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Radar Interferometry-Based Investigation of Land Subsidence in Shiraz Plain Using ENVISAT ASAR C-Band Data: A Case Study of the South Zagros Region- Iran

Alireza Karimi [a*]

[a*] *Department of Geographical Information System and Remote Sensing, Islamic Azad University , Yazd Branch, Yazd, Iran*

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A B S T R A C T

Objective: Land subsidence is the gradual or sudden downward movement of the earth's surface, often resulting from the extraction of groundwater, minerals, or hydrocarbons. This phenomenon, which can cause significant structural damage and environmental degradation, is increasingly prevalent in regions with excessive groundwater abstraction. The primary objective of this study was to assess subsidence in Shiraz Plain, using radar interferometry to analyze ground deformation due to groundwater depletion and other environmental factors, such as droughts and historical lake bed conditions.
Methods: This study employed ENVISAT ASAR C-band radar images from 2007-2009 to investigate subsidence patterns in the Shiraz Plain. The images were processed using ENVI5.3.1 software with the SARscape plugin, including interferometry, ADAPT filters, and Goldstein filtering to mitigate errors and improve image quality. The final phase-to-displacement conversion and geocoding steps resulted in subsidence maps, which were used to analyze displacement across different regions. The data were validated by comparing the generated subsidence maps with field observations.
Results: The analysis revealed subsidence rates ranging from -14 cm to +5 cm, with the most significant displacements observed in the southeast of Shiraz and parts of Beiza. Ground displacement in urban and agricultural areas was also notable, with an average subsidence rate of -3.5 cm. The primary causes of subsidence in these regions were identified as excessive groundwater extraction, historical lake bed conditions, and geological factors such as fault zones.
Conclusion: The study highlights the importance of sustainable groundwater management to mitigate subsidence risks, and recommends continued monitoring and implementation of water conservation strategies to prevent further ground displacement in the region.

1. Introduction

Environmental hazards, ranging from natural phenomena to human-induced activities, are significant barriers to sustainable development, often disrupting ecosystems and human settlements. Among these

* *Corresponding author.* Tel.: 0098-7143340364
E-mail address: arkarimi0455@gmail.com

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hazards, land subsidence poses a critical threat to many plains in Iran today. Defined as the gradual sinking of the earth's surface, this phenomenon arises from both natural and artificial processes, with its consequences sometimes reaching catastrophic levels (Sekkeravani et al., 2022).

Human activities, especially the unregulated exploitation of natural resources, have intensified the frequency and severity of such risks. Studies across subsidence-prone plains in Iran identify primary causes such as groundwater depletion, dissolution of subsurface formations, and karst subsidence. Additional contributors include land-use changes, construction activities, operation or loading of engineering structures, organic soil drainage, subsurface mining, and oil extraction (Bagheri-Gavkosh et al., 2021). Among these, groundwater over-extraction has been particularly damaging, resulting in profound economic, social, and environmental repercussions. The extent and severity of these impacts largely depend on the scale of subsidence and the characteristics of the affected region (Bagheri-Gavkosh et al., 2021)

Alarmingly, the rate of subsidence in some Iranian plains far exceeds global critical thresholds. For instance, in the Tehran plain, the annual subsidence rate surged from 17 cm in 2006 to 36 cm in 2023, compared to the global critical rate of 4 mm per year. According to Mahmoudpour et al. (2013), consecutive droughts and climate change have exacerbated the subsidence rates nationwide, with each plain exhibiting unique patterns and rates of subsidence.

Geological fractures induced by subsidence, such as those observed in the Beijing Plain, accelerate soil erosion and compromise regional infrastructure development (Long et al., 2018). Accurate assessment of groundwater exploitation's role in subsidence is essential for informed decision-making. For instance, a groundwater subsidence model developed for Tongzhou, China, revealed widespread subsidence across the region and enabled the classification of early warning zones based on subsidence rates (Congnan & Liang, 2023).

Recent droughts in Iran have exacerbated groundwater depletion and the desiccation of rangeland vegetation, including trees and shrubs (Sadeghi & Hazbavi, 2022). Long-rooted plants, essential for stabilizing soil, have been lost, leading to weakened soil structure and increased vulnerability to subsidence (Woldesenbet et al., 203). The interplay of poor resource management, increasing population pressure, rising food demands, and climatic stressors has further compounded the subsidence issue.

Land subsidence, characterized by the gradual or sudden sinking of the earth’s surface, poses significant challenges to infrastructure, agriculture, and the environment (Shirzaei et al., 2021). This phenomenon is primarily driven by excessive groundwater extraction, particularly in arid and semi-arid regions (Shirzaei et al., 2021). The Shiraz Plain, situated Zagros region of Iran, has experienced increasing in the South subsidence due to prolonged droughts, over-extraction of groundwater for agriculture, and historical geological conditions such as former lake beds (Rahnema & Mirassi, 2016).

This study aimed to assess the extent and underlying causes of subsidence in this region using radar interferometry techniques, providing insights into the geophysical and environmental dynamics contributing to ground deformation.

The research utilized ENVISAT ASAR radar images (C-band) spanning 2007-2009 to examine subsidence patterns across the Shiraz Plain. Using the ENVI5.3.1 software and SARscape plugin, advanced image processing methods were applied, including interferometry, ADAPT filtering, and Goldstein filtering, to enhance data accuracy. The final phase-to-displacement conversion and geocoding steps produced detailed subsidence maps, which were corroborated with field observations. The results offered a spatial understanding of subsidence intensity and its correlation with local environmental and geological factors.

This study follows the following hypothesis:

- Excessive groundwater extraction in the Shiraz Plain is the primary driver of land subsidence, with more severe subsidence observed in regions with higher densities of agricultural wells and prolonged water abstraction.
- Historical geological features, such as ancient lake beds and fault zones, amplify subsidence in specific areas of the Shiraz Plain, where loose, fine-grained sediments and tectonic activity exacerbate ground deformation.

2. Material and Methods

2.1. Study Area

Shiraz, the capital of Fars province in southwestern Iran, lies centrally within the province. The city spans approximately 40 km in length and varies in width between 15 to 30 km, covering an area of 1,268 square kilometers in a rectangular shape (Varesi et al., 2023). It is bordered by the Drak Mountain to the west and the Bamo, Sabzpooshan, Babakohi, and Chehel Magham mountains to the north. This natural enclosure by surrounding mountains grants Shiraz a unique geographical and climatic position (Fig. 1).

Geographically, Shiraz is situated at 29°36' N latitude and 52°32' E longitude, with an altitude ranging between 1,480 and 1,670 meters across different parts of the city. The city's climate varies significantly across seasons, with average temperatures of approximately 30°C in summer, 5°C in winter, 17°C in spring, and 20°C in autumn. The overall annual average temperature stands at 18°C, complemented by an average annual rainfall of 337.8 mm. Spring is considered the best season for visiting Shiraz due to its pleasant weather conditions (DehghanSh et al., 2017).

The Shiraz plain, a rectangular area with a length of approximately 40 km and a width of about 15 km, extends from west to east. The plain's slope inclines from west to east, where numerous springs and aqueducts emerge in the western region, supporting irrigation across the plain. At the eastern end, the wastewater and floodwaters from the surrounding mountains accumulate, forming Maharloo Lake (also known as Namak Lake). This saline lake, located 24 km east of Shiraz, spans approximately 6 × 10 km and contains highly salty water (DehghanSh et al., 2017).

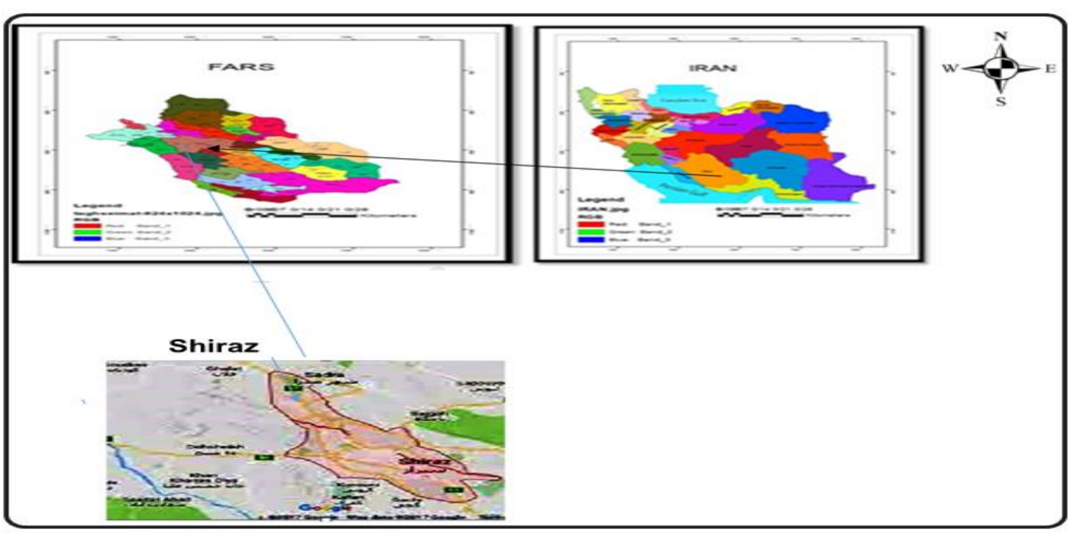

Fig. 1 - Map of the study area of Shiraz plain subsidence

2.2. Methodology and Data Acquisition

1. Introduction to InSAR Technology

Since the early 1990s, Synthetic Aperture Radar Interferometry (InSAR) has emerged as an efficient tool for studying earth surface changes caused by natural and human-induced phenomena (Pepe & Calò, 2017). This technique relies on analyzing the radar phase information reflected from the ground. Changes in the earth's surface create phase differences between two radar images captured at different times over the same area (Pepe & Calò, 2017). By modeling and analyzing these phase differences, ground surface deformations can be accurately quantified.

Initial applications of InSAR technology include mapping displacements caused by earthquakes, volcanoes, glaciers, landslides, and salt slides, as well as irregular phenomena such as groundwater extraction, oil outflows, and subsidence (Bhattachary & Mukherjee, 2017). Surface phenomena such as floods, fires, and vegetation growth can also be monitored. The first InSAR application for ground deformation was performed by Gabriel et al. in 1989, who used SEASAT satellite imagery to study surface uplift caused by selective irrigation in California's Imperial Valley. However, it wasn't until the 1992 Landers earthquake that InSAR became widely recognized within the earth science community as a valuable geodetic tool.

Key milestones in early InSAR studies include:

- Mapping displacement from the 1992 Landers earthquake using ERS-1 imagery.
- Measuring Antarctic ice flow velocities directly from space using ERS-1 images.
- Monitoring surface deformation of Mount Etna volcano to predict potential eruptions.

These early achievements inspired extensive research and development, leading to new satellites specifically designed for InSAR, such as RADARSAT, JERS, ERS, and ENVISAT (Cigna et al., 2014). Table 1 lists available and planned satellites supporting InSAR technology, with increasing precision and resolution.

2. Applications of InSAR

InSAR enables high-resolution mapping of surface deformations and has revolutionized the study of natural disasters and environmental changes (Cigna et al., 2014). Key applications include:

- Measuring glacier and ice cap movements.
- Studying land subsidence caused by groundwater extraction and other factors.
- Producing digital elevation models (DEMs) with horizontal resolutions of up to 30 meters and altitude accuracies of a few meters.

Monitoring tectonic activities, such as earthquakes and volcanic eruptions.

NASA's TOPOSAR project, for example, used InSAR to create a global DEM with unprecedented accuracy (Campbell & Resler, 2016). This technology now facilitates monitoring surface changes globally, with millimeter-level precision, regardless of weather conditions or time of day.

3. Data Acquisition for Shiraz Plain Study

For this study, radar images were obtained from the European Space Agency (ESA). The Advanced Synthetic Aperture Radar (ASAR) sensor aboard the ENVISAT satellite was used to collect data from the Shiraz plain. The ASAR sensor operates in the C-band (wavelength: 5.5 cm; frequency: 5.331 GHz), enabling detection of surface changes with sub-millimeter accuracy. Data from 2007–2009 were used for this analysis. The general specifications of the ENVISAT ASAR satellite and the collected data are presented in Table 1.

4. Methodology: Differential Interferometry (D-InSAR)

The D-InSAR technique was employed to analyze surface deformations. This method involves combining the phase information of two radar images to generate an interferogram, which represents the phase differences caused by surface changes.

Steps for Analysis:

- Data Collection: Radar images from different times were downloaded from ESA’s website.
- Image Preprocessing: ASAR images were calibrated and prepared for analysis.
- Interferogram Generation: The two radar images were combined to produce an interferogram.
- DEM Creation: A Digital Elevation Model (DEM) was created using C-band radar images (Fig. 2 illustrates the steps for DEM preparation).
- Phase Unwrapping: Phase differences were unwrapped to quantify surface deformations.
- Validation: Results were validated against field data and previous studies to ensure accuracy.

Fig. 2 provides a detailed workflow for preparing a DEM map using radar images.

5. ENVISAT ASAR Satellite Specifications

Table 1 below summarizes the technical specifications of the ENVISAT ASAR satellite and the data used in this study.

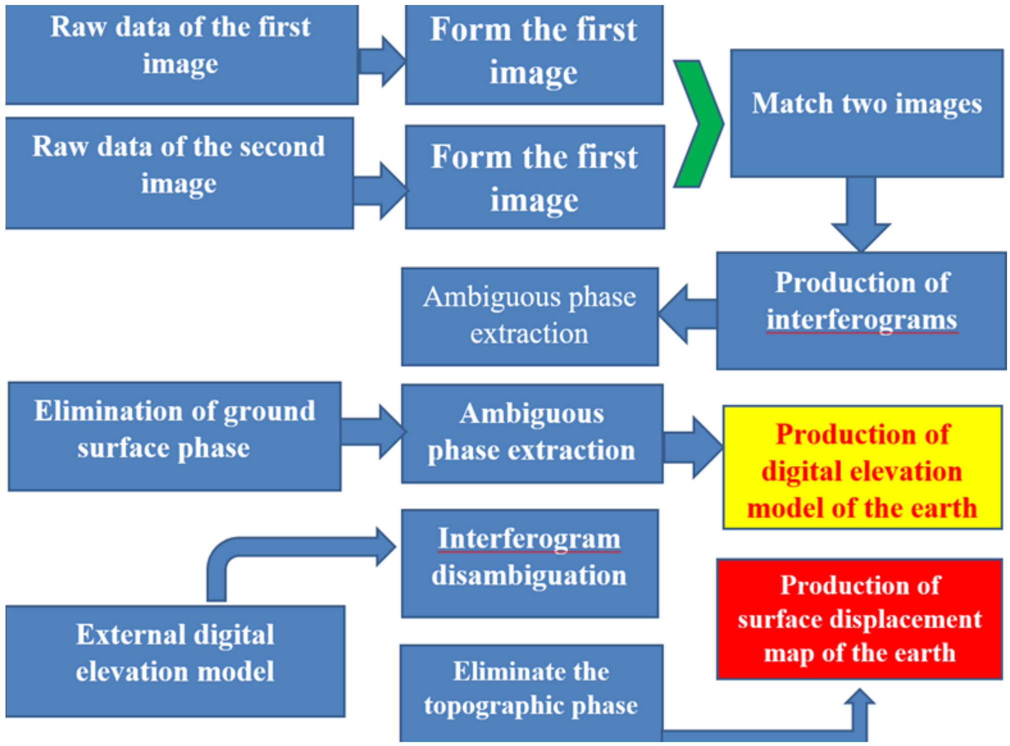

Fig. 2 - Steps to prepare a DEM map of C-band radar images for 2006-2007

Table 1- Information of C-band radar images from 2006-2007 for use, prepare a subsidence map

Imaging mode	Image Mode	Wide Swath Mode	Altemating/Cross Polarization	Wave Mode	Global Monitoring
Polarization	VV or HH	VV or HH	HH/HV or VV/HH VV/VH or	VV or HH	VV or HH
Spatial resolution	28 m x 28 m	150 m x 150 m	29 m x 30 m	28 m x 30 m	950 m x 980 m
Extraction width	Up to 100 km	400 km	Up to 100 km	5km	>=400 km
Frequency			5.331 GHz (C-band)		

1. Radar Image Preparation

Radar images were acquired from the European Space Agency (ESA) website for two distinct time intervals, with a 24-hour temporal baseline.

The images were converted to the Single Look Complex (SLC) format, a prerequisite for interferogram generation.

2. Baseline Estimation

To assess the feasibility of interferogram generation, the spatial baseline between the two images was calculated. Acceptable baselines ensured successful interferogram production without significant errors.

3. Interferogram Generation

The interferogram was created by multiplying the first radar image by the complex conjugate of the second image. Key properties of the interferogram include:

- Amplitude: Represents the product of the amplitudes of the original images.
- Phase: Reflects the phase difference between the two images, which is critical for calculating ground displacement.

The resulting interferogram provided the foundational data for analyzing surface deformation.

4. Managing Incoherence

Areas with severe incoherence due to factors like topography, shadow effects, or surface changes were identified and mitigated. This step improved the quality of the interferograms.

SARscape software's radar power menu was utilized to refine the images for better coherence, ensuring accurate analysis.

3. Results

3.1. Subsidence Mapping and Data Analysis

1. Subsidence Map Generation

The production of the interferogram involves calculating the phase difference between two radar images. This phase difference is obtained by multiplying the first image with the conjugate of the second image, resulting in an interferogram where the phase values represent the ground deformation. Fig. 3 illustrates the phase difference derived during the interferogram production process. These variations in phase are crucial for detecting and quantifying ground displacement with high accuracy.

2. Advantages of Radar Imaging

Unlike field surveys that provide high-accuracy elevation points at discrete locations, radar imaging offered continuous spatial data. This capability allowed for more comprehensive analysis and mapping, particularly in areas difficult to access for field observations.

3. Challenges in Data Processing

Severe incoherence in some regions, caused by topographic shadowing or surface changes, introduced errors in the analysis. Proper baseline estimation and interferogram production mitigated these issues to a significant extent, ensuring the reliability of the subsidence maps.

4. Validation of Results with Field Data

The generated subsidence maps were validated against GPS-based field measurements, showing strong agreement. Phase variations observed in the interferograms directly correlated with subsidence caused by excessive groundwater extraction, highlighting the utility of radar interferometry for such studies.

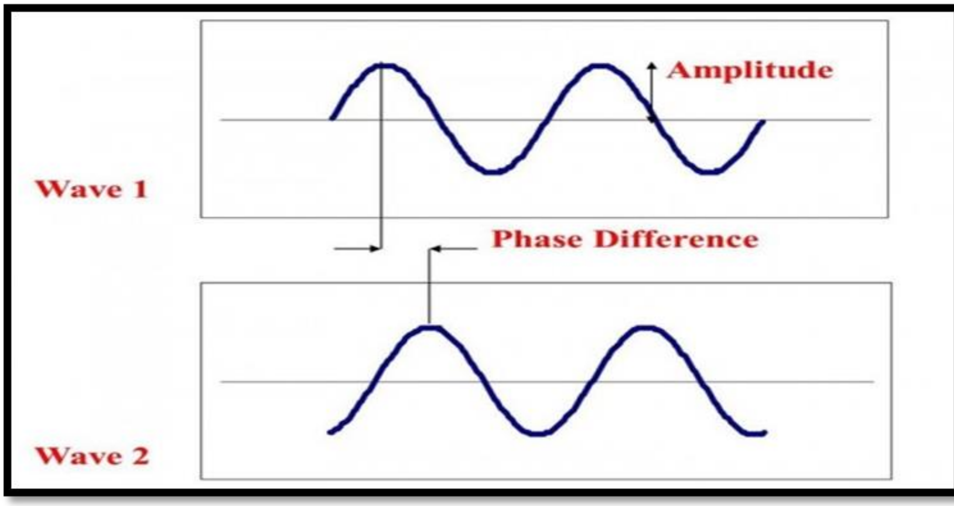

Fig. 3: Phase difference between two images in interferogram production

3.2. Analysis of Subsidence Findings

In this section, we analyze the findings of the study based on the generated radar images and interferograms. We also highlight the modifications and corrections applied to ensure high accuracy in the subsidence maps. Specific figures referenced in this section illustrate key observations and analyses.

1. Analysis of Interferogram Outputs

The process of generating subsidence maps begins with the creation of interferograms, which contain information about phase differences between radar images. These interferograms are affected by phenomena such as RAMP, JAMP, and BAMP, which need to be corrected to ensure accuracy. Filters such as Adaptive, Goldstein, and Boxcar are applied depending on the level of incoherence observed in the data:

- Adaptive filter: Maintains high phase accuracy and is effective when the level of incoherence is low.
- Goldstein filter: Reduces phase inconsistency significantly but may lower accuracy. Used when incoherence is severe.
- Boxcar filter: A balanced approach, modifying phases to a limited extent.

These steps are crucial for refining the interferograms to eliminate errors caused by topographic effects, atmospheric interference, and sensor vibration.

2. Subsidence Mapping

2.1 Subsidence Map Overview (2007–2009)

The processed data was used to generate a subsidence map for the Shiraz and Beiza plains. The map demonstrates areas of significant subsidence, highlighted in red, and is accompanied by a histogram illustrating the distribution of subsidence rates. Fig. 4 depicts the subsidence map with red zones representing the most affected areas, along with the corresponding histogram for 2007–2009.

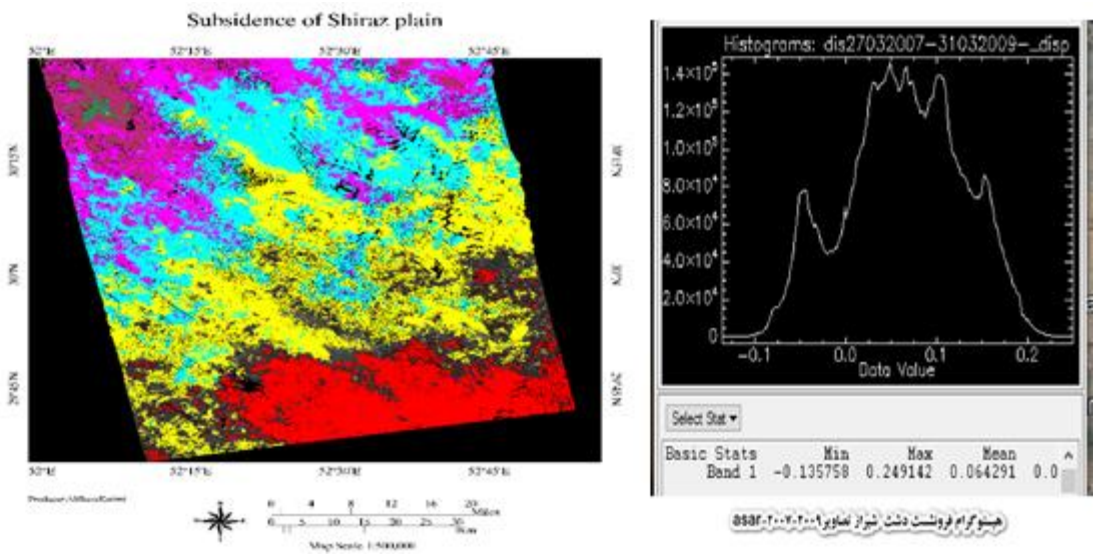

Fig. – 4 Subsidence Map (2007-2009) with Red Color Indicating Subsidence Areas and Histogram

2.2 Transverse Profile Analysis

To gain a better understanding of the subsidence pattern, a transverse profile map was created, which visualizes the variations in subsidence across a specific cross-section of the region. Fig. 5 presents this transverse profile map, enabling the identification of localized deformation trends and their correlation with subsurface conditions.

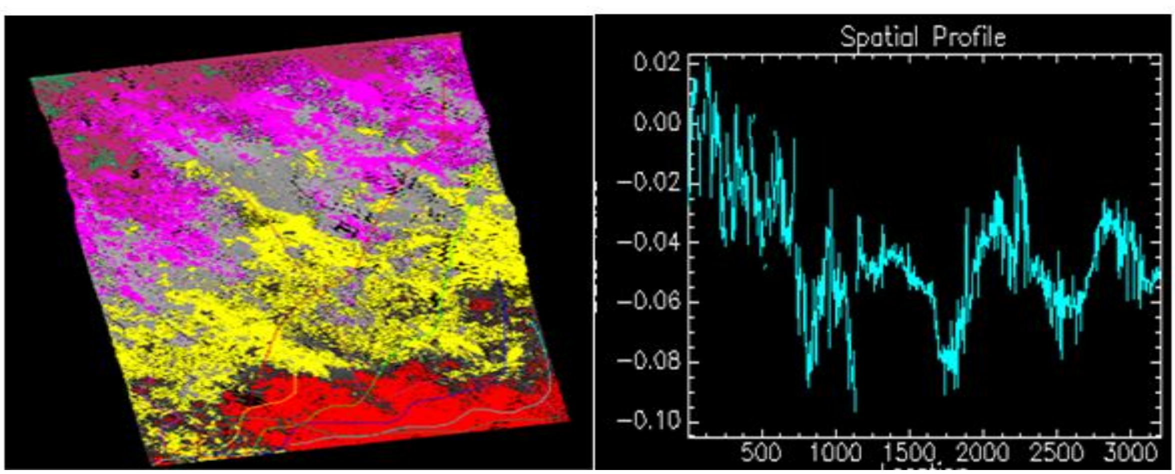

Fig. 5 - Transverse Profile of Subsidence

2.3 Subsidence Map of Beiza Plain

The Beiza plain, located near Shiraz, was also analyzed for subsidence. The generated map highlights areas of deformation, with red zones indicating significant subsidence. Fig. 6 illustrates the subsidence map and histogram for the Beiza plain, further supporting the findings from the Shiraz plain.

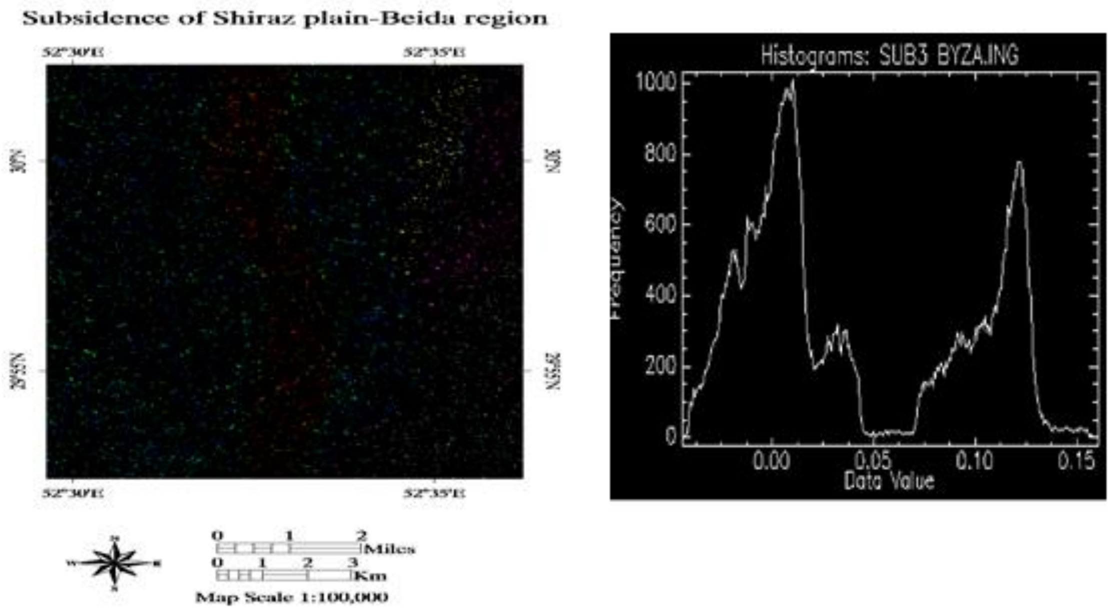

Fig. 6 - Subsidence Map and Histogram of Beiza Plain, Shiraz City Environs, with Subsidence Areas Highlighted in Red

2.4 Combined Analysis of Shiraz and Beiza Plains

To summarize the findings, examples of subsidence from the Shiraz and Beiza plains were selected and annotated on the subsidence maps. These examples highlight the consistency of deformation patterns observed across the study area. Fig. 7 provides visual examples of the subsidence areas.

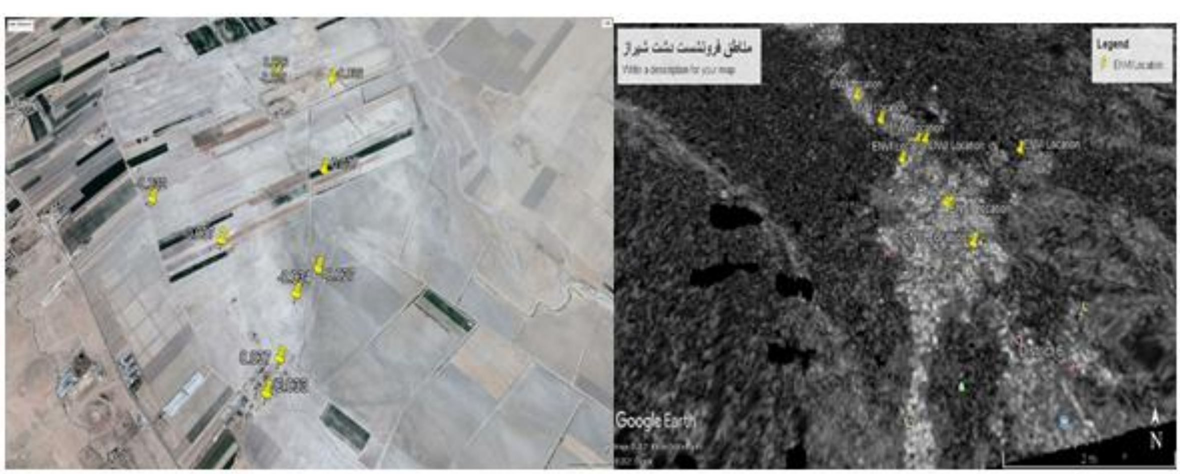

Fig. 7 - Examples of Subsidence in Shiraz and Beiza Plains Based on the Subsidence Map

4. Discussion

Subsidence is a critical phenomenon in many regions around the world, often associated with groundwater depletion, natural disasters, and human-induced activities. In this study, the subsidence patterns of Shiraz Plain, located in the southwest of Iran, were analyzed using radar interferometry, specifically focusing on data acquired from the ENVISAT ASAR sensor. This advanced technique enables the detection of ground deformations with millimeter-level precision, which is essential for understanding the underlying causes and dynamics of subsidence in regions affected by both natural and anthropogenic factors.

The findings from this study indicate a gradual subsidence across various regions of Shiraz, which aligns with previous observations of ground movement in arid and semi-arid regions. The plain of Shiraz, characterized by its slope from west to east, is particularly susceptible to subsidence due to the influx of groundwater and seasonal river flow into Maharloo Lake. The lake, which has historically been a natural sink for water, has faced significant reductions in water volume due to prolonged droughts and increased water extraction for agricultural and drinking purposes. This reduction in water depth is a major factor contributing to the ongoing subsidence observed in the region.

In line with previous studies in arid regions, including those in Iran and globally, groundwater abstraction is often a primary driver of land subsidence. Studies have shown that excessive extraction of groundwater can lead to a loss of support for the underlying soil and aquifers, resulting in the gradual sinking of the ground (El-Hadidye, 2024; Huning et al., 2024). The findings in Shiraz corroborate this theory, as the area's subsidence is closely linked to the increasing number of wells, the intensity of groundwater abstraction, and the significant reduction in the groundwater table over time.

Furthermore, the increasing salinization of groundwater in Shiraz, exacerbated by drought conditions, has led to the accumulation of fine-grained sediments in the area. These sediments, which are more prone to compaction, can exacerbate the subsidence process, as observed in the study area. This phenomenon is consistent with previous studies (Feizizadeh et al., 2022) which have highlighted the role of fine sediments and saline water in accelerating land subsidence, particularly in agricultural zones.

Another significant factor contributing to subsidence in the region is the widespread agricultural activities across Shiraz Plain. The expansion of cultivated land, combined with intensive water use, has led to an unsustainable rate of groundwater abstraction. As the groundwater level continues to decline, the soil becomes more susceptible to compaction, leading to further land subsidence. This is particularly true for areas where the soil has a high clay content, which is prone to shrinkage and settlement under reduced moisture conditions. In this study, the subsidence rates observed in agricultural areas ranged from -3.5 cm to -14 cm, with some areas experiencing even greater land loss, which is indicative of the growing pressure on groundwater resources.

Additionally, surface fires in the region, particularly in areas that were once covered by lakes or freshwater springs, have also contributed to subsidence. These areas, which were previously rich in vegetation and organic matter, now contain thin plant roots and sediments that are highly susceptible to drying and combustion. As a result of these drought conditions, the underlying soil becomes more fragile, leading to the formation of deep cracks and the collapse of the soil bed. This process, often referred to as "self-burning soil bed," is a unique form of subsidence that results from both natural and human-induced factors. The occurrence of large fires in these areas accelerates the subsidence, as the burning of organic material and the subsequent collapse of the soil exacerbates the ground deformation. This phenomenon was observed in several locations in Shiraz, where the combination of drought and fire significantly worsened the subsidence rates.

The results of this study align with previous research on subsidence in other parts of the world, where similar factors have been identified as contributing to ground deformation. For instance, studies in California and Mexico (Pacheco et al., 2006) have highlighted the role of groundwater extraction in triggering land subsidence, and the findings from Shiraz echo these observations. Moreover, the use of radar interferometry in this study has proven to be an effective tool for monitoring subsidence, as demonstrated by earlier studies in China (Ng et al., 2017), where InSAR was successfully applied to monitor ground deformation caused by both natural and human activities.

The observed rates of subsidence in Shiraz, ranging from negative 14 cm to positive 5 cm, are consistent with previous findings in areas affected by over-extraction of groundwater. In many regions globally, such as the San Joaquin Valley in California, Taiwan and north China, similar subsidence rates have been reported due to excessive groundwater pumping (Hwang et al., 2016). In Shiraz, the highest subsidence rates were observed in areas with the greatest agricultural activity, which supports the hypothesis that intensive irrigation and groundwater extraction are key drivers of land subsidence in the region.

In terms of policy, the study underscores the need for more sustainable water management practices, including the regulation of groundwater extraction and the implementation of conservation strategies to mitigate the effects of drought. Furthermore, it is crucial to monitor and manage the impact of surface fires on soil stability, especially in areas previously covered by lakes or springs. As Shiraz continues to face the challenges of water scarcity and land subsidence, it is essential to adopt integrated approaches that address both the immediate and long-term causes of ground deformation. Continued monitoring using advanced radar technologies, combined with field data, will be essential for tracking subsidence trends and ensuring the resilience of Shiraz and similar regions to the adverse effects of land deformation.

5. Conclusion

This study successfully utilized radar interferometry (InSAR) to analyze subsidence in Shiraz Plain, revealing significant ground deformation patterns caused primarily by groundwater depletion, agricultural practices, and environmental factors such as drought and surface fires. The results indicate subsidence rates ranging from -14 cm to +5 cm, with the most severe deformations occurring in agricultural zones due to excessive groundwater extraction. The study highlights the role of fine-grained sediments and salinization in exacerbating subsidence, while also identifying the unique impact of surface fires in areas previously covered by lakes and springs.

Given the findings, it is evident that sustainable water management strategies are essential for mitigating further subsidence. Regulatory measures to control groundwater extraction, along with the promotion of water-efficient agricultural practices, are critical. Additionally, addressing the impact of surface fires and restoring vegetation in vulnerable areas will help stabilize the soil. Future monitoring using advanced radar technologies, complemented by field surveys, will be crucial for tracking the progression of subsidence and informing adaptive management strategies. This integrated approach will ensure the resilience of Shiraz Plain and similar regions facing subsidence due to human and environmental factors. By drawing on the lessons learned from this study, policymakers and land managers can take proactive steps to mitigate the impacts of subsidence, protect groundwater resources, and safeguard the future of Shiraz Plain.

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Consent to Publish (Authors consent to publishing)

Authors Contributions (All co-authors contributed to the manuscript)

Code availability (Not applicable)

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