

Analysis of Surface Deformations in Bursa and Its Surroundings Using the InSAR method

Bursa ve Çevresinde Yüzey Deformasyonlarının InSAR Yöntemi ile Analizi

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Abstract

This study investigates surface deformation in the Bursa region using semi-monthly Interferometric Synthetic Aperture Radar (InSAR) analysis from both ascending and descending satellite tracks. The cumulative deformation time series reveal widespread and significant subsidence across much of the study area over an observation period of approximately three years. Exceptionally high subsidence rates are detected in the Kestel and Gürsu regions, where cumulative deformation exceeds 300 mm in the ascending track and 400 mm in the descending track, with deformation velocities locally surpassing 130 mm yr⁻¹. Additional pronounced subsidence is observed near the Ürünü and Alaaddinbey districts, particularly along the margins of data gaps, reaching rates of up to 250 mm yr⁻¹ in the descending geometry. Although Bursa is located close to the North Anatolian Fault system, the observed deformation magnitudes significantly exceed regional tectonic slip rates, indicating that tectonic processes alone cannot explain the measured subsidence. Spatial correlations between deformation patterns and industrial and agricultural zones suggest that intensive groundwater extraction may be a dominant contributing factor. However, definitive attribution requires integrated field investigations and hydrogeological data. The results highlight the need for further multidisciplinary studies to support sustainable groundwater management and mitigate long-term environmental and socio-economic impacts in the region.

Keywords: InSAR, Land subsidence, Groundwater extraction, SBAS

Özet

Bu çalışmada, Bursa bölgesindeki yüzey deformasyonları, yükselen ve alçalan yörüngelerden elde edilen yarı aylık İnterferometrik Sentetik Açıklıklı Radar (InSAR) verileri kullanılarak incelenmiştir. Yaklaşık üç yıllık gözlem dönemine ait kümülatif deformasyon zaman serileri, çalışma alanının büyük bir bölümünde yaygın ve belirgin bir çökmenin meydana geldiğini göstermektedir. Kestel ve Gürsu bölgelerinde yüksek çökme tespit edilmiş olup, kümülatif deformasyon değerleri yükselen yörüngede 300 mm'yi, alçalan yörüngede ise 400 mm'yi aşmakta; deformasyon hızları yer yer 130 mm/yılın üzerine çıkmaktadır. Ayrıca, Ürünü ve Alaaddinbey ilçeleri çevresinde, özellikle veri boşluklarının sınırlarında, alçalan yörüngede 250 mm/yıl'a varan yüksek çökme hızları gözlenmiştir. Bursa, Kuzey Anadolu Fayı sistemine yakın bir konumda yer alsa da gözlenen deformasyon büyüklükleri bölgesel tektonik kayma hızlarının oldukça üzerindedir; bu durum, tektonik süreçlerin tek başına bu çökmeyi açıklamakta yetersiz kaldığını göstermektedir. Deformasyon desenleri ile sanayi ve tarım alanları arasındaki mekânsal ilişki, yoğun yeraltı suyu kullanımının önemli bir etken olabileceğine işaret etmektedir. Ancak kesin bir nedensel ilişki kurabilmek için saha çalışmaları ve hidrojeolojik verilerle desteklenen bütüncül araştırmalara ihtiyaç vardır. Bu çalışma, sürdürülebilir yeraltı suyu yönetimi ve uzun vadeli çevresel ve sosyoekonomik etkilerin azaltılması açısından ileri çalışmaların gerekliliğini ortaya koymaktadır.

Anahtar Kelimeler: InSAR, Toprak çökmesi, Yeraltısuyu çıkarımı, SBAS

1. Introduction

Interferometric Synthetic Aperture Radar (InSAR) is a well-established remote sensing technique that enables the detection of ground surface displacement with centimeter to millimeter level precision by exploiting the phase difference between radar signals acquired at different times over the same area (Rosen et al., 2000). By analyzing the phase changes of coherent radar targets, InSAR can measure surface deformation along the satellite line of sight (LOS) direction over large spatial extents and long time periods. Among time-series InSAR approaches, Persistent Scatterer Interferometry (PSI) (Ferretti et al., 2001) and Small Baseline Subset (SBAS) (Berardino et al., 2002) methods are widely used to reduce atmospheric artifacts and decorrelation effects. The PSI method focuses on stable, point-like scatterers with high phase coherence, typically found in urban or rocky environments, whereas the SBAS technique utilizes networks of interferograms with short spatial and temporal baselines to retrieve deformation signals over distributed targets. Together, these methods provide robust tools for monitoring gradual surface deformation processes (Hooper et al., 2012).

InSAR has been widely applied to investigate land subsidence associated with groundwater extraction, mining activities, and natural compaction processes worldwide (Castellazzi et al., 2016; Ghorbani et al., 2022). In Türkiye, numerous studies have successfully employed time-series InSAR techniques to detect and quantify subsidence in the Konya Basin, where excessive groundwater withdrawal has resulted in widespread surface deformation and the formation of sinkholes (Canaslan Comut et al., 2015; Eren et al., 2024; Gezgin 2022; Orhan et al., 2021, 2024; Üstün et al., 2015). In addition, the impacts of underground coal mining on surface subsidence have been extensively investigated in the Zonguldak hard coal basin using InSAR-based approaches (Abdikan et al., 2011; Akcin et al., 2010; Can et al., 2011). Collectively, these studies demonstrate the effectiveness of InSAR in identifying spatial patterns of subsidence, estimating deformation rates, and supporting hazard assessment in regions affected by hydrogeological and mining-related processes. Furthermore, utilizing InSAR technology, Kutoglu et al. (2014) identified previously unmapped parallel strike-slip faults in the Bursa basin, revealing a pull-apart basin geometry that led to the revision of Turkey's official active fault maps.

Bursa, one of Türkiye's major industrial and agricultural centers, is characterized by intensive water use and a complex geological setting influenced by regional tectonics. In recent years, the region has experienced increasing pressure on water resources, and during the summer of 2025, severe drought conditions led to planned water-use restrictions in several parts of the province. These conditions raise concerns regarding the sustainability of groundwater resources and their potential impacts on surface stability. Furthermore, previous studies have indicated that subsidence within the Bursa Basin is largely associated with groundwater extraction (Aslan et al., 2019). Despite the socio-economic importance of the region, detailed InSAR-based investigations of surface deformation in Bursa remain limited. This study aims to address this gap by analyzing semi-monthly InSAR data to characterize surface deformation patterns and assess potential links with groundwater-related processes.

2. Study area

The study area, as illustrated in Figure 1, encompasses an approximately 2100 km² region in the southeastern Marmara Region, including on the metropolitan area of Bursa. This region is geographically defined by the coastal district of Mudanya to the north, the industrial corridor of Kestel to the east, the lacustrine environment of Lake Ulubat to the west, and the prominent Uludağ National Park to the south. Topographically, the area exhibits a dramatic gradient between the Uludağ massif, which reaches an elevation of 2543 m, and the low-lying Bursa Plain, primarily composed of thick Quaternary alluvial and fan deposits. Geologically, the area presents a complex lithological framework comprising metamorphic, ophiolitic, volcanic, plutonic and sedimentary units spanning Paleozoic to Quaternary eras. The structural evolution of city has been strongly influenced by active fault system, particularly the Bursa, Soğukpınar and Ulubat faults, which play a significant role in shaping the regional tectonic setting (Kuşcu, 2024).

Furthermore, Bursa is one of Türkiye's major industrial cities, with a long-standing manufacturing tradition extending from historical silk production to modern large-scale industry. Today, it is a leading center for automotive, textile, machinery, and metal industries, hosting multiple organized industrial zones. This sustained industrial growth has driven rapid urbanization and increased resource demand across the region (Akkuş, 2022). This major industrial and agricultural hub characterized by rapid urban expansion, region's intensive groundwater exploitation and unconsolidated sedimentary layers create a complex environment susceptible to both tectonic deformation and anthropogenic land subsidence.

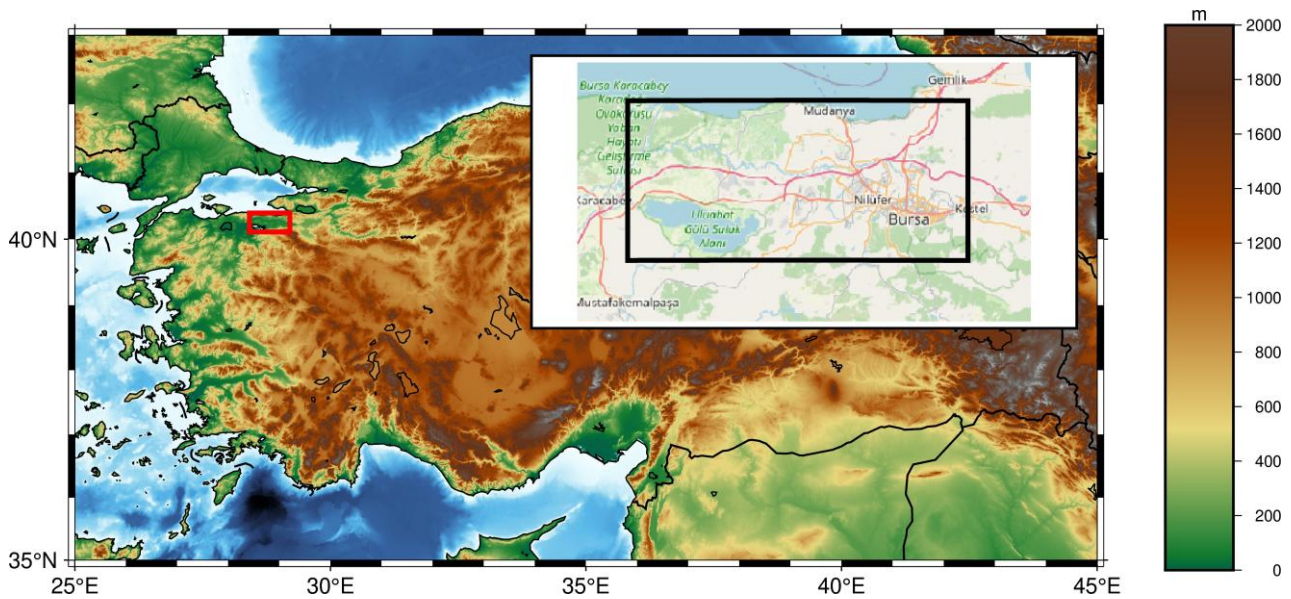


Figure 1. The study area is indicated by a black rectangle in the inset map, while its location within Türkiye is highlighted by a red rectangle on the regional map. The background represents surface elevation

3. Materials and Methodology

Within the scope of this study, Sentinel-1 interferometric products generated by the LiCSAR (An Automatic InSAR Tool for Measuring and Monitoring Tectonic and Volcanic Activities) (Lazecký et al., 2020) are utilized. LiCSAR is an automatic InSAR processing framework developed and maintained by COMET (Centre for the Observation and Modeling of Earthquakes, Volcanoes and Tectonics) for systematic monitoring of tectonic and volcanic deformation. The LiCSAR system processes Sentinel-1 acquisitions using a standardized and reproducible workflow to generate geocoded differential interferograms (Morishita, 2021). For each Sentinel-1 acquisition, interferograms are formed by pairing the image with three preceding and three subsequent acquisitions, resulting in a dense and temporally connected interferometric network. The generated interferograms are multi-looked by factors of 20 in azimuth and 5 in range, yielding an effective ground pixel spacing of approximately 100×100 m. This multi-look strategy improves the signal-to-noise ratio while preserving sufficient spatial resolution for regional-scale deformation analysis.

To exploit complementary viewing geometries and improve sensitivity to vertical and horizontal surface displacements, both ascending and descending Sentinel-1 orbit data are considered. However, due to gaps in the LiCSAR interferometric network, the temporal coverage differs between the two viewing geometries: descending-orbit data span from January 2022 to December 2024, whereas ascending-orbit data are available from January 2022 to June 2024. For the study area, a total of 74 and 88 SAR acquisitions are available from the ascending and descending orbits, respectively, resulting in the generation of 273 ascending and 317 descending interferograms. The LiCSAR processing chain includes precise orbit correction using updated Sentinel-1 orbit information, accurate co-registration of SAR acquisitions, formation of differential interferograms, and removal of the topographic phase using a reference digital elevation model (DEM). Subsequent processing steps involve phase filtering to suppress noise and phase unwrapping to retrieve continuous line-of-sight (LOS) displacement fields. The resulting interferometric products provide spatially and temporally consistent measurements of ground deformation suitable for time-series analysis and deformation characterization.

Time-series deformation analysis is performed using the open-source LiCSBAS package (Morishita et al., 2020), which implements the SBAS inversion technique to estimate cumulative surface displacement and mean velocity from LiCSAR interferograms. The SBAS approach optimizes phase stability by selecting an interferometric network characterized by minimal spatial and temporal baselines. By inverting this interferogram network, the SBAS method retrieves a consistent deformation time series for each coherent pixel. The deformation time-series do not solely represent ground displacement but also contain contributions from other phase components, including tropospheric delay, DEM errors and noise related to the temporal and spatial decorrelation. The DEM error component that is proportional to the perpendicular baseline is estimated and subtracted from displacement series. On the other hand, tropospheric delay which remain a major source of uncertainty in INSAR time-series analysis. To mitigate this GACOS (Generic Atmospheric Correction Online Service) products are utilized. GACOS employs an iterative tropospheric decomposition (ITD) method that separates stratified and turbulent atmospheric components by combining numerical weather model data with

spatial filtering techniques (Yu et al., 2018a; Yu et al., 2018b). The resulting tropospheric correction maps are applied to the interferograms prior to time-series inversion, significantly reducing atmospheric phase artifacts. Furthermore, because Sentinel-1 operates in the C-band, for which ionospheric phase delays are generally weak, ionospheric effects are assumed to be negligible and are therefore not explicitly corrected in this study (Bekaert et al., 2015). The frequently used parameters provided by the default LiCSBAS batch file are employed for processing.

It is worth noting that, although external validation datasets are planned to be used for comparison and interpretation of the InSAR-derived observations, such data are not available for the study area. The only continuous GNSS station in the region, namely BURS, does not provide reliable or usable data after 2016, as indicated by the Nevada Geodetic Laboratory (2026). In addition, groundwater level records were formally requested from the General Directorate of State Hydraulic Works; however, no response has been received at the time of this study. Consequently, the present analysis relies solely on InSAR observations. Nevertheless, future work is planned to incorporate complementary datasets, including GNSS measurements and groundwater level information, to enable a more comprehensive assessment of the observed deformation.

4. Result and Discussion

The temporal reference epochs are 12 January 2022 for the ascending track and 6 January 2022 for the descending track. Given the short temporal separation of six days between these reference dates, they are considered equivalent for the purposes of comparative time-series analysis. Spatially, all deformation time series are referenced to a point located at the Bursa Grand Mosque, which serves as a common reference for both viewing geometries.

The deformation velocity fields for the ascending and descending tracks are presented in Figure 2. As shown in the figure, the majority of pixels are consistently detected in both viewing geometries, indicating good spatial agreement between the ascending and descending datasets. The most prominent data gap is observed in the southwestern portion of the study area, primarily associated with Lake Ulubat and the surrounding forested regions, where low coherence limits reliable deformation retrieval. Additional localized gaps occur near 40.2° N and 28.9° E, corresponding to forested and agricultural zones encompassing the Ürünlü and Alaaddinbey districts. In the descending track, the central area around 40.3° N and 28.7° E exhibits a slightly higher density of missing pixels compared to the ascending track; however, these gaps are relatively low when compared to the extensive incoherent region in the southwest and do not significantly hinder deformation analysis. Overall, approximately 130000 coherent pixels are available for the ascending track and about 124500 for the descending track.

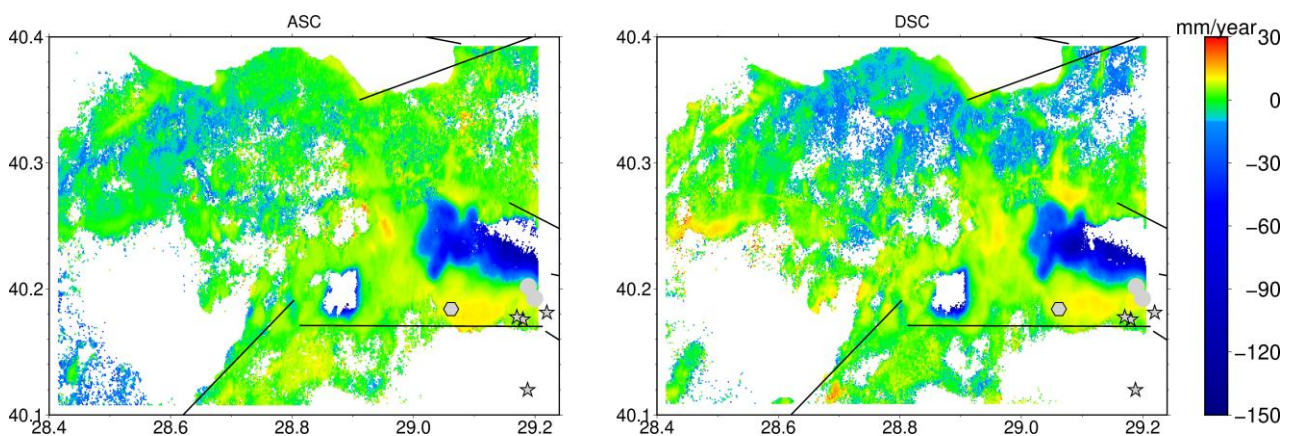


Figure 2. LOS displacement velocity maps. The gray hexagon marks the reference point, gray circles denote industrial areas, gray stars indicate water production facilities, and black lines represent active faults

As shown in Figure 2, the most prominent feature of the deformation velocity fields is the exceptionally high subsidence rates observed in the Kestel and Gürsu industrial districts. Subsidence rates exceed 132 mm yr^{-1} in the ascending track and reach approximately 134 mm yr^{-1} in the descending track. The consistent spatial patterns and velocity rates observed in both datasets indicate persistent and significant subsidence in this region. Considering the entire study area, identifying the driving mechanisms responsible for such pronounced deformation is therefore of primary importance, and the characteristics of these zones are examined in detail.

As an initial hypothesis, the observed high subsidence is attributed to fault-related tectonic processes, given that Bursa is located in close proximity to the North Anatolian Fault (NAF). However, Emre et al. (2018) report slip rates of approximately $15\text{--}22 \text{ mm yr}^{-1}$ for the NAF and Aslan et al. (2019) stated that subsidence rate of Bursa is about 25 mm

yr^{-1} , indicating that such tectonic motion alone is insufficient to account for the magnitude of the measured subsidence. Notably, the subsiding zones coincide with two major organized industrial areas (OIAs) in Bursa, Kestel and Uludağ (Gürsu) shown by orange circles in Figure 3. The Uludağ OIA covers approximately 181 ha and primarily hosts chemical, food, and textile industries, whereas the Kestel OIA extends over about 74 ha and is predominantly occupied by textile manufacturing facilities. Given that the textile industry is recognized as highly water-intensive (Shaikh, 2009), groundwater abstraction associated with industrial activity may represent a contributing factor to the observed subsidence. Nevertheless, no direct evidence is available to definitively link the detected deformation to excessive groundwater extraction in these industrial zones. Consequently, a detailed investigation of the relationship between industrial water consumption and surface subsidence is required but lies beyond the scope of the present study.

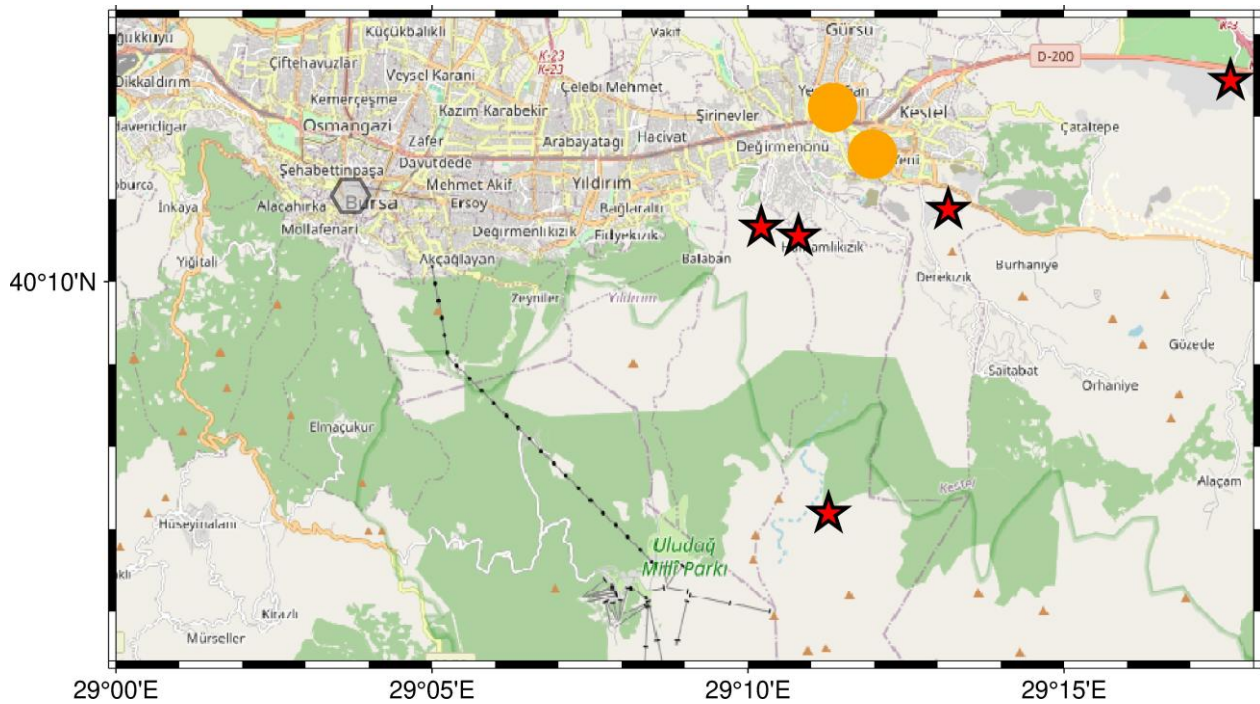


Figure 3. The locations of organized industrial areas are highlighted by orange circles, while red stars represent bottled water production facilities

Further investigation focuses on other industrial and commercial activities in and around the Kestel and Gürsu districts that may contribute to the observed subsidence. Bursa, particularly the Uludağ region, is well known for its natural and mineral water resources, which are extracted, bottled, and distributed by several commercial enterprises (Haktırr, 2013). Consequently, special attention is given to groundwater abstraction associated with bottled water production facilities located near the subsiding areas. According to the Preliminary Feasibility Report for a Packaged Water Production Facility in Bursa Province published by the Bursa–Eskişehir–Bilecik Development Agency (BEBKA, 2021), a total of 26 companies in Bursa Province are engaged in groundwater extraction for commercial water production. Although the report indicates that seven of these facilities are located in the Kestel region, the locations of five currently active companies are identified and shown as red stars in Figure 3. As illustrated in the figure, four of these facilities are situated in close proximity to the area experiencing the highest subsidence rates. While the report also notes the presence of eight production facilities in the İnegöl region, approximately 22 km away in straight-line distance, these sites are not considered in the present analysis due to their relatively large separation from the deformation zone. To facilitate a clearer interpretation of the relationship between subsidence and human activities, industrial and production areas are also visualized in Figures 2, 4, 5, and 6. However, it should be noted that some production sites are not shown in certain figures when they fall outside the defined study area, in order to maintain clarity and readability. Therefore, readers are referred to Figure 3 for the complete spatial distribution of industrial and production areas.

Given the critical importance of this area, which hosts two OIAs and at least four water bottling facilities, together with the exceptionally high subsidence rates observed and their implications for environmental safety, the analysis is extended further. For this purpose, LiCSAR data spanning from January 2018 to December 2021 are utilized for both ascending and descending tracks.

The deformation time series are again retrieved using the SBAS method, and, to ensure consistency with the previous analysis, the same spatial reference point is adopted. In this extended analysis, both datasets also share a common temporal reference epoch, providing approximately four years of continuous observations for each viewing geometry.

Figure 4 presents the deformation velocity maps derived from ascending and descending orbits for the period prior to 2022. As shown in the figure, deformation patterns similar to those observed in Figure 2 are also evident during the earlier period, indicating that the detected subsidence is not a recent phenomenon but rather a persistent process. This observation suggests that the deformation has been continuous for at least seven years and likely extends even further back in time. The estimated subsidence rates reach approximately 172 mm yr^{-1} for the ascending track and 117 mm yr^{-1} for the descending track. Although the descending rates are broadly consistent with those obtained for the later period, the ascending rates exhibit a difference of about 40 mm yr^{-1} , which is attributed to variations in the network geometry and inversion strategy between the two analyses. The cumulative subsidence exceeds 600 mm in the ascending and 500 mm in the descending datasets for the pre-2022 period alone. When combined with the post-2022 results, this implies a total cumulative subsidence of approximately 1 m between January 2018 and the end of 2024, an exceptionally large value that warrants detailed geotechnical and hydrogeological investigation.

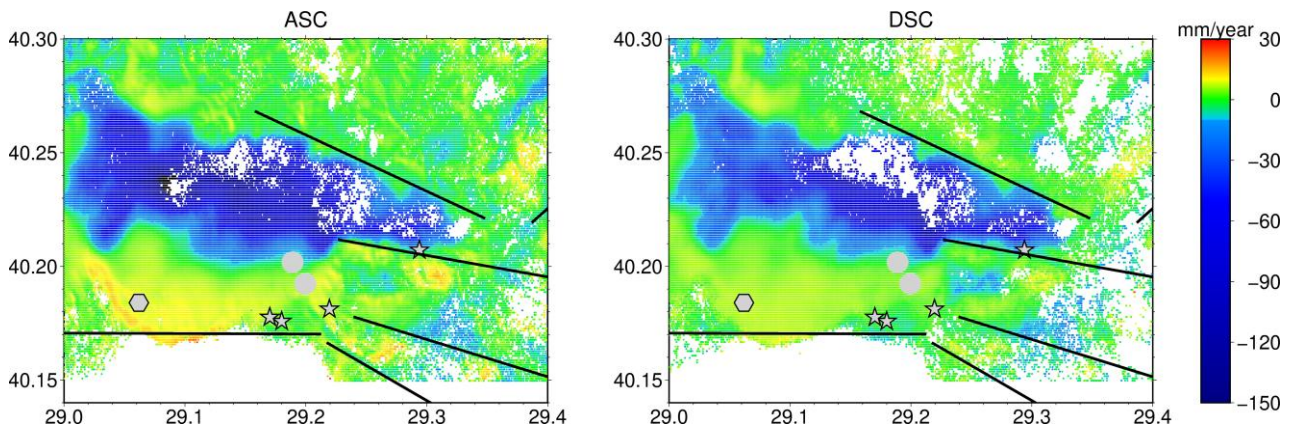


Figure 4. LOS displacement velocity maps pre-2022. The gray hexagon marks the reference point, gray circles denote industrial areas, gray stars indicate water production facilities, and black lines represent active faults

The exceptionally high subsidence rates observed in the Kestel and Gürsu regions are believed to be closely associated with intensive groundwater extraction by nearby water production facilities, based on their spatial coincidence and documented groundwater use. These results highlight the need for further investigation into the relationship between groundwater withdrawal and land subsidence in the region. Such investigations are essential not only for ensuring the long-term sustainability of industrial activities but also for mitigating potential impacts on infrastructure, urban safety, and overall quality of life.

Another notable observation is that the highest subsidence rates occur along the margins of a data gap near the Ürünlü and Alaaddinbey districts, reaching approximately 140 mm yr^{-1} in the ascending track and up to 250 mm yr^{-1} in the descending track. Although this area is characterized by a large data gap, the deformation pattern along its boundaries clearly indicates pronounced subsidence. This suggests that deformation rates within the gap itself may be sufficiently large to cause temporal decorrelation, thereby limiting the ability of InSAR to reliably capture the deformation signal in this zone.

Across the remainder of the study area, subsidence constitutes the dominant deformation signal. In contrast, the Bursa city center exhibits slight uplift in both ascending and descending tracks, although the corresponding uplift rates are very small. Subsidence is particularly pronounced within the region bounded by 40.3° – 40.4°N and 28.6° – 29.2°E , where the signal is more clearly expressed in the descending orbit. Similarly, the Mudanya city center shows minor uplift comparable to that observed in Bursa, with low uplift rates in both viewing geometries. In the ascending track, the Bursa and Demirtaş organized industrial areas also display weak uplift signals. The Karacabey region, located in the central western portion of the study area, exhibits contrasting deformation patterns between the two tracks: a relatively high uplift rate is detected in the descending orbit, whereas the uplift rate in the ascending orbit remains minimal. This discrepancy suggests a pronounced directional component in the deformation field or potential geometric effects related to line-of-sight sensitivity. Overall, while subsidence rates reach values exceeding 140 mm yr^{-1} and 249 mm yr^{-1} in the ascending and descending tracks, respectively, the maximum observed uplift rates are considerably smaller, attaining only about 30 mm yr^{-1} in the ascending track and 45 mm yr^{-1} in the descending track.

The cumulative deformation time series, sampled at approximately six-month intervals, are shown in Figures 5 and 6 for the ascending and descending orbits, respectively. Both viewing geometries indicate that the maximum subsidence occurs in the same area, centered around the Ürnlü and Alaaddinbey districts. The maximum cumulative subsidence reaches approximately 380 mm in the ascending track and 727 mm in the descending track. Although this area partially overlaps with a data gap, the deformation pattern along the margins of the gap clearly reveals pronounced subsidence that exceeds the deformation observed in the Kestel and Gürsu regions. Ürnlü and Alaaddinbey are predominantly rural areas, where local economic activities are largely based on agriculture. Given the rural settlement characteristics, groundwater extraction through water wells is likely widespread. Nevertheless, definitive attribution of the observed subsidence requires detailed field investigations integrated with satellite observations, which are beyond the scope of the present study.

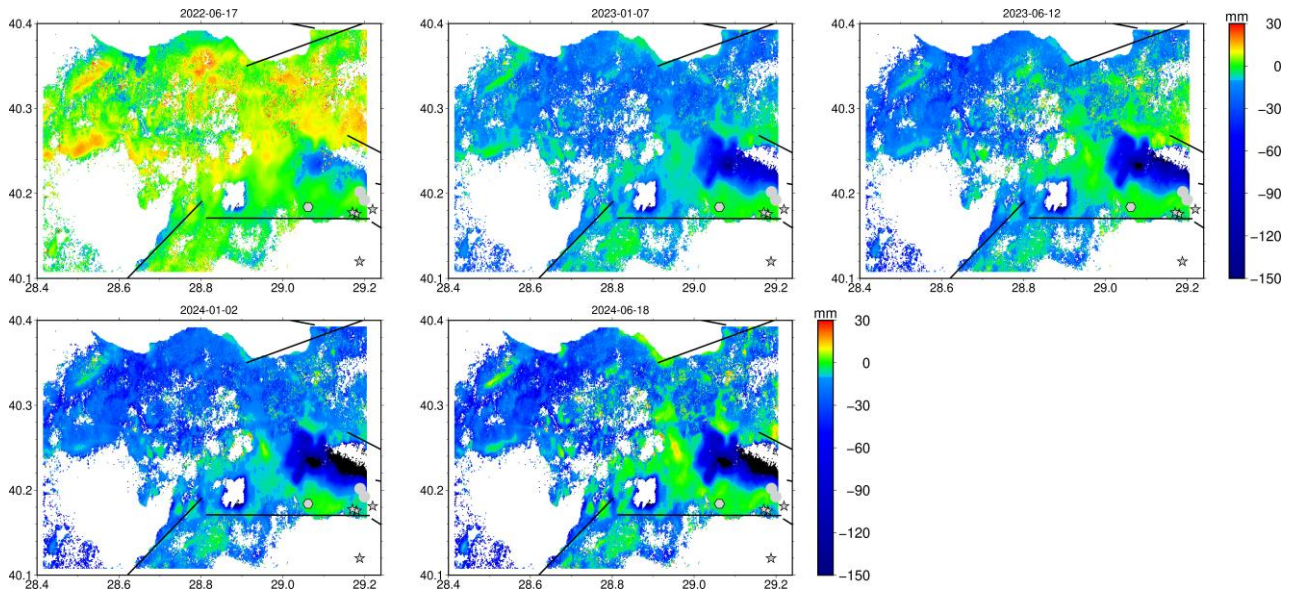


Figure 5. LOS cumulative displacement maps for ascending orbit. The gray hexagon marks the reference point, gray circles denote industrial areas, gray stars indicate water production facilities, and black lines represent active faults

Although the ascending and descending tracks cover closely spaced areas, the locations of maximum uplift differ between the two viewing geometries. In the ascending orbit, the maximum cumulative uplift of approximately 70 mm is observed near Çatalağıl village, whereas in the descending orbit, the maximum cumulative uplift of about 100 mm occurs near Harmanlı village. Despite the presence of localized uplift, the deformation patterns shown in the figures indicate that subsidence is the dominant signal across most of the study area for both ascending and descending observations. In particular, pronounced cumulative subsidence in the Kestel and Gürsu regions is clearly evident, with maximum values reaching approximately 310 mm in the ascending track and 438 mm in the descending track. Considering that such substantial subsidence has been detected over a deformation time series spanning approximately three years, and given the strong likelihood of a correlation with intensive groundwater extraction, it is evident that further investigations incorporating larger datasets and a greater diversity of data sources are required. Such studies are critically important not only for sustainable groundwater and environmental management, but also for preserving the quality of life of local communities and ensuring the long-term continuity of key industrial activities in the region.

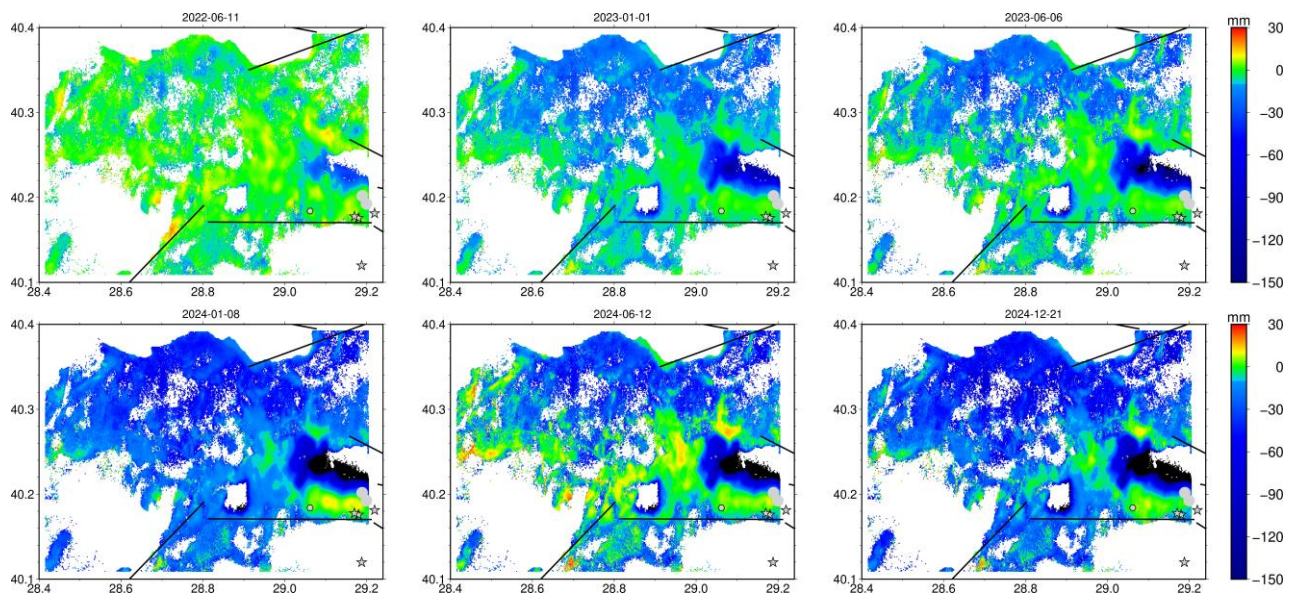


Figure 6. LOS cumulative displacement maps for descending orbit. The gray hexagon marks the reference point, gray circles denote industrial areas, gray stars indicate water production facilities, and black lines represent active faults

The cumulative deformation time series indicate that subsidence within the identified zones is temporally persistent and progressively increases throughout the observation period, with no clear evidence of stabilization or recovery. The consistent temporal evolution observed in both ascending and descending tracks suggests that the detected deformation signal is robust and not related to orbit-specific artifacts. To better characterize the subsidence behavior, five representative points are selected across the study area. Point P1 is located within the zone of maximum subsidence, while points P2–P5 are distributed within the Kestel region. The cumulative displacement time series in Figure 7 demonstrate a consistent subsidence trend at all points, with varying magnitudes reflecting their relative positions within the deformation field. Point P1 exhibits the largest displacement.

Points P2–P5 display similar temporal patterns, and notably, the strong agreement between ascending and descending observations confirms both the reliability of the processing workflow and the persistence of the deformation signal. The most pronounced discrepancy is observed at point P1, where the ascending track indicates continuous subsidence from the beginning, while the descending track shows a short initial uplift phase of approximately three months before transitioning to subsidence. Despite this early divergence, the cumulative deformation from both tracks converges after approximately two years, exhibiting a consistent overall deformation pattern.

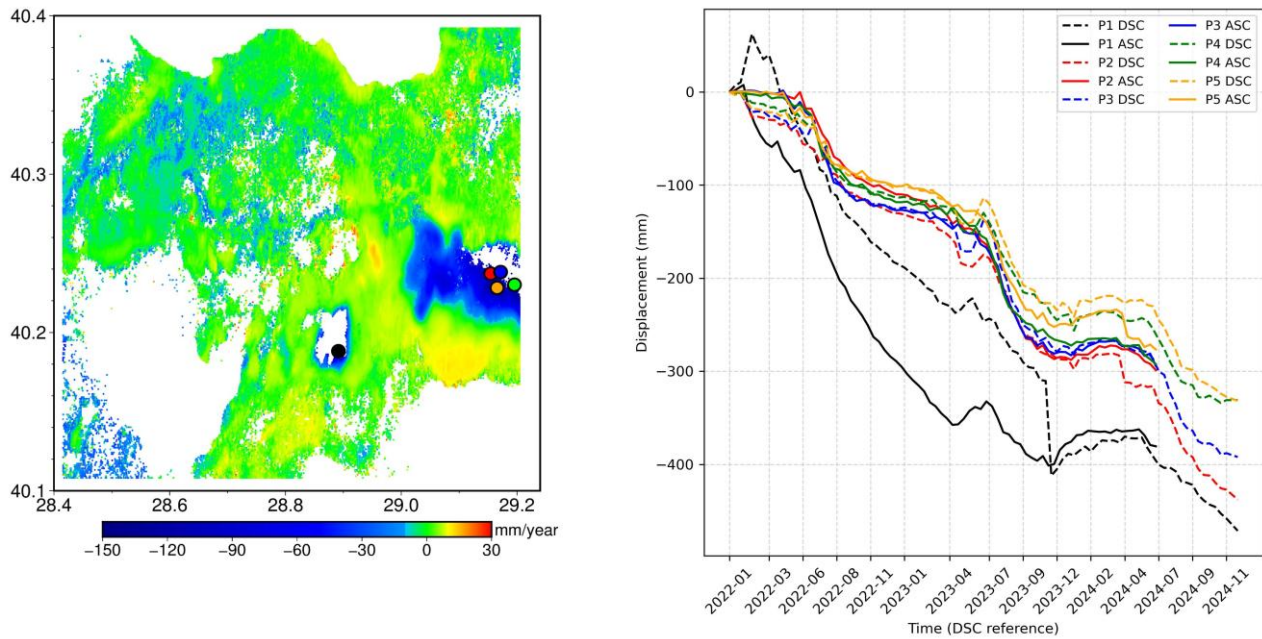


Figure 7. The locations of five selected points are shown in the left deformation map, while their cumulative deformation time series are displayed in the right panel. Consistent colors are used to link each point across both spatial and temporal representations

A clear contrast is observed between relatively stable urban centers and rapidly subsiding industrial and agricultural areas, implying the influence of localized driving mechanisms. Notably, the sharp deformation gradients along the margins of data gaps provide further evidence that deformation within these zones is likely too rapid to be reliably captured by InSAR due to decorrelation effects.

Moreover, the cumulative deformation maps reveal a systematic asymmetry between ascending and descending geometries, with consistently larger deformation magnitudes observed in the descending track. This pattern suggests that the deformation is predominantly controlled by a vertical component, as further supported by Figure 8. As illustrated in this figure, the deformation is clearly more pronounced in the vertical direction. The subsiding regions maintain strong spatial coherence throughout the observation period despite atmospheric noise, seasonal variability, and data gaps, indicating a long-term and persistent deformation process. Seasonal uplift signals, typically associated with elastic aquifer response, are limited and do not compensate for the cumulative subsidence, implying predominantly inelastic compaction of the subsurface. Finally, the gradual lateral expansion of subsiding zones over time points to a regional-scale deformation process rather than isolated or localized sources.

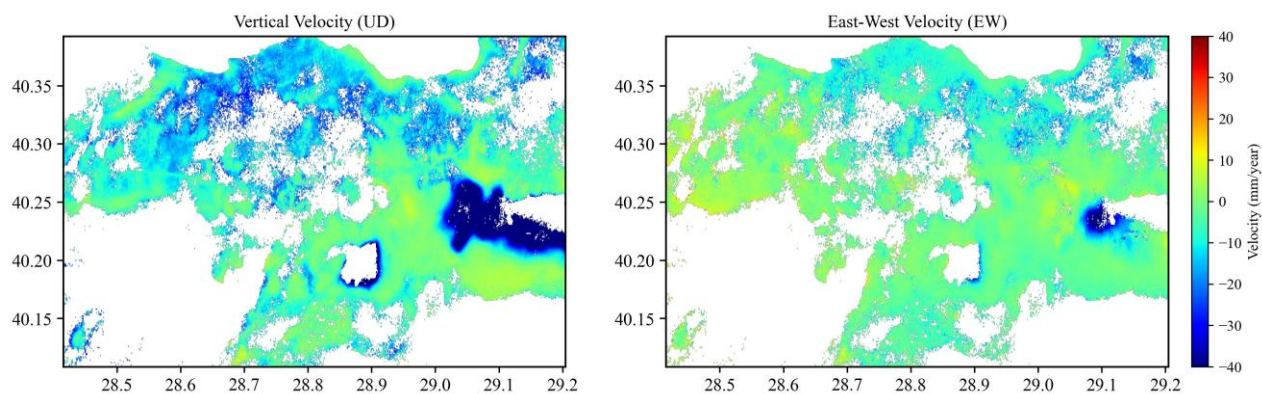


Figure 8. Vertical (up-down (UD)) and East-West (EW) velocity fields derived from InSAR time-series decomposition

5. Conclusion

This study presents a 2.5-year InSAR-based assessment of surface deformation in the Bursa Basin using about semi-monthly Sentinel-1 data acquired in both ascending and descending geometries. The deformation velocity fields reveal that subsidence is the dominant and spatially coherent signal across the study area over the approximately three-year observation period, with particularly severe deformation concentrated in the Kestel and Gürsu industrial districts. In these areas, subsidence rates exceed 132 mm yr^{-1} in the ascending orbit and reach approximately 134 mm yr^{-1} in the descending orbit, demonstrating strong agreement between viewing geometries and indicating a robust and reliable deformation signal.

Cumulative deformation time series further emphasize the critical magnitude of surface lowering in these regions, with cumulative subsidence reaching $\sim 310 \text{ mm}$ (ascending) and $\sim 438 \text{ mm}$ (descending) in Kestel–Gürsu. Even more pronounced deformation is detected near the Ürnlü and Alaaddinbey districts, where cumulative subsidence attains approximately 380 mm in the ascending geometry and 727 mm in the descending geometry. Although this area partially coincides with a data gap, the sharp deformation gradients along the margins strongly suggest that deformation within the gap is even more severe, likely exceeding the coherence limits of InSAR due to rapid surface changes.

The extended analysis using LiCSAR data from January 2018 to December 2021 demonstrates that this subsidence pattern is not a short-term or transient phenomenon, but rather a long-term and persistent process active for at least seven years. When the cumulative deformation from both periods is combined, total surface lowering locally approaches $\sim 1 \text{ m}$ by the end of 2024, underscoring the exceptional severity of subsidence in the Bursa Basin. Such magnitudes are rarely observed in urban–industrial environments and highlight a critical geohazard for the region. Localized uplift signals are observed near Çatalağıl and Harmanlı villages; however, these remain spatially limited and significantly smaller in magnitude than the widespread subsidence. Relatively stable conditions are confined to restricted areas, such as the city centers of Bursa and Mudanya, further reinforcing the localized nature of the dominant driving mechanisms.

The magnitude, persistence, and spatial distribution of the observed deformation cannot be adequately explained by tectonic activity alone and are more plausibly attributed to intensive groundwater extraction related to industrial, agricultural, and commercial water use. This interpretation is further supported by the presence of two organized industrial zones and multiple water bottling facilities within the most severely affected areas, as well as recent drought conditions and water-use restrictions implemented in Bursa. Despite the absence of independent validation data such as GNSS or groundwater level measurements, the strong consistency between ascending and descending results and the long-term temporal continuity provide high confidence in the detected deformation patterns. Nevertheless, future work integrating in-situ observations, hydrogeological modeling, and geotechnical data is essential to quantitatively link subsidence to groundwater dynamics and to assess associated risks.

Overall, this study highlights the Bursa Basin as a region experiencing critical land subsidence that poses serious implications for infrastructure stability, environmental safety, and sustainable water resource management. Immediate attention is required from both scientific and regulatory communities to monitor, model, and mitigate this ongoing geohazard, in order to safeguard industrial productivity, urban development, and ecological sustainability.

Acknowledgement

We confirm that any artificial intelligence tools used in the preparation of this study were employed solely for supportive purposes, and that the originality, scientific contribution, and full responsibility for the research rest entirely with the author(s). Map figures are generated using the Python interface to the Generic Mapping Tools (PyGMT) (Tian et al., 2025).

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