

Groundwater Overdraft and Climate-Driven Land Subsidence in the Sulaimani-Sharazoor Basin, Iraq: Insights from InSAR Techniques

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Abstract

The lack of extensive quantitative monitoring hinders the assessment of global groundwater depletion and its impacts. This study integrates satellite data to evaluate surface subsidence in the central part of the Sulaimani-Sharazoor Basin from 2017 to 2024, linking groundwater extraction, climatic factors, and land use changes to surface displacement. Sentinel-1 SAR data, comprising 91 pairs of single-look complex (SLC) images, were processed using the European Space Agency Sentinel Application Platform (ESA SNAP) toolbox and Differential Interferometric Synthetic Aperture Radar (DInSAR) to quantify subsidence. Results reveal significant subsidence in unconsolidated aquifers, driven by groundwater extraction, drought, and extensive well drilling. Vertical displacement might have peaked at -27 cm in 2021 and -26 cm in 2017, coinciding with periods of decreased annual precipitation and limited surface drainage. Surface displacements may have decreased by -6 cm in 2018 and -3 cm in 2019, respectively, indicating heightened rainfall and recharge rates. Urban areas experienced infrastructure damage, while agricultural areas and water bodies contributed to irregular displacement patterns. The study highlights groundwater extraction as a major driver of subsidence, exacerbated by climatic variability and land use changes. The statistical examination of the variable data revealed that all essential parameters remained within acceptable bounds, thereby bolstering the study's validity. These findings underscore the need for sustainable groundwater management and enhanced monitoring to mitigate subsidence risks in the area and similar regions.

Keywords:

Groundwater extraction, Drought, Surface displacement, Well-based validation, Semi-arid region.

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1. Introduction

Groundwater is a vital component of global water resources and serves as the primary source of freshwater worldwide. It plays a critical role in sustaining ecological systems and ensuring food security, particularly in arid and semi-arid regions (Arriana Brand et al., 2011; Aeschbach-Hertig and Gleeson, 2012; Famiglietti, 2014; Majumdar et al., 2020; Mohammed et al., 2022). Approximately 50% of the global population relies on groundwater for drinking water, while 43% depends on it for agricultural irrigation (UNWWAP, 2015). However, the over-extraction of groundwater has led to significant

environmental challenges, including the irreversible compaction of subsurface sediments, which accounts for nearly 60% of land subsidence globally (National Research Council, 1991). In regions heavily dependent on groundwater for irrigation, extraction rates often exceed natural replenishment rates, resulting in substantial declines in water storage and groundwater levels. This overexploitation has led to widespread groundwater degradation, with severe consequences for ecosystems and human activities. For instance, Poland (1984) identified 17 major subsidence areas in the United States caused by groundwater depletion, with subsidence rates ranging from 0.3 to 9.0 meters per year.

Differential subsidence and the flexure of surface sediments, often caused by groundwater extraction, can lead to surface deformation. This deformation poses significant risks to infrastructure, including buildings, pipelines, roads, and other subsurface structures, due to the development of tensional or compressional stresses (Vasco, 2019; Land Subsidence Task Committee, 2022). Remote sensing has emerged as a powerful tool for detecting, mapping, and monitoring Earth's resources and natural hazards across spatial and temporal scales (Dubovyk, 2017).

The integration of remote sensing with Geographic Information Systems (GIS) enables the creation of extensive databases for research, often without the need for field verification (Khan et al., 2020; Alkaradaghi et al., 2022). Among these techniques, Interferometric Synthetic Aperture Radar (InSAR) has become a key methodology for measuring land-surface deformation with high spatial precision.

The European Space Agency's (ESA) Copernicus program provides continuous and open access to Synthetic Aperture Radar (SAR) data from the Sentinel-1 mission, which consists of two identical satellites (Torres et al., 2017). Recent Sentinel-1 and ESA SNAP-based studies in neighboring regions highlight the severity of land subsidence linked to groundwater depletion, providing critical context for the current work. In Turkey, Yeşilmeden et al. (2021) demonstrated groundwater over-extraction in the Konya Basin using Sentinel-1 data, revealing subsidence rates exceeding 50 mm/year in agricultural zones. Similarly, Ghorbani et al. (2022) quantified subsidence in Iran's Ardabil Plain, correlating deformation hotspots with overexploited aquifers, while Elhag et al. (2025) identified urban infrastructure risks from InSAR-derived displacement patterns in Makkah City, Saudi Arabia. These studies underscore the regional applicability of InSAR for groundwater management but also reveal a critical gap. No comparable work exists for Iraq, despite shared hydrogeological stressors (e.g., aridification, unregulated drilling, and groundwater overdraft). Our study fills this void as the first to assess groundwater-induced subsidence in Iraq using Sentinel-1 and SNAP, advancing the theoretical

framework of Terzaghi (1925) and Ohenhen and Shirzaei (2022), who attributed irreversible compaction to clay-layer susceptibility. The Kurdistan Region of Iraq faces a pressing challenge of increasing groundwater demand, driven by rapid population growth and urban expansion (Hamamin, 2024; Khalil et al., 2024). This study focuses on the impact of surface displacement in rural and urban areas within the Sulaimani-Sharazoor Basin from 2017 to 2024.

The SSB, designated as a hydrogeological hotspot, provides an ideal setting for investigating groundwater dynamics and their environmental interactions. Notably, the basin is dominated by intergranular unconfined aquifers, which provide an optimal medium for conducting studies on groundwater-related surface deformation. Current assessment methods here rely on outdated techniques and lack modern geospatial tools, a critical limitation in a region with weak institutional water management frameworks. Therefore, this study aims to be the first to assess groundwater-induced subsidence in Iraq using Sentinel-1 data and SNAP software. The primary objectives are to: (1) quantify the rate and spatial extent of land surface displacement in the SSB from 2017 to 2024; (2) establish a novel correlation between InSAR-derived displacements, hydrologic data (surface runoff, spring records), and field surveys to validate the impact of compounded climatic and human factors on groundwater depletion and associated infrastructure damage; and (3) provide empirical evidence to support policy reform and prioritize regulatory interventions, offering a transferable monitoring model for data-scarce regions.

2. Location of study area

The Sharazoor Sub-Basin (SSB) is the central part of the Sulaimani-Sharazoor Basin and encompasses an area of 638.8 km² in the southeastern part of the Sulaymaniyah Governorate, Kurdistan Region, Iraq. It is delineated by geographical coordinates ranging from 35°12'54" N to 35°28'29" N in latitude and from 45°29'0.4" E to 45°50'16" E in longitude. The region's altitudes vary from 471 to 1403 meters above mean sea level. The basin's principal urban centers comprise Arbat, Zarain, and Halabjae-taza, in addition to villages and camps such as Kani Panka, Greza, and Barikae-kon. The SSB

encompasses Darbandikhan Lake to the east and southeast, while the Baranan hills are situated to the south and southwest, with Arbat marking its western boundary (Fig.1).

The study area is considered one of Iraq's most agriculturally and industrially prosperous areas, with a population of around 180,000, comprising 110,000 urban inhabitants and 30,000 rural inhabitants. The demographic divide is characterized by densely populated urban regions with sophisticated infrastructure, in contrast to rural communities dependent on subsistence agriculture and conventional water sources (Osman, 2021).

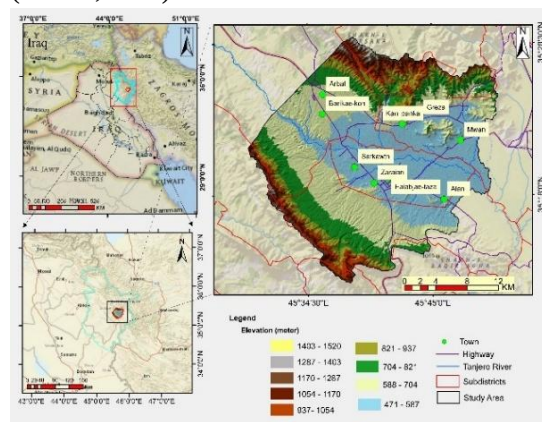


Fig. 1: Location map of the study area (Google Earth, 2022).

3. Tectonic and Geological settings

The Arabian Plate, particularly Iraq, characterized by its three primary tectonic zones, was significantly impacted by the Nabta Orogeny (680–640 million years ago) (Stern and Johnson, 2010; Jassim and Goff, 2006). The Arabian and Eurasian tectonic plates merge in Kurdistan. Collisions during the Laramide orogeny resulted in the formation of SSB tectonics. The upper folded zone features dextral strike-slip faults in the vicinity of Halabja-Said Sadiq. The High Folded Zone (HFZ) features steep gorges and carbonate fold structures that originated during the Late Cenozoic Zagros orogeny (Sissakian et al., 2014). The uplifts of the Cretaceous, Paleocene, and Oligocene periods formed Eocene molasse basins (Jassim and Goff, 2006), whilst the southwest anticlines feature significant thrust faults. The limestone-rich Baranan Mountain escarpment delineates the southern boundary of the research area (Numan and Al-Azzawi, 1993). Numerous stratigraphic units are observable and truncated in

the study area. The oldest rocks, the Valanginian–Turonian Balambo Formation, are visible at the crests of anticlines, whilst the younger units, the Kometan and Shiranish formations, are found in the limbs and troughs of synclines. Central to the word Derbandikhan Lake are the Quaternary deposits. Quaternary sediments exhibit a thickness of 5–150 meters and consist of clay, silt, sand, and gravel. Erosion transported sediments and particles of diverse sizes around higher mountains to occupy depressions and valleys. Rock fragments are transported by seasonal stream floods subsequent to significant rainfall (Ali, 2007). The substantial Upper Cretaceous–Paleogene flysch sequence of the early Zagros Foreland Basin, known as the Tanjero Formation, is situated under the Quaternary deposits in the research region (Sharbazheri and Muhammed, 2009). Fig. 2 illustrates this. The Oligocene Kolosh Formation comprises marlstone. Slippage on Kolosh marlstone leads to Sinjar carbonate outcrops, and the southern area is marked by the Gercus and Pila Spi formations and the Baranan Mountain anticline (Karim and Ali, 2004).

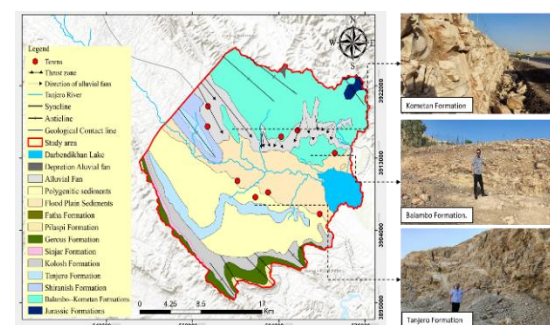


Fig. 2: Geological map of the study area (modified from Sissakian and Fouad, 2015).

4. Hydrology and Hydrogeological setting

The SSB is acknowledged as an essential hydrological plain distinguished by intricate terrain, featuring steep gorges and narrow valleys (Sissakian, 2014). Precipitation in SSB predominantly occurs from October to May, averaging 650–700 mm per year, while evapotranspiration measures 690 mm. Primary water sources comprise direct precipitation and the Tanjero River, which feeds into the Darbandikhan Reservoir. Hydrogeologically, multiple formations contribute to groundwater snowmelt, and three principal tributaries are notable resources,

including the karstic Sinjar Formation and the high-yield karstic fissure aquifer of the Balambo and Kometan formations. The Shiranish Formation acts as an aquiclude for deeper aquifers, whereas the Tanjero Formation comprises layers that establish semi-confined conditions. Groundwater in the SSB is utilized for both domestic and irrigation purposes via a network of wells. Pumping tests performed in the sub-basin reveal aquifer transmissivity values between 5 and 409 m²/day, hydraulic conductivity ranging from 0.2 to 4.9 m/day, well discharge rates from 52 to 1,642 m³/day, and static water levels at depths of 3 to 59 meters beneath the ground surface. Unconfined aquifers are the predominant type in the region (Ali, 2007; Stevanovic and Iurkiewicz, 2004; Al-Basrawi and Al-Jiburi, 2014; Hamamin and Nadiri, 2018). Groundwater extractions display notable spatial variability, with discharge rates categorized into three classifications utilizing GIS natural breaks (Fig. 3).

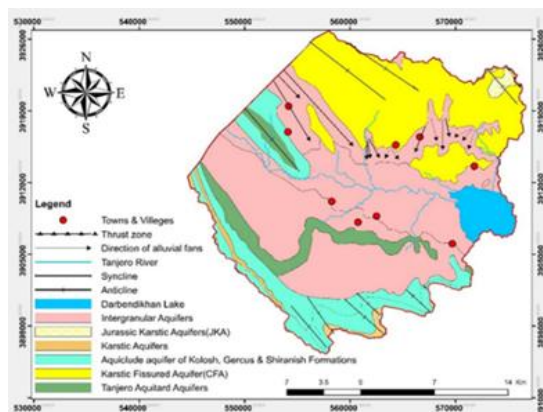


Fig. 3: Existence of aquifers within the SSB.

The groundwater output from 358 wells was categorized into five classifications based on groundwater withdrawals, highlighting significant geographical disparities in supply throughout the SSB utilizing GIS natural breaks (Fig. 3). The discharge rates vary widely, with elevated values (70-298 l/sec) mainly found along mainstream channels, indicating strong groundwater-surface water interactions. Intermediate rates (23-69 l/sec) form transitional buffers around high-discharge areas, while the lowest rates (<23 l/sec) are observed farther from primary streams, particularly affecting the Tanjero and Shiranish formations and indicating diminished aquifer recharge.

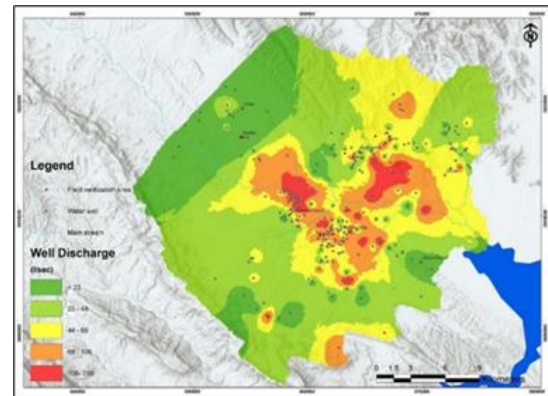


Fig.4: Spatial distribution of average well discharge (liter/sec). Data sourced from well profiles provided by the Sulaimani Groundwater Directorate (2025).

5. Methodology

A. DInSAR

This study integrates six primary datasets to analyze surface displacement and hydrological dynamics in the SSB, which include:

1. ESA Data and InSAR processing parameters for Sentinel-1 in the SSB.
2. DINSAR techniques face three inherent constraints.
3. Field validation protocols. The European Space Agency (ESA) Copernicus program provides open access to Synthetic Aperture Radar (SAR) data from the Sentinel-1 mission, which operates in exclusive instrument acquisition modes:

<https://browser.dataspace.copernicus.eu/>.

The mission includes two identical satellites. This study uses Sentinel-1 C-band data from the S1A satellite platform, available since 2014, with a descending orbit repeating every 12 days. It employs the Interferometric Wide (IW) mode, yielding dual-polarization data processed through the ESA SNAP 9.0 toolbox to measure land displacement from 2017 to 2024 using 232 Level-1 SLC images, each with a spatial resolution of 32 m. The Terrain Observation and Progressive Scan (TOPS) technique was incorporated to mitigate noise and scalloping effects (De Zan and Guarnieri, 2006) (Fig. 5). Image pairs were selected based on three criteria: (1) temporal baseline (12 days) to minimize decorrelation, (2) perpendicular baseline (76-150 m) to reduce

geometric distortions, and (3) seasonal matching (dry-to-dry/wet-to-wet periods) to isolate groundwater-induced deformation from precipitation effects. The co-registration of SAR images was followed by the generation of interferograms, which incorporated flat-earth phase (5 degrees with over 500 estimation points), topographic influences utilizing the SRTM DEM, atmospheric conditions, and deformation signals. The Goldstein phase filter ($\alpha = 0.64$ -128, window size 32×32 pixels) was employed to enhance phase quality; however, its efficacy was constrained in low-coherence regions (threshold $\gamma > 0.2$). Phase unwrapping addressed elevation ambiguities by transforming wrapped phases into absolute displacements, subsequently converting these into line-of-sight surface deformation (in meters) via the Phase to Displacement operator. The analysis omitted 50 of 236 Sentinel-1 acquisitions, representing 21%, due to persistent incoherence ($\gamma < 0.3$), primarily during peak vegetation growth (May-September 2020-2022) and significant precipitation events (November 2019, March 2021). The areas of Barikae-kon, Halabjae-taza, Zarayan, and Arbat towns experienced a loss exceeding 40% of their data; however, the winter months (December-February) maintained over 85% of usable coverage. DInSAR techniques are subject to three intrinsic limitations: (1) atmospheric delays result in a vertical uncertainty of ± 1.1 cm, especially during humid summer months; (2) alterations in

vegetation within irrigated croplands lead to seasonal coherence loss ($\Delta\gamma > 0.3$ between planting and harvest cycles), requiring InSAR augmentation; and (3) pronounced topography ($> 15^\circ$ slopes) at basin peripheries causes layover distortions, impacting certain image footprints. While short temporal baselines (< 12 days) diminished phase unwrapping inaccuracies, the 32m pixel resolution constrained the identification of small-scale features.

To address these factors, we employed multi-track validation (descending orbits) and eliminated pixels with low confidence (coherence < 0.3 or atmospheric SNR < 2). In order to assure accurate results, displacement values were obtained from the nearest high-coherence pixels ($\gamma > 0.4$) within a 10-meter radius of each well's GPS-verified coordinates, considering Sentinel-1's intrinsic

resolution constraints ($\sim 5 \times 20$ m). This methodology adheres to recognized groundwater-InSAR research (Chaussard et al., 2014) and incorporates geolocation uncertainties intrinsic to SAR geometry. For wells containing multiple valid pixels within the buffer zone, we utilized averaged displacements, while omitting other wells affected by nearby structures that induced layover or shadow effects.

The geocoding utilized a DEM with a resolution of 12.5m to correct geometric distortions, with the final outputs exported as KMZ files for visualization in Google Earth (Braun and Veci, 2020). Spatial analysis was performed in ArcMap 10.8, incorporating geological, hydrological, and land-use maps alongside DEM-derived raster computations (Mogaji and Lim, 2017) (Fig. 5).

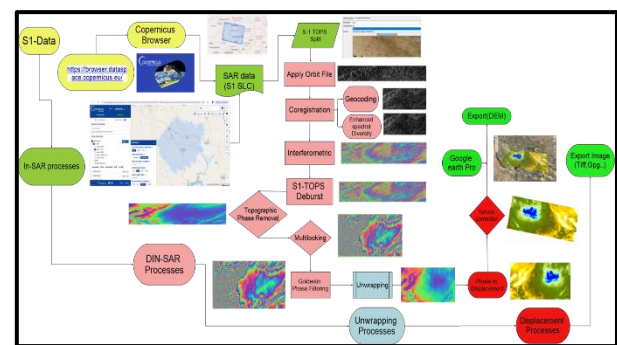


Fig. 5: Workflow for dataspace in Copernicus web side, InSAR images from Sentinel-1, DInSAR processing, displacement processing and export image displacement, using the ESA SNAP toolbox.

Table 1: Sentinel-1A SAR data specifications used in the study.

Parameter	Specification
Satellite platform	Sentinel-1A
Processing level	Level-1 Single Look Complex (SLC)
Acquisition mode	Interferometric Wide Swath (IW)
Orbit direction	Descending
Relative orbit no.	1-175
Repeat cycle	12 days
Polarization	VV, VH (dual-pol)
Swath	IW1
Bursts per image	5-7
Spatial resolution	32 m (range) $\times$ 32 m (azimuth)
Temporal coverage	March 2017 – December 2024
Total acquisitions downloaded	232 SLC images
Distorted SLC	50
SLC Used	182 images SLC
DInSAR	91 images
Processing tool	ESA SNAP 9.0

B. Hydrological data integration

1. Thickness of Recent Deposit (RD)

A map illustrating the thickness of recent deposits (RD) was produced utilising GIS software, integrating data from more than 128 wells and monitoring boreholes. The alluvial

deposits display a thickness variation of 0 to 140 meters, with maximum thickness recorded in the plain region, especially within the central depression and the Tanjero stream corridor, where depths attain 100 meters. The thickness progressively escalates towards the peripheries of Darbandikhan Lake, varying from 45 to 140 meters, whereas the northwestern and southern

areas are distinguished by superficial deposits with thicknesses between 0 and 50 meters (Fig. 6). The variations in thickness are affected by local geological and topographical factors, such as sediment sources from erosion, tectonic activity, and climatic changes (Syvitski, 2003).

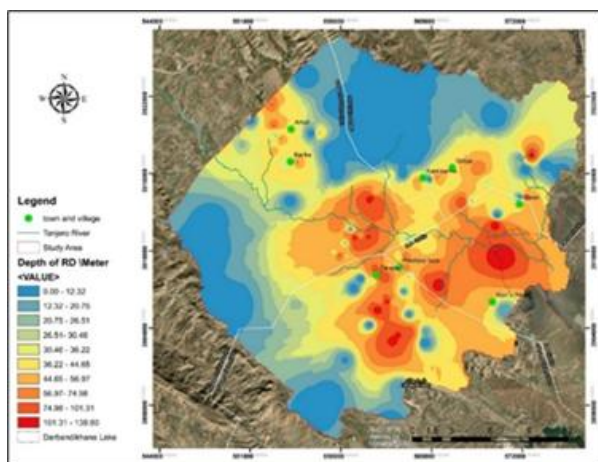


Fig. 6: Isopach map of the depth distribution of RS.

2. Monitoring well data

Piezometric data are crucial for the preparation and analysis of maps depicting variations in groundwater levels (Rafiei et al., 2022). This study utilized data from nearly 100 production wells, along with monthly groundwater level time-series data from five monitoring wells in the unconfined aquifer of the SSB. The monitoring well data, spanning from 2017 to 2024, were collected and managed by the Groundwater Directorate of Sulaymaniyah.

The historical groundwater level data were initially categorized by year, and trends in water level fluctuations for each well were examined. The average fluctuations in groundwater levels throughout the study area were assessed.

The Inverse Distance Weighting (IDW) interpolation method was utilized to interpolate groundwater level data and produce flow net maps (Fig. 7). The groundwater map demonstrates flow dynamics and potential within the study area, revealing pronounced hydraulic gradients particularly near Gazetteer Village and the Arbat district. Groundwater predominantly flows from elevated regions, such as Baranan Dagħ mountain, to lower areas including Zarayan town, Mwan village, and Halabjae-taza district, affected by human activities near wells. Primary recharge sources encompass rivers, springs, and lakes, which maintain groundwater levels in locations such as the Tanjero stream and Darbandikhan lake, whereas areas like Greza and Kharaba villages demonstrate diminished potential and increased deformation risks.

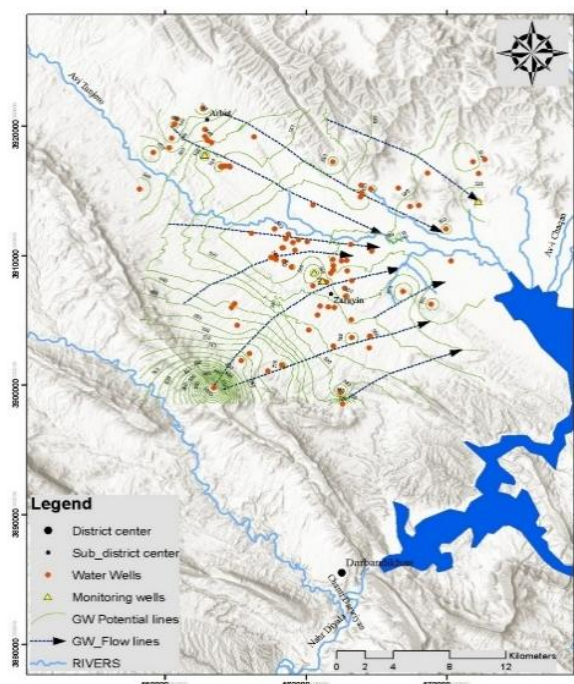


Fig.7: Spatial distribution of groundwater levels and flow directions.

3. Surface water discharge measurements

The discharge data for the Tanjero River and prominent springs within the SSB were acquired from the Department of Watershed Management,

Irrigation Directorate of Sulaimani (IDS, 2025). The surface runoff data derived from karst springs spanning the years 2017 to 2024 offer valuable insights into the characteristics of aquifers and the unique attributes of karst rock-fissure massifs (Table2). The analysis of annual hydrograph curves and methodical evaluations of the flow discharge from Kanipanka springs serve as essential instruments for comprehending water levels and groundwater depletion from 2017 to 2024. The dataset comprises discharge measurements in m³/sec for the Tanjero River and the Kanipanka springs (Upper Qalijo Channel, Lower Qalijo Channel, and Mwan stream) spanning from 2017 to 2024. The measurements are encapsulated in Table 2.

Table 2: Annual average inflow rate of Tanjero stream and Kanipanka springs from 2017-2024 (as acquired from the IDS, 2025).

Year	Tanjero stream (m ³ /sec)	Kani Panka (m ³ /sec)
2017	13.1	0.45
2018	25.1	0.6
2019	55.2	1.9
2020	9.5	0.65
2021	7.3	0.1
2022	6.1	0.15
2023	9.2	0.35
2024	24.9	0.55
Avg.	18.8	0.59

According to IDS (2025), the surface runoff data derived from karst springs spanning the years 2017 to 2024 offer valuable insights into the characteristics of aquifers and the unique attributes of karst rock-fissure massifs (Table4.2). The analysis of annual hydrograph curves and methodical evaluations of the flow discharge from Kanipanka springs serve as essential instruments for comprehending water levels and groundwater depletion from 2017 to 2024 (Fig. 8).

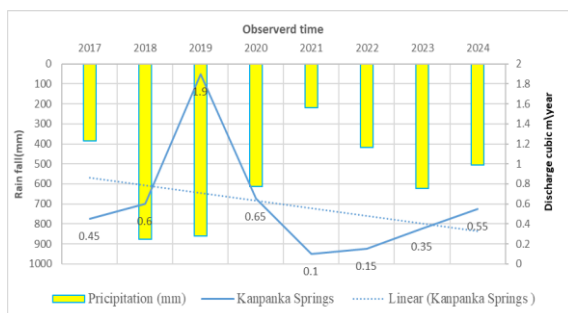


Fig. 8: The comparison between total rainfall (mm) and annual discharge of the Kanipanka springs (Kanipanka channels, Qalinjo and Mawan). (IDS, 2025).

6. Results

This study investigates the interaction between water-bearing units and evaluates land subsidence in the SSB using processed radar imagery. Additionally, monitoring well data were analyzed to assess groundwater level changes, and the relationship between these changes, surface runoff, and land subsidence was examined.

6.1. InSAR Verification

A reduction in groundwater levels markedly affects the effective stress in aquifers, resulting in consolidation, compaction, and subsequent land subsidence, as outlined by Valizadeh et al. (2005). Terzaghi (1925) elucidates that diminished pore-fluid pressure resulting from decreased groundwater levels leads to the compaction of the aquifer framework, whereas elevated pressures bolster its structural integrity, facilitating elastic rebound. Seasonal variations in groundwater generally produce slight, reversible deformations, considered normal within aquifer systems, as noted by Phillips and Galloway (2008). A detailed spatial analysis reveals a distinct hydro-mechanical relationship within the study area: steep groundwater potential gradients between 650 and 1000 m are associated with notable subsidence zones in regions like Arbat and Gazeteer Village, highlighting that considerable groundwater extraction intensifies land subsidence (Fig. 7). The study examines groundwater level (GWL) fluctuations to improve model accuracy and understanding of local aquifer dynamics. Piezometric data from 100 production wells and four monitoring wells in the unconfined aquifer are used to compare model predictions with local trends and remote sensing data. GWL data from 2017 to 2024 show short-term and long-term changes. Data collection issues, especially the COVID-19 pandemic, affected measurement consistency. The GWL was unstable from 2017 to 2020, but it improved in 2019. The dropping significantly since 2021, indicating groundwater overextraction. Improvements from 2023 to 2024 may indicate management or precipitation changes affecting aquifer replenishment (Fig. 9).

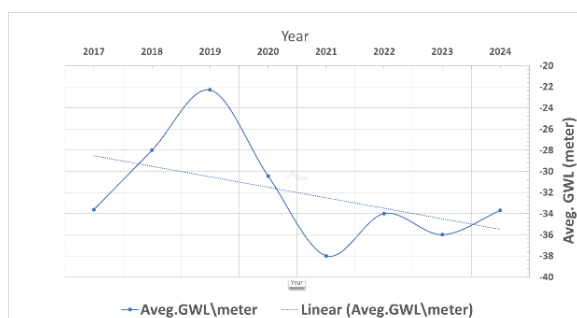


Fig. 9: Annual groundwater level trend in the SSB (2017-2024).

The correlation between the groundwater level curve and deformation patterns suggests that flow disruptions near densely clustered wells, particularly around Zaraian, Barikae-kon, and Nasir Camp, align with subsidence hotspots, thereby reinforcing this hydro-mechanical connection. The slight shift of -3.7 cm during 2018-2019 indicates diminished groundwater extraction, recovery of pore pressure, and heightened annual precipitation relative to the norm. During the drought period and extensive well drilling and extraction from 2020 to 2021, which continued into 2024, the SWL reached its maximum depletion, accompanied by significant surface displacement in certain areas of the study (Fig.10).

The hydrogeological structure of unconfined aquifers demonstrates that declining water tables reduce pore pressure, leading to compaction. The isopach map visually corroborates this trend (Fig. 6; Fig. 4), demonstrating more pronounced water-level declines in unconfined aquifers compared to confined systems. Moreover, the basin's stratified aquifers demonstrate differing levels of susceptibility, especially the Shiranish and Tanjero formations. The marlstone and marly limestone, varying in thickness from 20 to 35 meters across both formations, may constitute 68% of the overall compaction resulting from delayed drainage. Karim and Surdasy (2006) assert that the Tanjero Formation comprises a significant sequence of bluish to white marl, which closely resembles the lithology of the Shiranish Formation in the area of interest. The karstified regions of the Balambo limestone exhibit a swift reaction of the water table with negligible compaction, leading to a differential subsidence of 0.5-1.2 cm annually along lithologic boundaries.

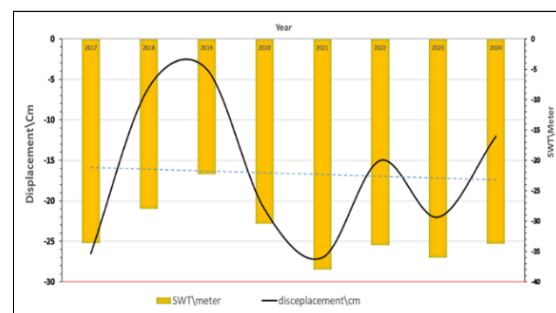


Fig. 10: The correlation between SWL and surface displacement.

The correlation between precipitation, aquifer dynamics, and land subsidence becomes more evident during droughts, particularly in years characterized by low precipitation, such as 2016-2017 and 2020-2021 (Fig.11).

The recorded displacement of -26 cm in 2020-2021 corresponds with the year's insufficient rainfall of only 220 mm, signifying aquifer overexploitation and the compaction of unconsolidated clays and silts, a phenomenon corroborated by Galloway et al. (1999). In contrast, periods of increased precipitation, specifically 2017-2018 and 2018-2019, led to diminished subsidence levels owing to improved groundwater recharge, temporarily stabilizing the unsaturated aquifer system in the SSB. The minimal displacement of -3.7 cm documented between 2018 and 2019 illustrates diminished groundwater extraction and an increase in pore pressure recovery. These findings are comparable to observations in other regions, such as California's San Joaquin Valley, where extended drought conditions prompted heightened groundwater extraction and considerable subsidence, as recorded by Smith et al. (2017). The data obtained from the SSB supports this correlation, indicating significant subsidence during periods of low precipitation, as demonstrated by the -0.27 m displacement recorded in 2020-2021 with merely 200 mm of rainfall.

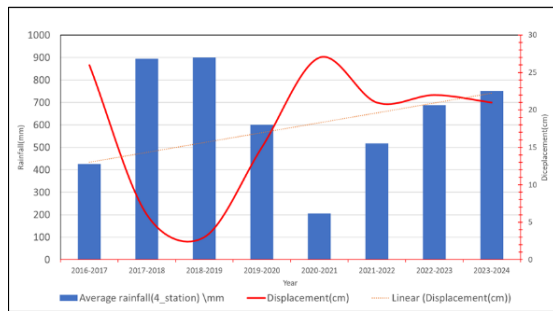


Fig. 11: The relationship between annual precipitation and surface movement.

6.2 Land subsidence and surface water discharge

This study investigates the influence of surface water resources on groundwater recharge and their resultant effects on subsurface compaction and land subsidence, specifically focusing on the Tanjero River and Kani Panka springs from 2017 to 2024. The analysis reveals a substantial correlation between surface water discharge and land subsidence, demonstrating that enhanced surface water availability can rejuvenate unconfined aquifers and alleviate subsidence (Fig.12). Data reveal that the total inflow from the Tanjero River rose from 13.1 m³/sec in 2017 to 24.9 m³/sec by 2024. Simultaneously, the discharge from Kani Panka Spring increased from 0.45 m³/sec to 0.55 m³/sec. These alterations corresponded with differing degrees of surface displacement throughout the examined years. In 2018, a significant increase in Tanjero River discharge to 25.1 m³/sec was associated with a decrease in subsidence to -0.06 m. A peak discharge of 55.2 m³/sec in 2019 led to negligible subsidence of -0.037 m, indicating that substantial surface water influx can beneficially affect groundwater levels.

Since 2020, there have been variations in discharge rates and surface displacement. In 2020, a decrease in inflow to 9.5 m³/sec caused subsidence of -0.21 m, and in 2021, additional reductions in discharge resulted in a notable subsidence of -0.27 m. The inverse relationships highlight the aquifer system's sensitivity to changes in surface water availability.

In 2024, the IDS data indicated a significant rise in total surface water availability. The findings suggest that increasing surface water discharge can effectively stabilize groundwater systems,

mitigating subsidence by enhancing aquifer replenishment. Conversely, reduced discharge rates lead to intensified subsidence resulting from decreased groundwater replenishment and increased subsurface compaction.

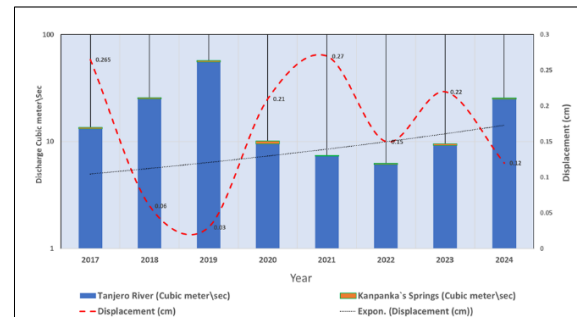


Fig. 12: Correlation between average runoff (m³/sec) and surface displacement.

6.3 Subsidence patterns and temporal trends

The data analyzed were produced by exporting pair-level-1 SLC images from C-SAR, Sentinel-1, into the ESA SNAP 9 software and subsequently converting them to TIFF format for raster analysis in ArcGIS following the completion of the DInSAR application. This study exclusively examines the risks associated with land subsidence due to the continuous depletion of groundwater resources, disregarding any positive (uplift) indicators. From 2017 to 2024, notable fluctuations in annual surface displacement were documented, closely correlating with climatic trends and groundwater extraction levels. The research utilizes DInSAR processing in conjunction with GIS raster computations to assess negative subsidence data, particularly focusing on values ranging from maximum subsidence to zero (Fig.13).

The examination of surface displacement during the specified period indicates significant alterations. In 2017, a significant increase in subsidence was observed, with a maximum displacement of -26 cm recorded. In 2018, a decrease to a minimum of -6.0 cm was observed. The minimum subsidence recorded during the study period was -3.0 cm in 2019, coinciding with significant precipitation and aquifer replenishment. The most substantial subsidence transpired in 2021, recognized as the driest year on record, with a measurement of -27.0 cm. In 2022, recorded displacement was -15.0 cm, whereas in

2023, subsidence reached a maximum of -22.0 cm. The ultimate documented displacement in 2024 was -12.0 cm.

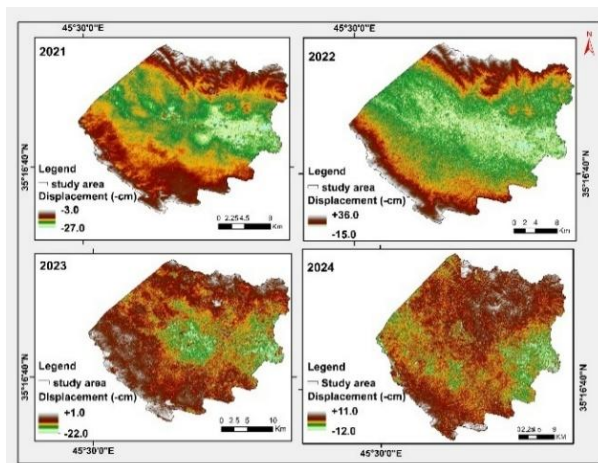


Fig. 13: Cumulative annual vertical subsidence maps for 2017–2024 in the SSB by m.y-1.

The average annual surface displacement over the eight-year study period is determined to be -10.5 cm per year (Fig.14), signifying a gradual subsidence of the land surface in the basin, particularly in its central and western areas.

The study identifies several towns and villages as pivotal sites undergoing substantial land subsidence. The areas adjacent to Arbat, Barikae-kon, Sarkawtn, Zarain, and Halabjae-taza exhibit the most significant negative displacement values. The geological context indicates that these hotspots are primarily located within the basin's unconsolidated deposits, marked by clay-rich layers that demonstrate increased vulnerability to contraction. Conversely, stable zones like Mwan and Alan exhibit diminished displacement values

in comparison to the central hotspots, signifying relative stability in these areas.

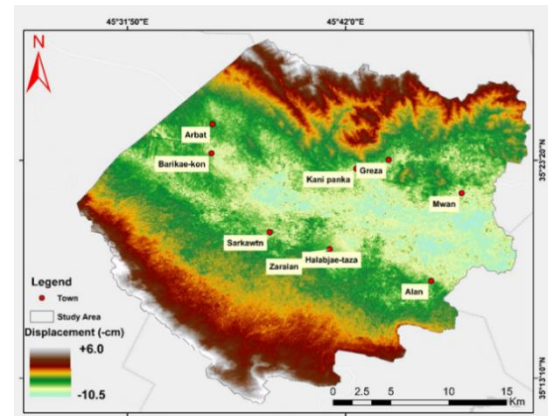


Fig. 14: Average annual cumulative subsidence (m.yrs-1) in the SSB from 2017 to 2024.

7. Discussion

7.1. Driver Analysis

The primary contributors to subsidence in the SSB basin appear to be groundwater overextraction and the prevalence of numerous clay layers within recent sediment; however, six supplementary factors warrant consideration as well.

1. Seasonal, topographic, and climatic factors significantly affect tropospheric water vapor, leading to 10 cm inaccuracies in deformation caused by 20% variations in relative humidity (Zebker et al., 1997; Qiu et al., 2023).
2. DInSAR is an accurate technique for monitoring ground displacement to the centimeter or millimeter level; nevertheless, atmospheric variations can compromise the reliability and precision of the results, complicating DInSAR processing.
3. The neotectonics map indicated vertical uplift movements in the HFZ ranging from 0.0022 to 0.0086 m/100 years; however, the precise amount of vertical displacement was not specified (Sissakian et al., 2020). According to Zebari et al. (2023) and Othman et al. (2018), the uplift rate in the Zagros Mountains is reported to be between 0.7 and 1.3 mm/year and 0.33 to 1.67 mm/year, respectively. The magnitude 7.3 quake in November 2017 during the Zagros Mountain development in the Sarpel Zahab vicinity demonstrated this occurrence in

the SSB, leading to considerable instantaneous modifications to the landscape near Darbandikhan Lake.

4. Urban expansion and subsidence assessed in the vicinity of Arbat, Sarkawtn Camp, and Halabjae-taza.
5. Clay shrinkage-swelling cycles, seasonal moisture variations, and flood length affect erosion and sediment deposition (Fernandez et al., 2025). Comparable amounts of disruption were noted, with soil moisture varying by as much as 10 degrees Celsius, approximately equivalent to 1 mm for a C-band wave, a specific microwave frequency utilized in radar and satellite communications (Beale, 2019).
6. Unexplained alterations may signify natural phenomena, including intricate subterranean conditions, unregulated human operations from industries, multiple storage facilities, and illicit well drilling.

7.2. Groundwater discharge and land subsidence correlation

Spatial examination of well discharge rates (varying from <23 to 300 l/sec) indicates a direct correlation with the extent of land subsidence in the research region. Regions characterized by comparatively low discharge rates (<44 l/sec), especially in the western and southwestern sectors of the examined territory, demonstrate negligible subsidence (<10 cm.yr-1), highlighting the stabilizing influence of natural replenishment and a reduced number of active production wells in contrast to the central region. Conversely, regions exhibiting moderate-to-high discharge (>70 l/sec) at the center and along primary streams correspond with elevated subsidence rates (>20 cm.yr-1), signifying aquifer overexploitation and ensuing compaction, as illustrated in deformation rate maps (Fig. 9), particularly in the years 2020, 2021, and 2023. Seasonal reductions in groundwater during droughts probably intensified this trend, demonstrated by a 3.0 cm/yr rise in subsidence in low-discharge wells, as illustrated in Fig. 7, aligning with global models of clay-layer compression (Galloway and Burbey, 2011).

These results support focused replenishment efforts in areas with diminished discharge to alleviate subsidence hazards.

7.3. Urbanization-Enhanced Subsidence

The analysis indicates that urban expansion has intensified groundwater-related subsidence through two primary mechanisms:

1. Direct loading effects: The density of buildings in Halabjae-taza town and Barikae-kon village in the western and central parts of the area has clearly risen.
2. Hydrologic disruption: The area of impervious surfaces increased by approximately 20 km², resulting in a reduction of natural recharge by about 10%, particularly in Arbat town and Sarkawtn Camp during the period from 2012 to 2024.
3. Fig. 15 demonstrates the expansion of the urban area from 2012 to 2024, highlighting the sudden establishment of three camps in 2014 behind Arbat town and Sarkawtn Camp, which resulted in an increased demand for groundwater through the drilling of over 17 wells.

Additionally, as indicated in Table3, the urban area experienced a 30% increase from 2017 to 2024, suggesting that the growth could exceed this range if assessed from 2012.



Fig. 15: The expansion of urban infrastructure (roads and buildings) in selected locations within the SSB from 2012 to 2024 in the SSB (Google Earth Pro).

Table 3: Subsidence attribution in the SSB.

Process	Key Evidence	Spatial Pattern
Groundwater extraction	Well density vs. subsidence $R^2=0.74$	Concentric around pumping wells, discharge, and SWL
Tropospheric noises	Terrain elevation, Local weather, convection, and wind	Elevation and weather parameters
Tectonics	InSAR fault-parallel trends	Linear along anticline
Horizontal deformation (Flooding, Farming, Channeling)	Field work	Seasonal deformation
Natural compaction and clay shrinkage-swelling	Deformation in undeveloped areas	Fluvial corridors
Urban loading	Building permits vs. subsidence	Radial near cities
Undocumented anthropogenic factors	Complex industrial factories, and illegal drilling wells, Land Use	

8. Validation

Due to the absence of precise leveling or GPS station data during the study period, Earth observation-based validation of DInSAR processing results was not feasible. Additionally, the lack of sufficient SAR data for the SSB necessitated the use of a comparative validation approach. For this purpose, DInSAR processing results were validated against groundwater level data from 4 monitoring wells and 2 surface water discharge measurements. Subsidence values at the monitoring well locations were extracted from the displacement maps and compared with the observed data. The study ultimately finds a commendable quantitative correlation between subsidence estimates obtained from InSAR data and those from monitoring wells, thereby validating the visual trends observed in displacement maps. Slight variations between datasets may be ascribed to the differing temporal acquisition periods of the imagery. Field surveys were executed to corroborate the findings by collecting additional evidence of subsidence in the SSB area.

8.1. Statistical comparison between variables

The Study performed an exhaustive statistical evaluation juxtaposing in-situ measurements with DInSAR-derived displacements, employing a hierarchical methodology that involved the examination of Pearson correlation coefficients (r) and coefficients of determination (R^2) from ordinary least squares regression. The results indicate substantial hydrological connections with surface movements throughout the SSB, particularly illustrated in Fig. 16.

In panel (a), a robust association was identified between total precipitation and displacement, with a Pearson coefficient of $r = 0.87$ and $R^2 = 0.75$. This suggests that around 75.7% of the variation in displacement can be accounted for by rainfall patterns, demonstrating a nearly linear correlation (slope = 0.62 cm/mm rainfall). The association highlights the synergistic impacts of immediate precipitation and postponed groundwater replenishment in the fractured aquifers of the area. The low p-values corroborate the statistical significance of these results. The one-tailed p-value is 0.000108, while the two-tailed p-value is 0.000217, both considerably below the standard cutoff of 0.05, indicating merely a 0.02% probability that these findings are attributable to random variation.

Panel (b) examines the correlation between static water levels (SWL), resulting in $r = 0.74$ and $R^2 = 0.55$. The results demonstrate that 55.0% of the variability in SWL can be attributed to aquifer compaction affected by urban development and agricultural groundwater withdrawal methods. The examination distinctly indicates a nonlinear pattern at SWL depths exceeding 15 m, implying stress-dependent compressibility in clay interbeds, in alignment with poroelastic theory. The notable p-value of 0.0002 further substantiates the strength of these results.

Panel (c) displays information for Kanipanka Springs, indicating an R^2 of 0.65 and an r value of 0.81, albeit with increased variability attributed to localized karst conduit flow impacting water retention. The correlation exhibits considerable significance with a p-value of 0.00199. Furthermore, panel (d) assesses the influence of Tanjero River runoff, assigning 64.0% of the variance in displacement to its effects ($r = 0.80$),

with a notably robust correlation noted during the spring snowmelt phase. The coefficient derived from this analysis is likewise noteworthy, registering below 0.01.

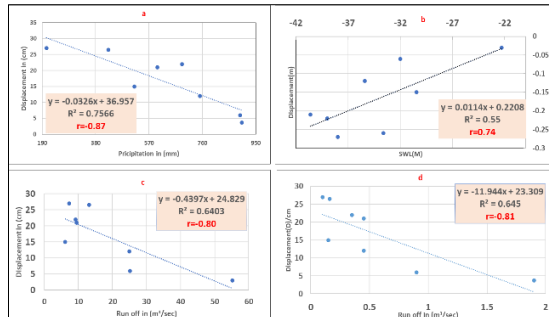


Fig. 16: Hydrological influences on surface displacement in the SSB: Correlations of InSAR-derived displacement with (a) Rainfall, (b) Static Water Level, (c) Kanipanka Springs discharge, and (d) Tanjero River runoff.

8.2. Field survey

The SSB exhibits distinct subsidence patterns tied to its aquifer characteristics and anthropogenic activities. In some areas of the basin, subsidence was accompanied by infrastructure cracks, especially in Barikae-kon village (Fig.17, FV-01,02), while in others, it occurred as uniform and homogeneous settlement. Specific areas within the basin exhibited significant deformation, including alteration of Tanjero River's meandering, irrigation channels, pools, and soil cracks (Fig. 17,

V-03, 04). These features generated anomalous signals in SLC images, which were used to assess displacement over the study period. In northwestern settlements (Arbat town, Barikae-kon village), damage to infrastructure, including cracked mosque foundations, fractured school walls, and ruptured pipelines, stems from excessive groundwater extraction via shallow wells (20-50 m depth) tapping unconfined aquifers of the floodplain sediments and aquiclude beds within the Shiranish Formation, respectively (Table 4, FV-03,04). The areas exhibiting the greatest distortion correspond to the rampant drilling of wells, both legal and illegal, in residential neighborhoods. The eastern regions adjacent to Darbandikhan Lake and the Tanjero River exhibit distinct processes: riverbank erosion and sediment deposition occur due to seasonal flooding (Fig.18, FV05-06), while areas near the Darbandikhan reservoir experience subsidence resulting from poroelastic loading during variations in water levels (Fig.19). An empirical study indicates that thin (10–45 meters) unconfined aquifers in alluvial sediments are the first to collapse under pumping stress. After the 2021 drought, most wells in Sarkawtn Camp and Barikae-kon Village were desiccated, although denser strata (70-140 m) exhibit more pronounced deformation, especially in Halabjae-taza and Mowan Village.





Fig. 17: Infrastructure deformation in Barika Kon town due to excessive well drilling, and subsidence effects in Kazhaw village (irrigation channels), Arbat, Halabjai Taza, and Nasser Camp (schools, mosques, and residential buildings).

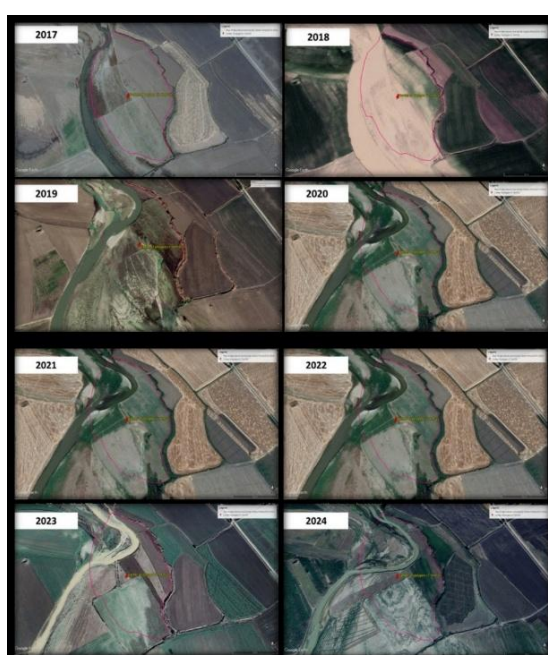


Fig. 18: Comparison of surface displacement in the SSB between 2021 (during drought conditions) and 2024 (following lake level recovery), derived from Sentinel-1 data.

Table 4: Field validation sites with quantified subsidence

Site ID	Location Name	Easting (X)	Northing (Y)	Elevation (m)	Deformation Type	Field Evidence	Coherence (γ)	Measurement Method
FV-01	Barika-Kon	554,006	3,916,912	615	Well tilt + cracks	9.8 cm tilt	0.32	Field Survey
FV-02	Irrigation Channel	572,705	3,909,821	487	Infrastructure damage	Pipe rupture	0.35	Field Survey
FV-03	Shallow Well	572,911	3,909,809	468	Well casing subsidence	7cm offset	0.29	Field Survey
FV-04	Swamp Area	571,571	3,910,451	490	Ground fissures	10m fissure	0.38	GPS survey
FV-05	Tanjero River	572,333	3,909,635	487	Channel migration	Bank collapse	0.41	Google Earth pro, Field Survey
FV-06	Polygon (2017-2024)	574,418	3,908,501	481	Composite	Vertical erosion by shifting of Tanjero River	<0.3	Google Earth pro

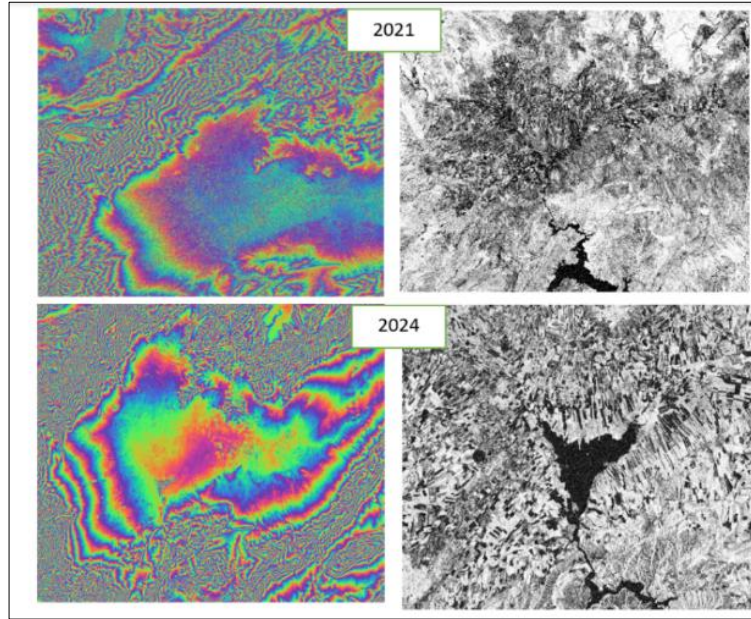


Fig. 19: FV-06, Signal decorrelation and phase distortion in Sentinel-1 DInSAR processing caused by fluvial geomorphological changes along the Tanjero channel shifts (1.1 km² study reach, 2017-2024) based on observed (Google Earth Pro, 2025).

8.3. Land use and recent sediment thickness

The validation of land use changes from 2017 to 2024 highlights the significant impact of human activities, including urban expansion and industrial development, on water resources. The proportion of wet years increased from 66.26% in 2017 to 69.30% in 2024, driven by consistent precipitation and improved irrigation practices.

By 2024, vegetation cover expanded across agricultural, urban, and aquatic environments, resulting in a 94% reduction in barren land (from 6.07 km² to 0.36 km²) due to enhanced land use and soil moisture retention (Lucas-Borja et al., 2020). Specifically, urban areas grew from 3.8% in 2017 to 5.03% in 2024, while cropland usage increased by 3.5% over the same period (Fig.20).

Surface water bodies reached their lowest extent in 2017 and 2021, as evidenced by Sentinel-2 imagery. In 2019, surface water coverage peaked at 0.25%, coinciding with minimal surface displacement (-3.5 cm).

In 2024, surface water coverage was 0.07%, with rainfall variability contributing to annual increases in water stress, as indicated by data on urban areas, croplands, and barren land (Table 5).

Table 5: Data collection of Land use/Land cover derived from Sentinel-2, 2025.

Year	2017	2019	2021	2024	(17-24) %
Land use			100%		
Water	0.048	0.25	0.028	0.07	46%
Tree	0.005	0.042	0.016	0.00	200%
Crop	66.26	69	63.68	69.30	4.6%
Urban	3.885	4.4	4.79	5.03	30%
Barren ground	0.956	0.039	0.042	0.06	-94%
Range land	28.84	26.3	31.44	25.55	-11.40

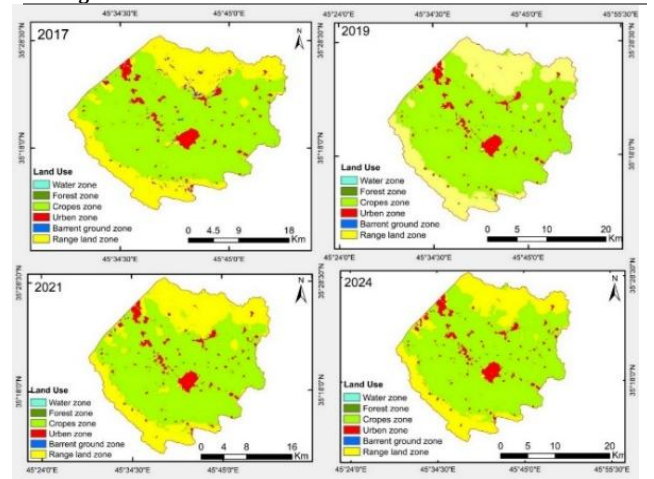


Fig. 20: Variations in land use and land cover in the SSB from 2017 to 2024, obtained from Sentinel-2 imagery (2025).

9. Limitation

The study acknowledges several technical constraints that influence interpretation of the subsidence patterns, including:

1. The radar coherence issues result in significant seasonal variation in temporal sampling and utility of DInSAR images over the SSB. As a result of heightened precipitation and soil moisture, coherence levels fell below 0.4 during the winter and rainy periods. These conditions alter surface dielectric properties and may lead to temporal decorrelation between image acquisitions (Zebker and Villasenor, 1992; Danklmayer et al., 2009).

2. Seasonal agricultural practices in autumn and spring lead to alterations in surface roughness and influence plant growth, resulting in volume dispersion and a decline in phase stability (Moran et al. 1977). Local meteorological and hydrological variables contribute to a reduced coherence in summer acquisitions.

3. Tropospheric interference in the Whole Sharazoor plain is influenced by rising water levels in the Darbandikhan lake, which increase ambient vapor pressure and alter tropospheric conditions. This leads to atmospheric phase delays (APDs) that complicate the identification of ground deformation signals (Hanssen, 2001; Doin et al., 2009). The unique conditions produce intermittent data gaps, particularly during humid periods, which impede analytical coherence thresholds. Notably, maximum effects are recorded in the southern and eastern mountainous margins of the basin. While atmospheric corrections and spatiotemporal filtering have been employed to address these issues, residual uncertainties persist in steep topographic areas.

4. Field validation efforts, while extensive, faced inherent accuracy limitations, including positional uncertainty from total station measurements and well depth estimation errors.

5. The groundwater level interpolation, while generally robust, showed edge effects within 500 m of basin boundaries where well density decreased, resulting in local root mean square error (RMSE) values up to 3.4 m. Additionally, the impact of water storage fluctuations in the Darbandikhan Lake on land stability remains underexplored.

6. The quantity of high-resolution images during the dry season exceeds that of the rainy season; for instance, in 2017, 2021, and 2023, the count of accurate and uninterrupted images

surpassed that of prior years. Drought affects the spatial resolution and coherence of DInSAR data, since it exacerbates decorrelation and diminishes soil moisture levels. Conversely, rainy seasons enhance vegetation, soil moisture, and ambient noise, resulting in expedited decorrelation and signal deterioration. This underscores the significance of accounting for environmental factors in InSAR data creation (Ferretti et al., 2005). The convergence of multiple validation methods (InSAR and ground surveys) provides confidence that these limitations do not alter the fundamental conclusions regarding dominant subsidence drivers in the SSB basin. Future studies should address these gaps to develop sustainable groundwater management strategies and mitigate subsidence risks in the SSB. Future studies should focus on integrating additional remote sensing data and expanding monitoring networks to improve the accuracy of subsidence predictions and support informed decision-making for water resource management in the region.

10. Conclusion

The study investigates the significant impact of groundwater extraction and climatic change on land subsidence within the SSB from 2017 to 2024, utilizing Sentinel-1 SAR data in conjunction with DInSAR algorithms to analyze spatiotemporal ground surface deformation. The findings establish a direct correlation between decreasing annual seasonal rainfall, total saturated SWLs, surface runoff, and vertical displacement. Groundwater over-extraction emerges as the principal cause of notable subsidence patterns, exacerbated by the unique lithology of the basin, which includes compressible clay and silt layers prone to irreversible compaction. The study emphasizes the necessity of employing InSAR and remote sensing technologies for effective subsidence monitoring and mitigation strategies to counteract environmental degradation. Local drought conditions have intensified the reliance on groundwater, while variable snowmelt has disrupted natural recharge dynamics, destabilizing pore pressure equilibrium.

Additionally, rapid urban development has increased surface loading and contributed to the subsidence crisis. Pilot measures in collaboration with the KRG aim to address these issues by prioritizing infrastructure inspections, choosing

suitable artificial recharge sites, and advising on water-efficient agricultural practices.

Results demonstrate a 15–20% reduction in displacement rates post-regulatory interventions at high-risk wells. This framework provides a basis for sustainable water management in data-scarce regions, and future studies may integrate real-time piezometric data to further refine assessments of groundwater dynamics and subsidence rates.

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12. Conflict of Interest

The authors declare that there are no conflicts of interest regarding the publication of this manuscript.

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الاستنزاف المفرط للمياه الجوفية وتأثير المناخ على هبوط الأرض في حوض السليمانية- شارزور، العراق: تحليل بواسطة تقنية InSAR

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الملخص

يعد نقص الرصد الكمي عائقاً امام تقييم استنزاف المياه الجوفية وتبعاتها على المستوى العالمي. تدمج هذه الدراسة بيانات الأقمار الصناعية لتقييم هبوط سطح الأرض في حوض السليمانية- شيرزورل (SSB) للفترة من 2017 إلى 2024، بربط تصريف المياه الجوفية والعوامل المناخية وتغيرات استخدام الأراضي بانزياح السطح. تمت معالجة بيانات Sentinel-1 SAR ، المكونة من 232 صورة رادارية (SLC) باستخدام ESA SNAP وأسلوب التداخل التفاضلي للرادار (DInSAR) لقياس الهبوط. أظهرت النتائج هبوطاً ملحوظاً في الطبقات الحاملة للمياه الجوفية الغير متماسكة تحت تأثير الاستخراج الجائر للمياه الجوفية ودورات الجفاف وعمليات الحفر المكثف للآبار. بلغ هبوط الأراضي ذروته عند -27 سم في 2021 و -26.5 سم في 2017، متزامناً مع انخفاض حاد في هطول الأمطار والتصريف السطحي. في المقابل، انخفض الانزياح إلى -6 سم في 2018 و -3 سم في 2019 بعد هطول أمطار أكثر من المتوسط وزيادة تغذية المياه الجوفية. تعرضت المناطق الحضرية لأضرار في البنى التحتية، بينما ساهمت الأراضي الزراعية والمساحات المائية في أنماط غير منتظمة للانزياح. تؤكد نتائج هذه الدراسة على أن الاستخراج الجائر للمياه الجوفية هو الفاعل الرئيسي للهبوط، تفاقم الحال تحت تأثير التغيرات المناخية واستخدام الأراضي. "تبرز هذه النتائج على ضرورة اعتماد سياسات مستدامة لإدارة المياه الجوفية في المناطق المعرضة للهبوط

الكلمات المفتاحية:

استخراج المياه الجوفية، الجفاف، انزياح السطح، بيئة شبه جافة، معايرة باستخدام بيانات الآبار.

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