations along the study corridor (Figure 3). Figure 4 presents the main assumptions and principles of the interferometric method.

Eight C-band Sentinel-1 SLC images, acquired between 2019 and 2022, were selected for the analysis. Each image covered an approximate area of 100 ×100 km. The selected images covered the study corridor during the observation periods. Five interferograms were generated from selected image pairs with temporal baselines of approximately one year or less.

The displacement values derived from Sentinel-1 data represent ground motion projected onto the satellite LOS direction. LOS measurements include contributions from both vertical and horizontal ground motion. Therefore, they cannot be directly interpreted as vertical displacement or actual land subsidence. Independent estimation of the vertical displacement component requires suitable observation geometries, such as data from both ascending and descending satellite orbits, or the integration of complementary geodetic measurements.

The accuracy of InSAR measurements depends on several factors. These include spatial and temporal coherence, atmospheric conditions, changes in land-surface characteristics, orbital errors, and the quality of the processing procedures. Spatial and temporal decorrelation can reduce the reliability of interferometric measurements, particularly in areas affected by vegetation, atmospheric disturbances, or changes in surface scattering properties.

Land surface displacement along the railway corridor was assessed using deformation maps and field observations. The Sentinel-1 SLC images were processed in SNAP to generate interferograms and estimate land surface displacement from interferometric phase information. The processing workflow included the removal or correction of topographic and orbital phase contributions, noise reduction, and atmospheric phase correction where applicable.

Throughout this study, all reported displacement values are interpreted exclusively as Sentinel-1 LOS measurements. The vertical component of land surface displacement was not independently estimated. Therefore, the results indicate LOS deformation and should not be considered direct measurements of vertical land subsidence.

a) Interferometric pairs that share a common acquisition. Image No. 2, which is common to both pairs, is highlighted in red.

b) Repeated acquisitions, highlighted in red, used to improve the estimation of atmospheric phase corrections for each acquisition date.

c) Baseline plot showing the temporal and spatial baseline distribution of the SAR data used in the analysis.

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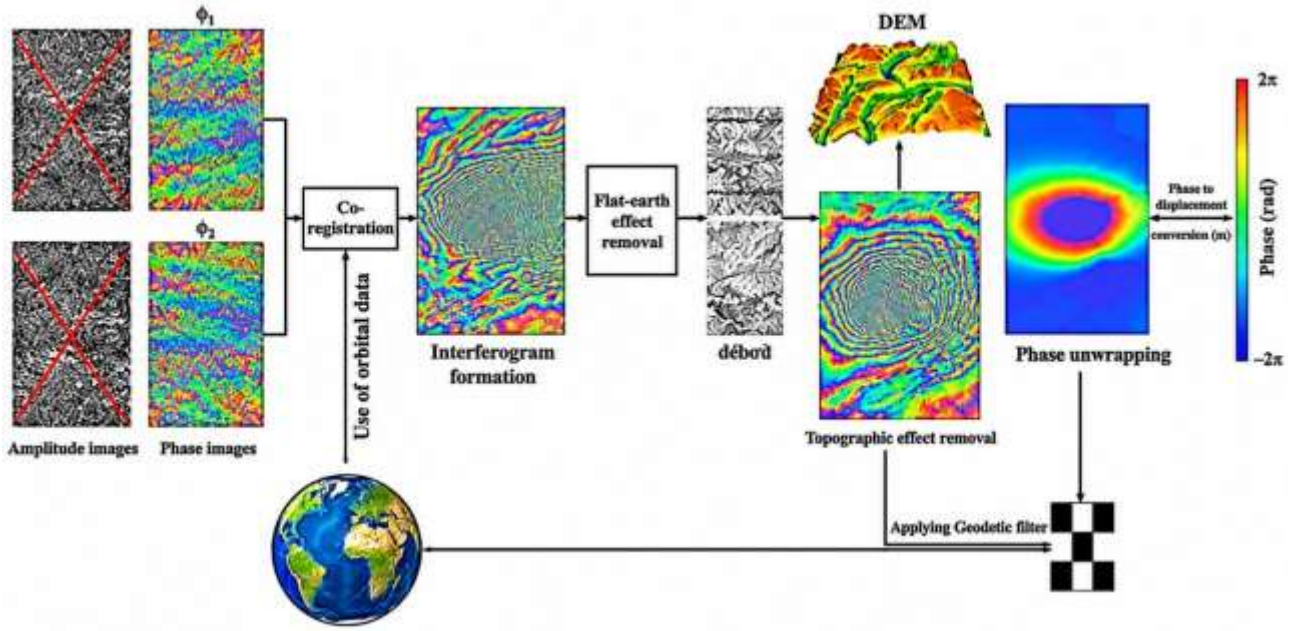


Figure 3. Schematic representation of the InSAR processing workflow used in this study

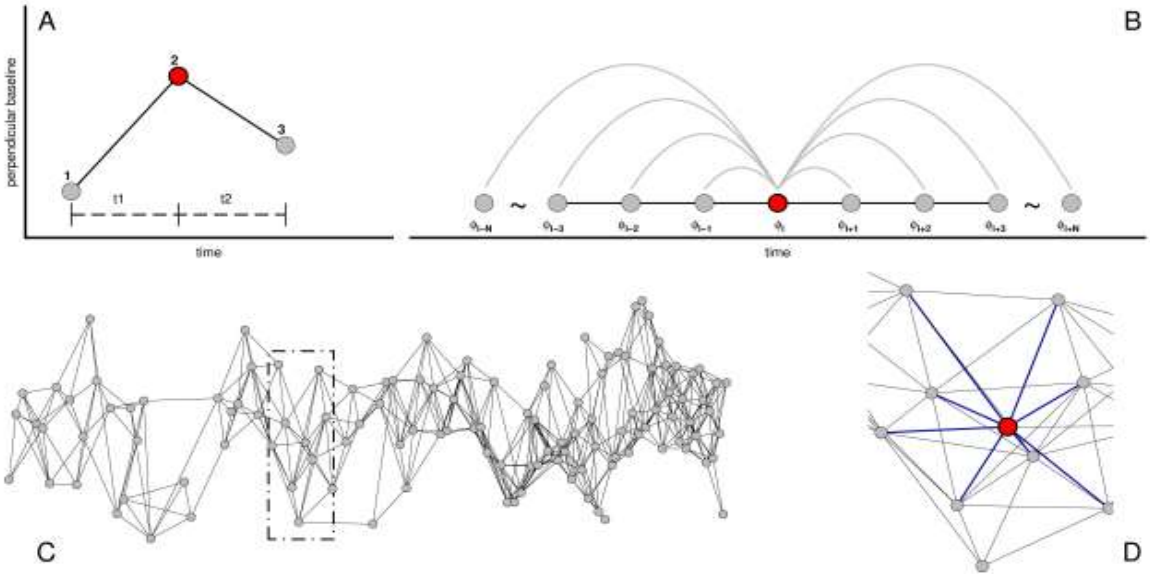


Figure 4. Graphical representation of the basic assumptions

Findings

The displacement values derived from Sentinel-1 processing represent ground-surface motion along the satellite LOS. Accordingly, under the sign convention adopted in the processing, positive and negative values indicate motion associated with an increase and a decrease, respectively, in the effective sensor-to-ground distance along the LOS direction. However, interpreting these values as vertical uplift or subsidence is subject to limitations because LOS measurements include contributions from both vertical and horizontal ground motion. Accordingly, positive and negative LOS displacement are used throughout the analysis, while the term land subsidence is used only where the available evidence and supporting information justify such an interpretation.

The groundwater-level hydrographs for the Qorveh–Dehgolan and Hamadan–Bahar railway sections (Figures 5 and 6) indicate an overall declining trend in groundwater levels. This decline is more pronounced in the Dehgolan–Qorveh area. In the Qorveh–Dehgolan plain, the highest groundwater-level elevation was recorded in 1991, at 1,875 m, whereas the lowest levels, below 1,807

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m, were recorded in 2018 and 2021. In the Hamadan–Bahar plain, the highest groundwater-level elevation was recorded in 1996, at more than 1,758 m, while the lowest level, below 1,737 m, was recorded in 2015.

The mean groundwater-level elevations were 1,821 m in the Qorveh–Dehgolan plain and 1,747 m in the Hamadan–Bahar plain. Over the 30-year study period, the reported mean annual groundwater-level declines were 1.3 m and 1.6 m, respectively. In the Hamadan–Bahar plain, the most pronounced annual decline occurred between 2012 and 2013, whereas the greatest increase was observed between 2017 and 2018.

Groundwater levels in the study area were evaluated over the period from 1991 to 2021. In addition, changes in groundwater levels were also examined at five-year intervals. According to the results presented in Figures 7 and 8, the greatest groundwater-level decline in the Qorveh–Dehgolan plain occurred during the fifth period (2012–2016), amounting to reaching about 10 m. The smallest decline was observed during the second period (1997–2001), with a value of less than 3 m.

In the Hamadan–Bahar plain, the greatest decline occurred during the fifth period, exceeding 7 m. In contrast, the smallest declines were recorded during the second and third periods, with values of less than 3 m. Furthermore, an increase of about 6 m in groundwater level was observed in the Hamadan–Bahar plain during the sixth period (2017–2021).

Figure 9 illustrates the groundwater-flow directions along the railway corridor in the Qorveh–Dehgolan and Hamadan–Bahar areas. The results indicate that the highest groundwater-level elevations occur in the central and upgradient sections of the railway corridor within the Qorveh–Dehgolan area, whereas the lowest elevations are observed in the downgradient sections of the Hamadan–Bahar area. Although groundwater-flow directions vary across the plains, the predominant regional flow direction is toward the northern part of the study area.

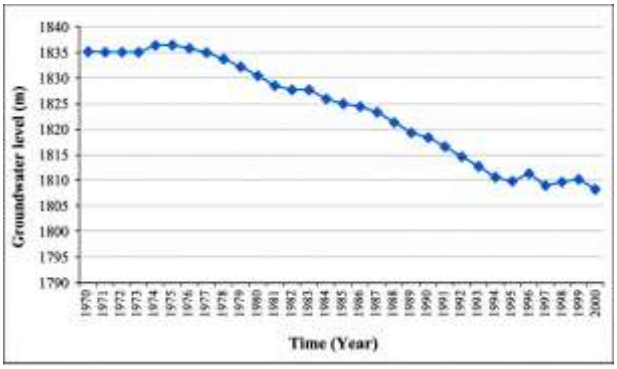


Figure 5. Groundwater-level hydrograph along the railway corridor in the Qorveh–Dehgolan plain (1991–2021)

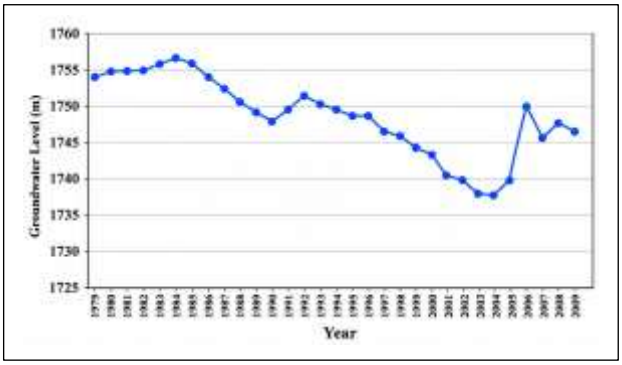


Figure 6. Groundwater-level hydrograph along the railway corridor in the Hamadan–Bahar plain (1991–2021)

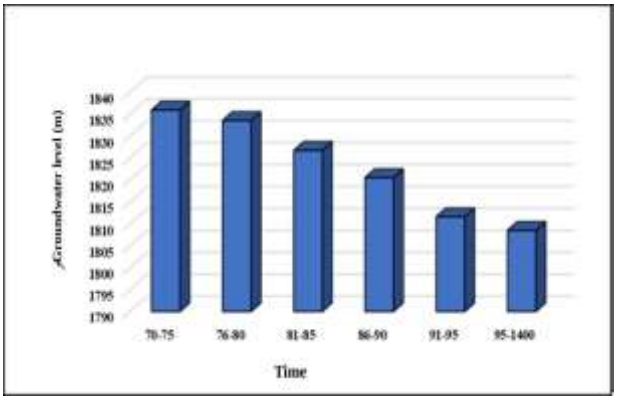


Figure 7. Groundwater-level changes along the railway corridor in the Qorveh–Dehgolan plain over five-year intervals (1991–

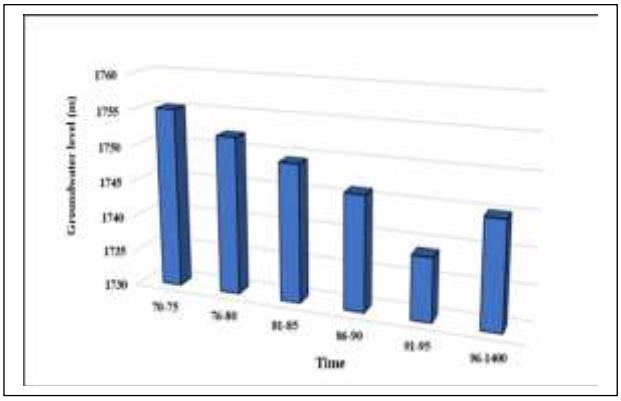


Figure 8. Groundwater-level changes along the railway corridor in the Hamadan–Bahar plain over five-year intervals (1991–2021)

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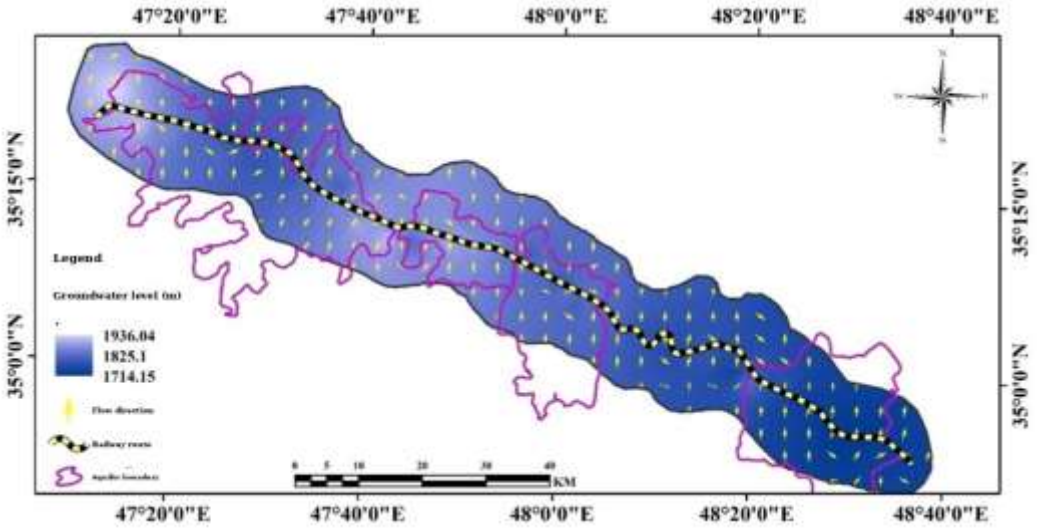


Figure 9. Groundwater-flow directions along the railway corridor

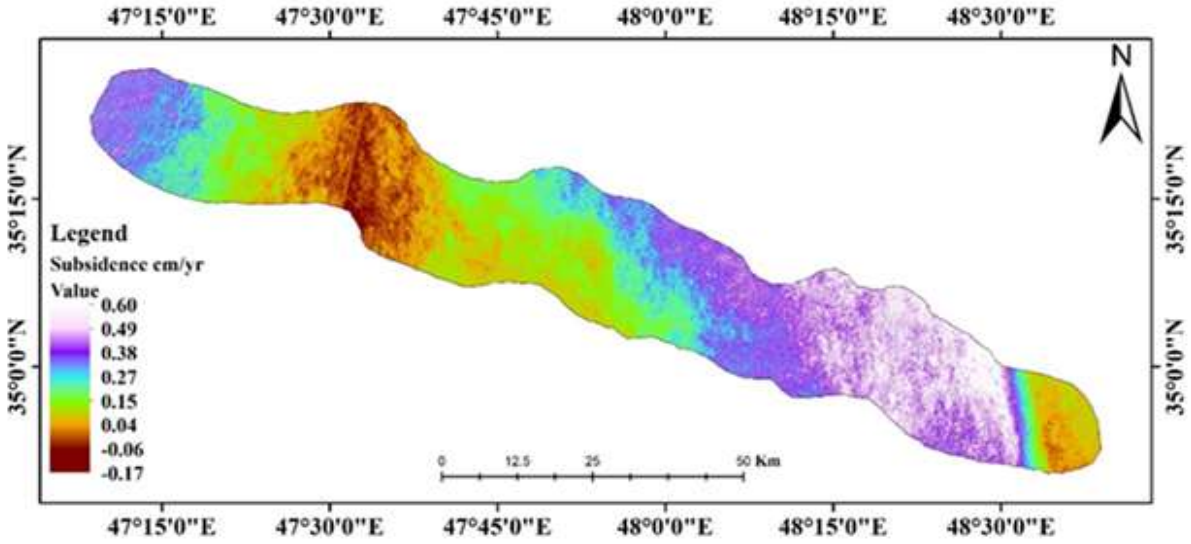


Figure 10. Spatial distribution of LOS displacement in the study area during the 2019–2020 observation period.

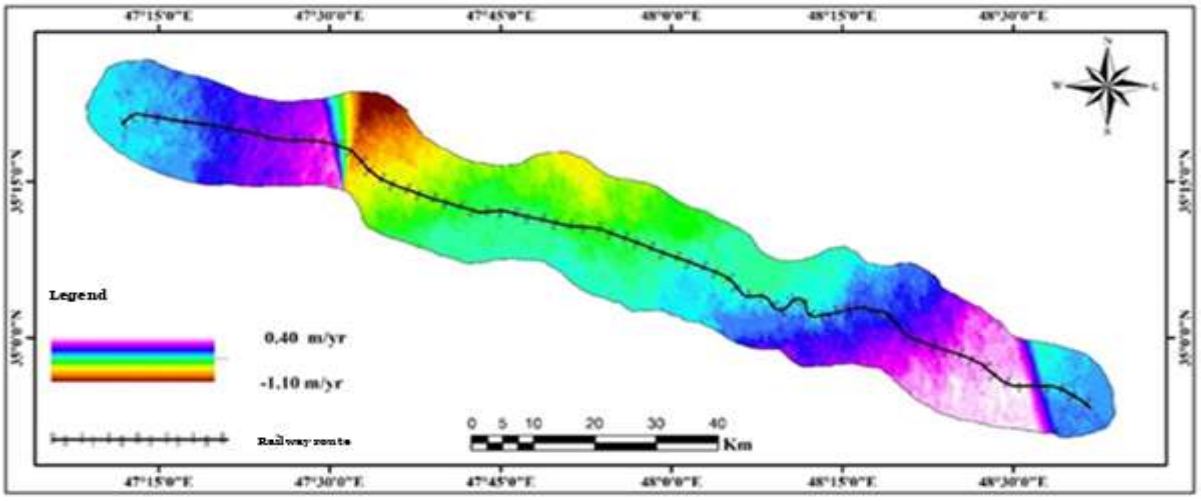


Figure 11. Spatial distribution of LOS displacement during 2020-2021

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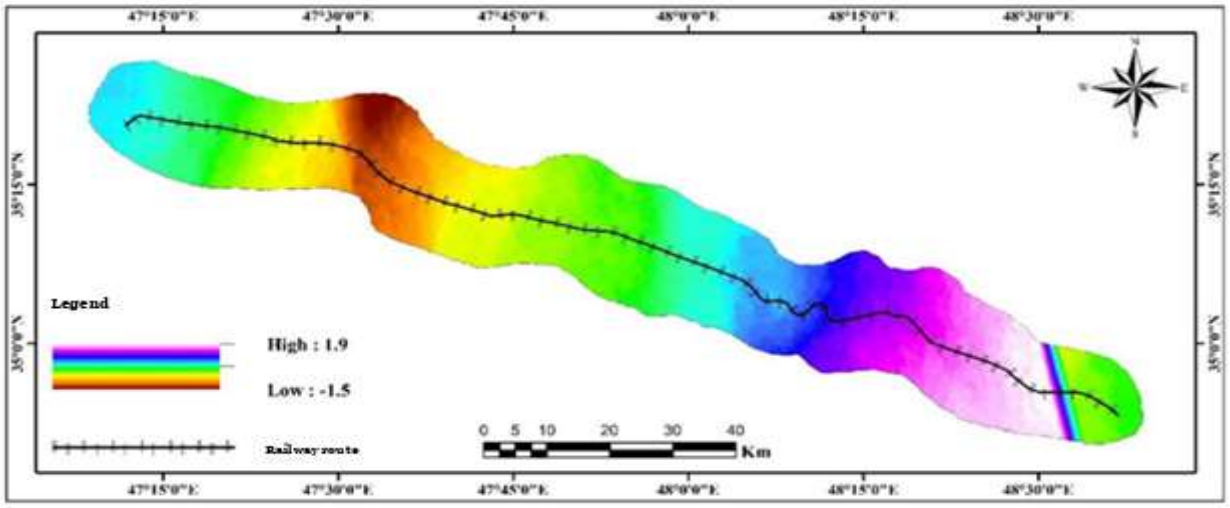


Figure 12. Spatial distribution of LOS displacement during 2021-2022

SAR Interferometric Analysis and Spatial Distribution of LOS Displacement

A) Observation Period 1 (2019–2020)

Synthetic Aperture Radar (SAR) signals contain two primary types of information: amplitude and phase. Amplitude represents the strength of the radar signal returned from surface targets, whereas phase represents the relative position of the complex radar signal within one complete wave cycle (2π radians). SAR phase is primarily related to the slant-range distance between the satellite antenna and ground targets, although surface-scattering properties influence the measured phase.

InSAR uses the phase difference between two complex SAR acquisitions of the same area, acquired from slightly different sensor positions and/or at different times, to extract information about surface topography and land surface displacement.

During the 2019–2020 observation period, the estimated land surface displacement along the LOS direction ranged from +0.60 cm to −0.17 cm, as shown in Figure 10. Both positive and negative values represent displacement measurements along the satellite LOS. Positive LOS displacement was confined to a relatively small area in the eastern part of the Hamadan–Bahar region, appearing as scattered white patches along the railway corridor.

Negative LOS displacement was mainly distributed across the northern and western parts of the study area, with additional scattered patches in the central region. The negative-displacement zones in the southern and central parts showed spatial overlap with the locations of piezometric stations, areas with documented groundwater-level declines, and areas of intensive agricultural activity. However, this spatial correspondence alone does not establish a causal relationship between groundwater depletion and land surface displacement.

The areas corresponding to the three displacement classes were estimated at 635, 578, and 1,213 km², respectively.

B) Observation Period 2 (2020–2021)

Geotechnical monitoring systems are generally installed in areas susceptible to significant land surface displacement because they provide accurate point-based measurements. However, their limited spatial coverage and relatively high installation and maintenance costs restrict their application in large-scale monitoring. In contrast, InSAR provides extensive spatial coverage and enables the monitoring of land surface displacement over large geographical areas.

During the 2020–2021 observation period, LOS displacement ranged from +0.40 cm to −1.10 cm, as shown in Figure 11. Compared with the 2019–2020 period, the magnitude of the maximum negative LOS displacement increased from 0.17 cm to 1.10 cm.

The spatial distribution of LOS displacement was consistent with the areas affected by groundwater-level declines. However, the available observations do not independently quantify groundwater abstraction or establish groundwater withdrawal as the sole cause of the observed land surface displacement.

The areas with LOS displacement values ranging from −1.10 to 0 cm covered approximately

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201 km². Areas with values ranging from 0 to +0.20 cm covered 1,344 km², while areas with values ranging from +0.20 to +0.40 cm covered 1,005 km².

C) Observation Period 3 (2021–2022)

The final observation period analyzed in this study was 2021–2022. As in the previous observation periods, the greatest negative LOS displacement was detected in the Dehgolan–Qorveh area and the central parts of the study region.

The maximum negative LOS displacement during this period reached −1.50 cm, whereas the maximum positive LOS displacement, recorded in the Hamadan–Bahar area, reached +1.90 cm.

The Dehgolan–Qorveh area experienced considerable negative LOS displacement during this annual observation period. In the most affected areas, negative displacement values ranged from −0.50 to −1.00 cm.

The areas corresponding to the three displacement classes were estimated at 572, 344, and 1,706 km², respectively (Figure 12).

Relationship Between LOS Displacement and Groundwater-Level Changes

A spatial comparison of the piezometric station locations with the deformation maps derived from radar imagery suggests a spatial association between negative LOS displacement and declining groundwater levels. Analysis of groundwater-level data over the six-year assessment period indicated a decline at the monitored wells. The spatial distribution of these declines broadly corresponded to areas classified as having moderate to high levels of land surface displacement (Table 3).

Table 3. Regression statistics for the relationship between LOS displacement and groundwater-level changes across the study area

Regression statistic	Multiple correlation coefficient (R)	Coefficient of determination (R^2)	Adjusted R^2	Standard error of the estimate	Number of observations
Value	0.81	0.67	0.59	0.12	6

The Multiple R statistic was 0.81, indicating a strong association between the observed and predicted values of the dependent variable. However, this statistic alone does not determine the direction of the relationship between the variables. The direction of the relationship must be established by examining the sign of the corresponding regression coefficient.

The regression results yielded a coefficient of determination (R^2) of 0.67. This indicates that the fitted model explains 67% of the variability in the dependent variable within the analyzed dataset. Nevertheless, this value alone does not establish a causal relationship between groundwater-level decline and land surface displacement.

Given the limited number of observations (n=6), the statistical results should be interpreted with caution. Additional observations and the consideration of other potentially influential factors are required to improve the reliability of the analysis and assess the extent to which the findings can be generalized to the entire study area.

Discussion and Conclusion

Radar interferometry is widely recognized as an effective technique for measuring deformation of the Earth's surface. Its extensive spatial coverage, high spatial resolution, and adequate measurement accuracy make it suitable for investigating various geohazards, including earthquakes, land subsidence, landslides, and volcanic activity. Land subsidence can result from both natural processes and human activities. In the study area, the spatial pattern of negative LOS displacement is associated with declining groundwater levels and areas of intensive human activity. However, this spatial association should not be interpreted as evidence of a causal relationship.

This study aimed to assess land surface displacement along the Hamadan–Sanandaj railway corridor and investigate its potential association with groundwater-level variations. The results obtained from Sentinel-1 imagery processing over three observation periods (2019–2020, 2020–2021, and 2021–2022) indicated that the most negative LOS displacement values were −0.17, −1.10, and −1.50 cm, respectively. The spatial analysis further showed that the largest magnitudes of negative LOS displacement occurred in the Dehgolan–Qorveh area.

Piezometric data were analyzed to assess groundwater-level variations and their potential relationship with land surface displacement. However, differences in the temporal coverage of the piezometric and radar datasets, together with the limited number of observations used in the regression analysis, require cautious interpretation of this relationship. The statistical results alone are insufficient to establish a causal relationship

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between groundwater-level decline and land surface displacement.

From a methodological perspective, it is important to emphasize that the displacement values derived from radar imagery represent motion along the satellite LOS. Without independently resolving the vertical and horizontal displacement components, these values cannot be directly interpreted as vertical land subsidence. Overall, the findings of this study can contribute to identifying sections of the railway corridor that require more detailed monitoring. To improve confidence in the results and better understand the processes governing land surface displacement, future investigations should incorporate ground-based measurements, temporally consistent piezometric observations, and complementary remote sensing techniques.

Study limitations

The main limitations of this study include the estimation of displacement along the satellite LOS without independent determination of the vertical displacement component, the limited number of observations used in the regression analysis, and the temporal mismatch between the piezometric and radar datasets. In addition, the individual effects of geological conditions, groundwater recharge and abstraction, precipitation, and land use were not independently quantified. Thus, the findings indicate spatial and statistical associations rather than established causal relationships. Further investigations are required to identify and quantify the relative contributions of these factors to land surface displacement.

Compliance with Ethical Guidelines

There were no ethical considerations in this research.

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Authors' Contributions

This article was derived from Somayeh Abdi's master's thesis. Mostafa Khabazi, as the thesis supervisor, was responsible for proposing the research topic, developing the methodology, and overseeing the preparation of the article based on the thesis. Somayeh Abdi was primarily responsible for data collection, liaising with the relevant organizations, data analysis, and map preparation. Naser Bay undertook a thorough review of the manuscript, addressed the identified issues, redrew selected maps, and revised the figures. Finally, Nader Oveisi was responsible for the final proofreading and revision of the manuscript, including the correction of writing and language issues in both the Persian and English texts.

Conflict of Interests

The authors declare no conflict of interest.

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