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Advancing the Monitoring of Slow-Moving Urban Landslides through Integrated InSAR and Real-Time Inclinometers: The Sarajevo Case Study

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Abstract

This study develops and applies an integrated ground- and satellite-based monitoring framework for slow-moving urban landslides in Sarajevo, improving the quantitative understanding of slope dynamics in complex built environments. Ground-based inclinometers identified deep-seated sliding surfaces (>7 m) with cumulative displacements up to 4 cm/year, while a real-time MEMS inclinometer captured short-term rainfall-induced accelerations. To extend spatial coverage, Sentinel-1 InSAR time series processed using both AMS P-SBAS and StaMPS were validated against in-situ measurements and subsequently applied to the 2022–2025 period to map deformation across the wider urban area. The integrated analysis demonstrates the strong potential of combining field surveys and remote sensing for landslide detection, mapping, and monitoring, and shows that deformation is concentrated in only a few localized zones, indicating that the previously assessed hazard level in Sarajevo is overly conservative.

1. Introduction

Sarajevo, the capital of Bosnia and Herzegovina, is situated in Southeastern Europe on the Balkan Peninsula (Fig. 1), within a basin encircled by steep limestone hills (Figs. 2a and 2b). The urban development of Sarajevo has been extensively discussed by Martin-Diaz et al. (2018) and Bublin (2022), who describe the rapid urban expansion into hilly areas over the past three decades and a significant increase in landslide susceptibility. These inadequately planned and constructed buildings often disregard sound engineering practices, leading to visible façade cracking whose causes are difficult to ascertain. Previous studies have consistently identified leaking water supply and sewage systems (Serdarević and Babić, 2019; Čakarić et al., 2021), improperly supported excavations (Skejić et al., 2023), and intense rainfall (Martin-Díaz et al., 2015) as the primary triggers of landslides throughout this region.

Among the many slopes surrounding Sarajevo, the Trebević hill massif stands out as one of the most critical zones of urban slope instability. Consequently, the present study focuses on the Soukbunar area (Figs. 1 and 2c), which was selected due to recent ground movements and structural deterioration, including visible cracks in several buildings. Engineering-geological and geotechnical investigations in the study area revealed thick colluvial and eluvial–deluvial soils, along with the presence of underground water. These conditions represent key predisposing factors for landslide formation. Previous studies have confirmed Soukbunar as a high-risk urban zone, where only continuous monitoring can reliably capture landslide dynamics and evaluate the effectiveness of remedial measures (Operta et al., 2017).

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Figure 1. The qualitative landslide susceptibility map of the Canton of Sarajevo, indicating stable, unstable, and conditionally stable areas (green – low susceptibility, yellow – medium susceptibility, and red – high susceptibility), Rokić et al. (2000). Basemap: Google Earth™ (Imagery © respective data providers), accessed on September 15, 2025.

The pioneering efforts in landslide mapping and susceptibility assessment in Sarajevo were conducted by Rokić et al. (2000) and Rokić (2001). Their map classified the terrain into three categories—low, medium, and high susceptibility areas—using a qualitative approach without quantitative methods (Fig. 1). The red contours in Fig. 1 indicate the zones considered most susceptible to landslides, showing that a large city area is highly prone to sliding. Building on this framework, the Institute for Construction of the Sarajevo Canton reported 869 highly susceptible regions in 2017, predominantly in densely populated areas. This statistic has since been repeatedly cited in the literature (Čustović and Zurovac, 2012; Operta and Golijanin, 2013; Martin-Díaz et al., 2018; Peragine, 2019; Čakarić et al., 2021) almost as fixed reference values, often adopted without critical assessment or validation against observational data. It is particularly concerning that these zones are frequently designated as active landslides, despite having been initially recognized only as areas of potential instability. This qualitative mapping approach has shaped the permitting and legalization of informal housing, while also distorting perceptions of actual landslide activity. Despite repeated calls for standardized quantitative mapping (Abolmasov, 2016; Fell et al., 2008; Shano et al., 2020), Sarajevo continues to rely on qualitative maps. Many of the most vulnerable zones are steep, densely built hillsides affected by slow-moving slope deformation. This challenge underscores the importance of continuous monitoring, as exemplified by well-documented nearby cases, such as the Umka landslide near Belgrade (Abolmasov et al., 2013, Abolmasov et al., 2017) and the Kostanjek landslide in Zagreb (Krkač et al., 2019), both of which continue to affect large urbanized areas. Traditional ground-based investigations, although essential, often struggle to capture the spatial and temporal evolution of slow-moving landslides. To overcome these limitations, recent studies have increasingly adopted integrated approaches that combine geotechnical monitoring with satellite-based remote sensing (Sadhasivam et al., 2024; Tu et al., 2024). Case studies from Italy and Spain demonstrate that such methods, particularly the integration of InSAR with in-situ measurements, effectively capture slow displacement rates, assess their impact on buildings and infrastructure (Peduto et al., 2020; Béjar-Pizarro et al., 2017), and can even be used to predict the time of failure (Carlà et al., 2018). Integrating geotechnical monitoring with satellite data helps clarify slope behavior and its impact on nearby structures. It is beneficial in densely built areas where geological factors and human pressures interact (Peduto et al., 2018; Ferlisi et al., 2019). Among satellite-based techniques, Interferometric Synthetic Aperture Radar (InSAR) has become a vital tool for monitoring slow-moving mass movements by analyzing time series to detect changes in deformation rates and to predict future slope behavior (Catani et al., 2005; Raspini et al., 2017; Ponziani et al., 2023; Zeng et al., 2024). Radar interferometry offers key advantages, including regular monitoring with revisit times of 6–12 days and detailed line-of-sight (LOS) coverage shown in 2D deformation maps (Dick et al., 2015). International experiences further confirm the benefits of integrating geotechnical monitoring with satellite interferometry for managing slow-moving urban landslides (Salleh et al., 2025; Celik et al., 2025; Liu et al., 2025; Tian et al., 2024; Necula et al., 2021; Lacroix et al., 2020). Although several recent studies have demonstrated the potential of InSAR for monitoring ground deformation, these approaches have not yet been systematically adopted in Sarajevo, where existing landslide inventories remain largely qualitative. In Bosnia and Herzegovina, InSAR applications have so far been limited to specific cases, primarily addressing ground subsidence induced by underground mining activities. The Tuzla region provides a

representative example of InSAR monitoring used to quantify surface deformations associated with mining excavations (Parwata et al., 2020; Bojić, 2023). More recently, InSAR has also been applied to assess earthquake-induced ground surface motions (Branko et al., 2024). Despite recent advances, no combined ground–satellite monitoring of rainfall-induced landslides has been carried out in Sarajevo or elsewhere in Bosnia and Herzegovina. The use of InSAR, together with ground-based monitoring, remains limited, although it could significantly improve understanding of landslide behavior.

To address this gap, this study introduces a multi-source monitoring approach applied to a representative urban slope in Sarajevo (Soukbunar site). The approach combines ten months of real-time MEMS (Micro-Electro-Mechanical Systems) inclinometer data with conventional inclinometer measurements and Sentinel-1 InSAR analysis. Special attention is given to the hydrometeorological control of slope activity, where MEMS provided a forensic perspective on small accelerations that did not evolve into failure, complementing the long-term deformation patterns captured by InSAR. Sentinel-1 results were validated against inclinometer data, showing good agreement at the local scale, before being extended to the entire urban area of Sarajevo for the period from 2022 to 2025. The citywide comparison with mapped high-susceptibility zones revealed notable discrepancies, underscoring the need to refine susceptibility maps by integrating ground and satellite-based evidence. As the first applications of combined MEMS and InSAR monitoring in Sarajevo, this study provides insights that may support more reliable operational landslide forecasting in complex urban environments.

2. Engineering geological aspects and sliding mechanisms of the slopes in the Sarajevo

The urban area of Sarajevo is situated in a geologically and geomorphologically complex area where slope instability is a significant hazard. Steep, heterogeneous slopes affected by tectonic activity and weathering, combined with uncontrolled urban expansion and poor drainage, have led to frequent landslides, severely constraining spatial planning and safe urban development.

2.1. Geological and Geomorphological Setting of Sarajevo Urban Area

The Sarajevo urban area lies within a narrow basin, surrounded by steep slopes of the Dinaric Mountains. The relief is characterized by strong altitude contrasts, with elevations ranging from about 500 m in the valley to over 1600 m on the surrounding hills. Steep gradients, intense rainfall, and extensive human modification of slopes have created conditions highly susceptible to both shallow and deep-seated landslides.

The Upper Miocene polyfacial complex, comprising marls, siltstones, sandstones, and debris, dominates the urban slope area and is highly susceptible to weathering, erosion, and shallow sliding on urbanized hillsides. Along the basin margins, the Lower Triassic polyfacial complex of quartz sandstones, marls, claystones, and siltstones is strongly tectonized and fractured, making it susceptible to deeper-seated

landslides up to 15.0–20.0 m (Rokić et al., 2000). Above the City, carbonate mountains with pronounced jointing and karstification favor block sliding and frequent rockfalls, particularly on Trebević Mount. The Trebević slope area is among the most geotechnically challenging urban zones in Sarajevo. A typical engineering geological cross-section for that area is presented in Fig. 3, based on numerous boreholes drilled over the last decade. The profile reveals sandy clays of variable thickness, underlain at depths of approximately 6.0–20.0 m by a highly heterogeneous rock mass. The composition varies from clayey limestone debris to weathered sandstones and claystones, reflecting locally variable geomechanical conditions and degrees of weathering that strongly influence slope stability. Qualitative examination of borehole cores identified several potential slip surfaces, mainly within the upper clayey horizons, as indicated by dotted red lines in Fig. 3. Groundwater was encountered in some boreholes within the sandy clay layers, while absent in others, suggesting complex and discontinuous hydrogeological conditions. At greater depths, limestone debris contributes to higher permeability of the lower strata, which generally show favorable geotechnical characteristics (SPT > 50/10) and greater strength and stiffness than the overlying materials.

Overall, engineering–geological investigations conducted on the slopes beneath Mount Trebević revealed the absence of competent bedrock even beyond 20.0 m depth, complicating the delineation of potential slip surfaces and the assessment of long-term slope stability.

2.2. Infrastructure and Housing Challenges Related to Slow-Moving Landslides

In Sarajevo, progressive ground movements associated with slow-moving landslides have led to extensive cracking of buildings and roads, deformation of retaining structures, and recurrent damage to underground utilities. These processes have been active for decades, leading to significant economic losses and disruptions to daily life. Their occurrence is further aggravated by informal housing, uncontrolled urbanization, inadequate surface and subsurface drainage, excavation works, and extreme rainfall events. Similar challenges have been documented in comparable settings by Cascini et al. (2009, 2014) and Di Maio et al. (2013). However, in addition to their long-term creep behavior, slow-moving landslides can locally evolve into rapid failures, posing serious risks to both property and human life. As reviewed by Cueva et al. (2025), such transitions are primarily controlled by hydrological fluctuations, variations in pore-water pressure, and repeated wetting–drying cycles that progressively reduce shear strength. The residual strength along pre-existing shear zones, coupled with rate-dependent material behavior, ultimately governs whether a creeping slope remains stable or accelerates toward catastrophic failure. In Sarajevo, similar failure mechanisms have been observed during prolonged periods of intense rainfall, when elevated pore pressures accelerate slope movements and occasionally trigger local failures. At present, the leading indicators of slope instability in Sarajevo are visual cracks on façades and pavements, combined with observed engineering-geological conditions, and these have been widely used in qualitative susceptibility mapping. However, in the absence of systematic monitoring, distinguishing whether the observed damage arises from slope movement or construction deficiencies

remains challenging. Although a detailed structural assessment is beyond the scope of this paper, the interaction between ground deformations and building response is addressed in the case study section.

3. Case Study from Sarajevo: Ten-Month Real-Time Monitoring in Soukbunar area

A unique example from Sarajevo illustrates how real-time monitoring contributes to understanding the overall behavior of slopes in urbanized areas. The purpose of this case study is to evaluate the acceleration threshold and to investigate the potential for using InSAR-derived line-of-sight (LOS) displacements for landslide risk management in urban environments. The Soukbunar area (Fig. 4), located on the southern slope of Sarajevo beneath Mount Trebević, was selected as a reference site due to its active slope processes and challenging conditions, including complex soil composition, steep terrain, and dense residential development. These conditions make Soukbunar highly representative of the difficulties faced in many urban areas where landslide risk directly threatens existing housing and infrastructure, emphasizing the need for reliable, multi-source monitoring approaches.

3.1. Ground-based observations

Ground-based observations provided the basis for assessing slope activity at the Soukbunar site and for validating satellite-based monitoring. This section first outlines site conditions and visible signs of instability, followed by inclinometer measurements that quantify subsurface displacements and the depth of the sliding surface. Together, these approaches establish the groundwork for integrating ground-based evidence with satellite observations in the later analysis.

3.1.1. Site Conditions and Visual Observations

At the Soukbunar site, selected as the case study location, evident signs of slope movement are visible even without detailed measurements (Fig. 5).

In the vicinity of the inclinometer boreholes IB1 and IB2 (indicated in Fig. 4), older residential buildings exhibit pronounced façade cracking, with widths exceeding 5.0 cm, reflecting the long-term impact of ground displacement and the consequent loss of serviceability (Figs. 5a and 5b). In several parts of the study area, retaining walls are heavily deformed, illustrating progressive instability over time. Although localized roadway repairs temporarily improve serviceability, they simultaneously obscure evidence of persistent slope movements, making the recognition of long-term progression more challenging. Similar challenges have been highlighted in published research, where monitoring was combined with an assessment of building vulnerability, showing that structural damage is often underestimated due to repair works and the variable resilience of building stock (Zhang et al., 2025). In contrast, houses constructed within the last two decades generally appear in better condition and show no significant damage, although minor signs of lateral creep can still be observed in some recently built buildings, particularly in the most critical zones. Such differences, primarily reflecting variations in construction

quality and foundation conditions, explain the variability in damage between buildings, while the overall pattern continues to indicate an active, slow-moving landslide process.

3.1.2. Inclinometer Monitoring

Across the entire Soukbunar study area, five conventional inclinometers were installed, as shown in the layout of Fig. 4, to ensure that critical ground deformations are captured for the calibration and validation of the real-time inclinometer system. Baseline (initial) readings were performed in April 2023. Subsequent measurements have been conducted periodically through September 2025, covering approximately 2.33 years of monitoring. In addition to these conventional devices, a real-time MEMS inclinometer was installed adjacent to one of the traditional boreholes in December 2024, providing continuous displacement monitoring up to September 2025 (approximately 10 months). An automatic inclinometer chain (vertical array), developed by the University of Parma in collaboration with ASE S.R.L. (the device called MUMS – Modular Underground Monitoring System), was installed to enable real-time monitoring. Each node in the vertical array integrates a 3D MEMS unit (accelerometer, magnetometer, and thermometer), allowing continuous measurements of tilt and displacement at high temporal resolution. The sensors are connected through a datalogger and supported by IoT-based data transmission, enabling near-real-time data acquisition, storage, and web-based visualization. This configuration has been successfully implemented in landslide monitoring and early warning systems, where it has proven reliable and robust compared to conventional manual inclinometer surveys (Segalini et al., 2014; Carri et al., 2021). The MEMS-based inclinometer was installed according to standard procedures commonly used in landslide monitoring. After drilling a 12.0 m-deep borehole, the inclinometer chain was positioned to allow displacement measurements at 1.0 m intervals along the depth. The borehole was then fully grouted to ensure proper coupling with the surrounding soil and reliable data acquisition. To enable comparison and validation of this relatively new real-time monitoring technique, one of the five conventional manual inclinometer casings (13.5 m deep) was installed immediately adjacent to the MEMS borehole. The two boreholes were located only 2.0 m apart, providing independent verification and control of the MEMS system and ensuring direct comparability of the results, thereby enhancing the robustness of the monitoring framework. Moreover, the core drilling performed for the installation of both inclinometer systems confirmed earlier findings regarding the site's geological conditions, as described in the geological settings sections.

Inclinometer readings are presented in Fig. 6. Figure 6a shows the total ground-surface displacements recorded by conventional inclinometers between April 2023 and September 2025 (2.33 years). The legend indicates the depth of the sliding surface for each installation where movement was detected, generally occurring below 7.0 m. Average displacement rates, annotated directly on the graph in centimeters per year, illustrate the long-term trends in deformation. The calculated annual rates range from 0.0 to 4.1 cm/year, with two locations exhibiting average movements exceeding 1.0 cm/year. Although the landslide is very slow-moving, the values are relatively high, especially given that the sliding surfaces are located at considerable depth within a densely populated urban area. At the inclinometer, which showed the highest rate (4.1 cm/year), the cumulative displacement over the 28 months reached

approximately 9.5 cm, representing the practical serviceability limit of the installation. This was confirmed during field measurements, as the probe could only be advanced with considerable effort due to the pronounced bending of the inclinometer casing. Beyond average rates, the time series also suggests slightly higher velocities between the initial and first follow-up measurements (April–July 2023), although the overall creep rate remained relatively constant. However, given the wide time intervals between records, such measurements cannot capture short-term accelerations that are crucial for early warning.

Figure 6b compares the conventional and real-time inclinometers, demonstrating good overall agreement in the results. Although both systems capture the same overall deformation pattern, the MEMS profile smooths the transition across the shear zone, while the conventional inclinometer pinpoints it within a narrower depth interval. This difference reflects the influence of sensor spacing and casing stiffness, rather than any substantial discrepancy in performance. Overall, the agreement between the two methods is excellent.

To investigate the influence of precipitation on slope displacement, data from the real-time monitoring system were analyzed over ten months (December 2024–September 2025). Figure 7a shows the resulting displacement–rainfall relationship on the active slope. The system provided high-temporal-resolution data (two readings per day). The overall creep trend was nearly linear, with only a single significant acceleration during a rainfall episode that did not lead to failure. Under normal meteorological conditions, cumulative displacements progressed slowly at rates generally below 0.2 mm/day (Fig. 7b), amounting to about 25.0 mm over the 10-month monitoring period. A marked shift occurred in late March and early April 2025, when daily rainfall exceeded 35.0 mm and weekly totals reached ~ 100.0 mm, driving velocities from ~ 0.05 mm/day to peaks of 0.8–1.0 mm/day. These thresholds illustrate the slope's critical hydrometeorological response and highlight how near-failure behavior can be captured in real time, supporting early warning and more informed urban planning in densely populated areas. This observation is consistent with Ghaderpour et al. (2024), who used PS-InSAR in Central Italy to estimate reactivation times and velocities of slow-moving landslides, demonstrating their close relationship with precipitation. Similar observations have been previously reported in the literature, where extensive, deep-seated landslides remained active for decades, displaying continuous displacement without immediate collapse (Stead and Eberhardt, 2013). In such long-term creep phases, temporary accelerations are often recorded but rarely culminate in failure, as they are usually driven by short-term hydrological influences such as seasonal snowmelt or heavy rainfall (Manconi, 2021). The correlation between precipitation events and displacement increments confirms the importance of hydrogeological factors, particularly elevated pore pressures, in triggering slope activity in Sarajevo. Interestingly, acceleration occurred soon after intense rainfall, revealing a rapid slope response driven by rapid infiltration and increased pore pressure in relatively permeable materials. The karstified limestone above the landslide (Fig. 2c), together with debris soil layers, likely enhances overall permeability, allowing rainwater to infiltrate rapidly into the sliding mass and trigger short-term displacement. However, this assumption should be verified in future studies through real-time pore-pressure measurements within the landslide mass.

3.2. Complementary InSAR Observations

In addition to ground-based monitoring, satellite radar interferometry was conducted using the Geohazards Exploitation Platform – Area Monitoring Service (AMS), which employs the Parallel Small Baseline Subset (P-SBAS) approach (Casu et al., 2014; De Luca et al., 2015; Manunta et al., 2019). The Geohazards Exploitation Platform (GEP) has already been successfully applied to landslide detection and monitoring using Sentinel-1 InSAR services such as SBAS and PSI, confirming its value for large-scale ground-motion analysis (Reyes-Carmona et al., 2020; Foumelis et al., 2022). The AMS P-SBAS service performs the complete end-to-end DInSAR processing chain, from the retrieval of Sentinel-1 SLC (Level-1) data to the generation of geocoded deformation products. The analysis was conducted in Multi-Temporal Analysis (MTA) mode, designed for long-term displacement monitoring. Input parameters, including reference point, polarization, and temporal coherence thresholds, were defined to optimize the quality of the results. The platform automatically executes all essential steps (orbit correction, interferogram generation, unwrapping, and geocoding) to deliver publication-ready outputs, including line-of-sight (LOS) displacement time series, mean LOS velocity maps, temporal coherence layers, and average scatterer elevation. Its main advantage lies in simplifying the otherwise complex InSAR processing workflow, while still ensuring millimetric precision in urban environments. For the Sarajevo case study, the service was used to derive LOS displacement trends and time series for the selected slope, enabling direct comparison with real-time MEMS monitoring data.

Furthermore, an independent InSAR analysis was performed using StaMPS (Stanford Method for Persistent Scatterers), with data preprocessing in the SNAP (Sentinel Application Platform) software to further verify and compare the results. The StaMPS method, initially developed for deformation analysis in natural terrains with few artificial structures, has proven to be successful and robust in numerous studies monitoring landslides, volcanic activity, and tectonic movements, and is now widely accepted in the scientific community (Hooper et al., 2004; Hooper et al., 2007). To ensure a homogeneous and reliable dataset, Sentinel-1 images were manually inspected to exclude unsuitable acquisitions (e.g., scenes with low coherence or processing errors) before uploading them into the AMS P-SBAS service and before StaMPS processing. Winter acquisitions were discarded to reduce decorrelation caused by snow and vegetation, thereby improving coherence over urbanized terrain. The final dataset for the AMS P-SBAS service consisted of 20 coherent IW SLC scenes in VV polarization from a single descending relative orbit, processed with the SRTM DEM and a temporal coherence threshold of 0.85. For the StaMPS processing, 59 IW SLC scenes from the descending orbit were used. Descending geometry was selected as it provided optimal radar visibility for the investigated slope. As shown in Figs. 4 and 8, the study area covers about 500,000 m², with the locations of the previously described ground-based monitoring points indicated. A real-time inclinometer was installed within this zone (Fig. 8) to validate the monitoring system along with conventional inclinometers. Figure 8 presents the InSAR-derived ground displacement rates over the Soukbunar area. In Fig. 8a (AMS P-SBAS service results), the resulting LOS values are classified into three categories: < 0.5 cm/year (green markers), 0.5–1.5 cm/year (yellow markers), and > 1.5 cm/year (red markers). The red polygon delineates the high-susceptibility

zone, previously identified through conventional susceptibility mapping and field investigations (Rokić et al., 2000). In Fig. 8b, the Sentinel-1 InSAR dataset was processed using the StaMPS algorithm, which provides higher spatial precision in urban areas and detects localized deformations that may be smoothed in the AMS analysis. The color scale in the StaMPS results was adjusted for better visibility and therefore differs from that in the AMS P-SBAS map. However, clear deformation patterns appear in the built-up zone, with red and orange points indicating higher LOS values in the highly susceptible area. Although slight variations are visible between the AMS and StaMPS results, they mainly reflect differences in data processing and input parameters. StaMPS focuses on persistent scatterers, while AMS P-SBAS combines both persistent and distributed scatterers, providing broader but less precise coverage. These contrasts are further influenced by the number of processed images and the coherence thresholds: AMS used 20 Sentinel-1 scenes and a higher coherence threshold (0.85), whereas StaMPS used 56 scenes and a more flexible threshold (0.4), resulting in denser, more statistically robust deformation estimates. Despite these differences, both approaches identify nearly identical active zones, confirming the reliability of the monitoring results.

LOS displacements from InSAR are not directly comparable with inclinometer readings, as LOS does not represent purely horizontal movement. Typically, the decomposition of ascending and descending InSAR data is required to derive vertical and horizontal motion components. This procedure separates the total displacement into a vertical and a predominantly east–west component. However, due to the satellite's observation geometry, the InSAR technique is least sensitive to north–south movements. In the present case, the analyzed landslide is oriented primarily in this direction, where dominant displacements are expected. Therefore, applying decomposition would not provide reliable results for the key motion component. For this reason, decomposition was not performed in this study, and comparisons were made under the assumption that the LOS values represent the projection of the actual three-dimensional displacement vector onto the satellite's line of sight. Nevertheless, both methods exhibit similar trends. Two inclinometers recorded annual displacements: IB1, with ~ 1 cm/year, adjacent to a yellow InSAR point (0.5–1.5 cm/year), and IB2, with 4.1 cm/year, adjacent to a red point (> 1.5 cm/year). The remaining three inclinometers showed little or no movement, consistent with nearby green InSAR points (< 0.5 cm/year). This agreement confirms the reliability of InSAR and its correspondence with ground-based monitoring, supporting its use in risk assessment and failure prediction in the urban area of Sarajevo. A comparison of InSAR results with the susceptibility map of Rokić et al. (2000) reveals a clear spatial correspondence, with zones previously classified as highly susceptible overlapping areas of the highest displacements in the analyzed area (Fig. 8). Nevertheless, it is evident that some zones of high susceptibility near the Study area, as indicated in Fig. 8a, have not recorded measurable displacements over the past three years, suggesting that the qualitative inventory may overestimate hazard levels in specific locations.

The displacement time series (Fig. 9) further demonstrates a strong agreement between InSAR-derived LOS values (the closest point) and real-time inclinometer surface readings, confirming that satellite observations reliably reproduce progressive slope movements detected on site. This correspondence highlights the potential of InSAR to serve as a robust tool for monitoring slow-moving landslides in

Sarajevo's urban area and for supporting broader risk management strategies where dense ground-based monitoring networks are not feasible.

The comparison given in Fig. 9 shows that real-time MEMS monitoring provides a continuous, smooth displacement record, enabling detailed tracking of incremental changes and velocity trends. By contrast, InSAR LOS observations, constrained by the 6–12 day Sentinel-1 revisit interval, produce a stepwise dataset that cannot fully capture short-term variations or acceleration phases. This limitation prevents InSAR from delivering the exact temporal resolution required for precise velocity analysis, highlighting the need to complement satellite data with ground-based measurements. Despite minor deviations between AMS and StaMPS results—primarily due to differences in data resolution and scatterer selection—the overall deformation trend remains consistent across the two techniques.

4. Evaluation of Susceptibility Maps Using InSAR Observations (2022–2025)

After validating the reliability of InSAR LOS results through direct comparison with real-time inclinometer monitoring at the Soukbunar site, the method was further applied to evaluate the accuracy of existing landslide susceptibility maps for Sarajevo, shown in Fig. 1. A three-year Sentinel-1 dataset (October 2022– June 2025) was analyzed to assess whether zones classified as highly susceptible correspond to measurable slope activity.

The Sentinel-1 LOS displacement map for the 2022–2025 period exhibits generally good coherence across the Sarajevo Basin, particularly in the central urban areas and along the southern hillslopes. Built-up structures and artificial surfaces act as strong, persistent scatterers, yielding reliable estimates of displacement. In contrast, coherence is locally reduced in forested and steep terrains—most notably on the higher Trebević slopes—where dense vegetation and rapid surface changes limit the density of coherent points.

To ensure robustness, both ascending and descending passes were analyzed. North-facing slopes are better captured in descending mode, while south-facing slopes show more precise results in ascending mode. Using only one pass could bias displacement interpretation, especially in complex terrain. Combining both provides a more reliable output of slope dynamics and improves the validation of susceptibility maps.

For this analysis, 16 Sentinel-1 scenes were used. Winter acquisitions (December–February) were excluded due to frequent snow cover and seasonal moisture effects, which introduce decorrelation and degrade phase stability. The resulting time series therefore prioritizes spring-to-autumn epochs, improving point density and the robustness of LOS displacement estimates in the urban core and on partially vegetated south-facing hillslopes. Despite these limitations, the density and continuity of coherent targets in the urbanized slopes of Sarajevo are sufficient to extract stable LOS displacements. The detected deformation anomalies from descending and ascending orbits are shown in Fig. 10, which

presents line-of-sight (LOS) displacement velocities across the Sarajevo urban area. To improve visualization, measurement points are classified into three categories based on annual displacement rates: stable (< 0.5 cm/year), moderately deforming (0.5–1.5 cm/year), and significantly deforming (> 1.5 cm/year). The map highlights the basin's northern and southern hillsides, as well as the Trebević mountain slope, with red contours denoting areas previously classified as highly susceptible to landslides (Rokić et al., 2000). Similar results were also obtained from the StaMPS InSAR analysis; however, they are not presented here for clarity. These additional findings further confirm the reliability of the presented results, which represent one of the first systematic InSAR-based assessments of ground deformation across the urban area of Sarajevo and have clear practical value for slope monitoring and hazard management.

Nevertheless, regions with low coherence—mainly vegetated or unbuilt slopes—require complementary field investigations or ground-based monitoring to confirm the absence of active displacements. It should also be emphasized that LoS displacement velocities reflect a projection of ground motion along the radar line of sight and cannot directly resolve true horizontal or vertical components. Consequently, the observed signals may integrate both slope-parallel movements and subsidence, underscoring the importance of combining InSAR with ground-based measurements for reliable interpretation.

The comparison between descending and ascending Sentinel-1 geometries demonstrates the need to combine both acquisition modes in complex mountainous terrain. Descending data capture the major deformation patterns along the southern slopes of Trebević, where north-facing hillsides are more exposed to the radar line of sight. In contrast, ascending data provide complementary coverage of south-facing slopes that remain poorly visible in descending mode. The observed agreement between previously delineated high-susceptibility zones and the areas of largest InSAR-derived displacements supports the relevance of susceptibility mapping, while emphasizing the added value of satellite monitoring in refining spatial prioritization for risk management.

A direct comparison with susceptibility maps reveals substantial discrepancies. Most areas classified as highly susceptible show no measurable displacements over the past three years, particularly along the northern hillsides of the Sarajevo Basin, suggesting that many mapped zones correspond to latent or fossil landslides rather than active processes. By contrast, the Soukbunar area on the southern hillside stands out, where InSAR detects clear subsidence signals that are consistent with real-time inclinometer monitoring results. This finding confirms Soukbunar as an actively deforming slope and underscores the importance of distinguishing between inactive hazard-prone areas and those undergoing measurable displacement.

Such discrepancies observed in Sarajevo highlight the limitations of qualitative susceptibility mapping approaches. They also demonstrate the value of combining multi-year InSAR observations with ground-based monitoring to calibrate and update susceptibility maps, as previously noted by Herrera et al. (2013) and Ferretti et al. (2015). The long-term Sentinel-1 time series, spanning multiple years with consistent acquisition intervals, enables the transition from retrospective case analysis to near-

operational slope monitoring. These results highlight the need to update hazard assessments in Sarajevo by integrating remote sensing with geotechnical investigations. This integration enables authorities to distinguish between inactive, hazard-prone areas and truly active deformation zones, allowing for more effective resource allocation for risk mitigation. While the Soukbunar slope (validated with real-time MEMS monitoring) represents a confirmed deformation hotspot (Creeping slope 1), additional yellow-to-red zones are visible on the southern hillside of the Sarajevo Basin, particularly around Trebević (Creeping slope 3), and Creeping slope 2 on the northern hillside.

These areas do not represent newly discovered instabilities but rather coincide with zones previously recognized by Rokić et al. (2000) as highly susceptible to slope failures. The identification of these deformation clusters provides decision-makers with valuable guidance on where to prioritize detailed investigations and allocate resources for risk mitigation.

5. Discussion

Effective landslide risk management in Sarajevo requires an integrated approach that balances protecting existing settlements with controlled development on unstable slopes. It should combine detailed geotechnical investigations, improved drainage, strict land-use regulation, and, when necessary, the relocation of highly exposed structures. Over recent decades, remediation has primarily relied on drainage trenches and retaining walls, whose performance has varied due to local geological conditions and inadequate maintenance. These experiences demonstrate that structural measures alone are insufficient without continuous long-term monitoring.

The lack of systematic displacement data has limited understanding of slope dynamics across the City for decades. Establishing integrated observation networks that combine monitoring data (inclinometers, MEMS sensors, and InSAR) with geological, hydrological, and geotechnical conditions is essential for reliable forecasting and sustainable management. In the analyzed case study, monitoring reveals ongoing ground movements, even though surface changes are barely visible, highlighting the challenge of managing slow-moving urban landslides. Official reports typically emphasize surface damage rather than quantitative measurements, making it challenging to distinguish ongoing activity from past deformation. Many damaged houses remain inhabited, and recurring cracks are often concealed by repairs, while the lack of coordinated remediation has normalized local instability. Bridging this gap between modern monitoring evidence and practical risk reduction remains a key priority.

The joint interpretation of field inspections, inclinometer data, and InSAR observations provides a comprehensive view of slope behavior. Structural damage in residential buildings confirms that ongoing deformation directly affects the built environment. Subsurface inclinometer records revealed slow but progressive movements punctuated by brief acceleration phases during intense rainfall, consistent with the observations of Cueva et al. (2025). Complementary InSAR results extended this understanding spatially, mapping line-of-sight displacement patterns and confirming trends detected by ground-based

instruments. Together, these findings show that instability driven by geological and anthropogenic factors is strongly modulated by precipitation, which serves as the primary short-term trigger.

At the time of reporting, the slope presented in the case study section remains active, and no permanent stabilization measures have been implemented. Continued monitoring is therefore essential to capture responses to future rainfall events. This case study demonstrates the value of combining real-time and conventional techniques to characterize both long-term progressive movements and short-term accelerations. From an engineering perspective, integrating such evidence into decision-making frameworks enables timely drainage improvements and optimized land-use planning based on validated monitoring data. These measures can effectively reduce pore-water pressures, limit progressive deformation, and allow early intervention before critical thresholds are reached, helping to preserve existing buildings and infrastructure in landslide-prone areas.

While previous forensic studies (Dick et al., 2015; Carlà et al., 2018; Cueva et al., 2025) mainly focused on slopes that eventually collapsed, using monitoring data to back-analyze failure timing, the Soukbunar case illustrates that forensic analysis can also be applied to slow-moving landslides that remain inhabited for decades without catastrophic failure. Real-time MEMS monitoring captured rainfall-induced acceleration phases, providing a detailed record of short-term slope response. Although the Fukuzono–Voight framework (Fukuzono, 1985) has long been regarded as a cornerstone of slope failure forecasting, our findings are consistent with previous studies, which show that not every acceleration episode culminates in collapse. As noted by Manconi (2021), near-real-time applications of in-situ monitoring and ground-based radar have demonstrated that slopes may display pronounced accelerating creep without progressing to catastrophic failure. This highlights that, while the theory of accelerating creep can be calibrated efficiently in back analyses, its universal applicability in operational early warning remains limited and should be considered with caution.

Consistent with Zeng et al. (2024), the findings demonstrate that validated InSAR displacement data can refine qualitative susceptibility maps for urban areas. In line with recent integrated approaches, such as the multi-source framework proposed by Peduto et al. (2025) for the Italian Apennines, this study shows that InSAR results provide a robust basis for verifying and strengthening susceptibility zoning. A key outcome is that many slopes previously classified as highly susceptible have not exhibited measurable displacements over the past three years, thereby reducing uncertainty in current inventories and allowing resources to be concentrated on high-susceptibility zones with confirmed activity. At the same time, consistent with Manconi (2021), the results confirm that Sentinel-1 DInSAR, while valuable for mapping long-term deformation, cannot reliably resolve short-term accelerations due to phase aliasing and temporal averaging. Findings from this study further show that InSAR is unable to capture rapid slope responses during rainfall, since precipitation, clouds, and surface wetness cause signal decorrelation and phase noise, leading to oscillations and reduced accuracy. Consequently, InSAR reflects the cumulative deformation rather than the immediate displacement response recorded by ground-based sensors.

6. Conclusion

This study presents the first operational integration of InSAR and real-time MEMS inclinometer monitoring in Sarajevo, addressing the long-standing lack of systematic displacement data that has limited the understanding of urban slope dynamics. The integrated framework enables continuous observation and interpretation of slope behavior, confirming ground creep of 1.0–4.0 cm/year and rainfall-induced accelerations, and establishes a replicable model for forecasting and managing landslide activity in similar urban environments. The following main conclusions can be drawn:

- The study defines specific rainfall–displacement relationships, showing that daily rainfall exceeding 30–40 mm and weekly totals of ~ 100 mm acted as critical thresholds that triggered acceleration of slope displacement at the Soukbunar site. Albeit significant, these accelerations did not culminate in failure but represented temporary responses to short-term hydrological forcing. Defining such site-specific thresholds enhances the predictive capacity of monitoring systems and provides a practical preliminary basis for developing an early-warning framework.
- InSAR provides broad spatial coverage and captures long-term deformation trends, whereas MEMS and conventional inclinometers deliver high-resolution temporal and depth-specific insights. Their integration has proven essential for detecting near-failure behavior and validating susceptibility zoning, offering a level of reliability and detail that no single method could achieve on its own. Both InSAR techniques, StaMPS and AMS P-SBAS, showed good agreement in identifying the active deformation zone and the overall displacement trend, as the time-series results from both methods closely match ground-based real-time monitoring data.
- The findings from the present study confirm that many areas previously considered highly susceptible show no measurable movement during the 2022–2025 period. This underlines the limitations of expert-based qualitative mapping and underscores the need to recalibrate susceptibility assessments. The operational thresholds established in this study provide a practical evidence base for early interventions, infrastructure assessment, and policy-making in Sarajevo, with clear potential for transferability to other urban environments exposed to similar geohazard threats.

Despite these advances, the MEMS monitoring currently covers a 10-month observation period, and future extensions of the monitoring network, including pore-water pressure measurements, would further strengthen the interpretation of slope behaviour. InSAR provided valuable spatial and temporal coverage, although its performance can be locally reduced in densely vegetated areas with lower coherence. Future work will therefore focus on expanding real-time monitoring to additional slopes and progressively integrating hydrogeological measurements to further enhance landslide forecasting reliability.

Declarations

Author Contributions

Conceptualization, A.S.; methodology, A.S, and M.B.; formal analysis, A.S. and M.B.; resources, A.S. and M.B.; writing—original draft preparation, A.S. and M.B; writing—review and editing, A.S. and M.B.; visualization, A.S. and M.B; supervision, A.S.; project administration A.S. and M.B

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Declaration of interests

 The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

 The authors declare the following financial interests/personal relationships, which may be considered as potential competing interests:

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Conflicts of Interest:

The authors declare no conflict of interest.

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Figures

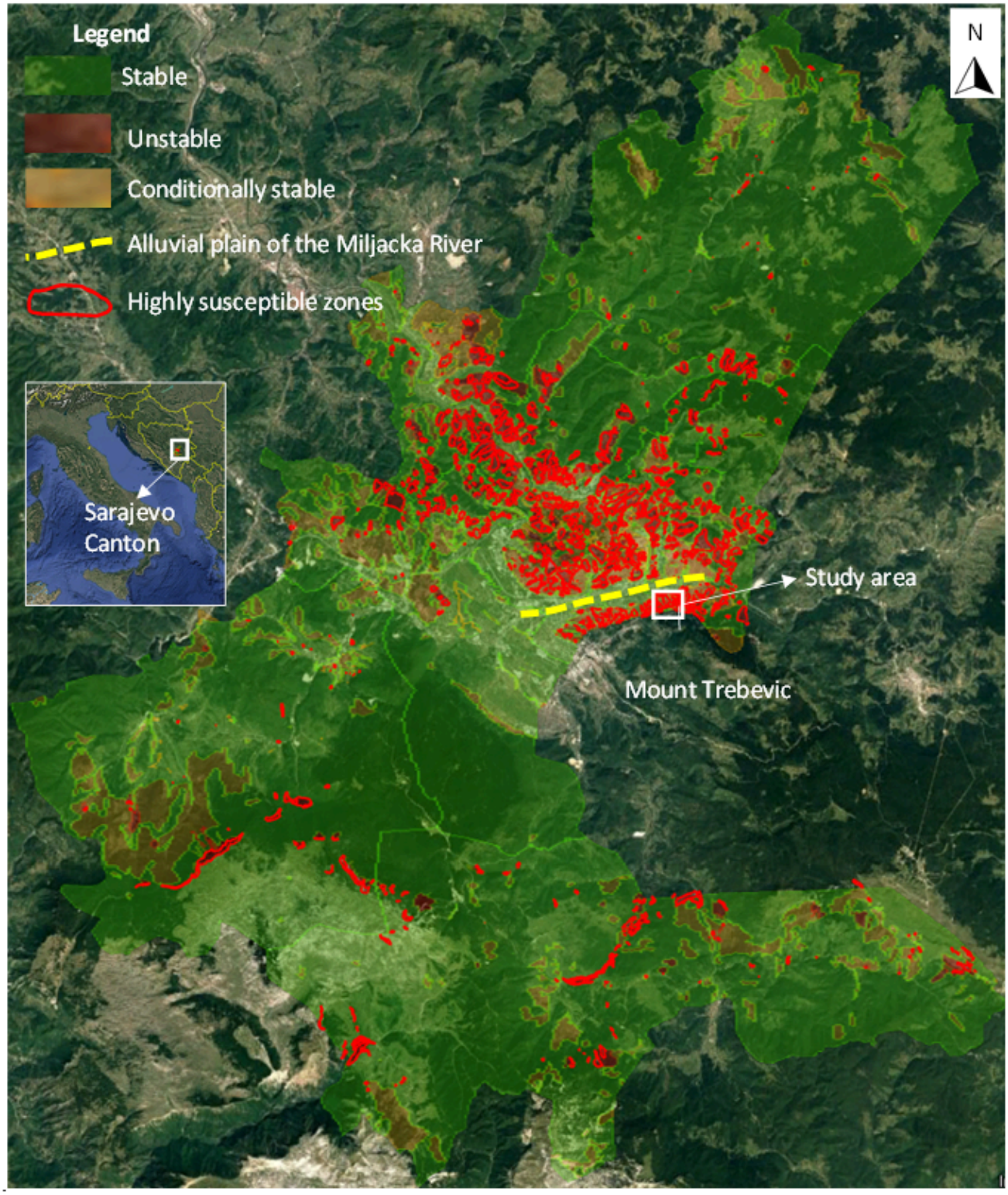


Figure 1

The qualitative landslide susceptibility map of the Canton of Sarajevo, indicating stable, unstable, and conditionally stable areas (green – low susceptibility, yellow – medium susceptibility, and red – high susceptibility), Rokić et al. (2000). Basemap: Google Earth™ (Imagery © respective data providers), accessed on September 15, 2025.



Figure 2

Drone photographs of the Sarajevo urban area: a) view on the northern hillslope and b) a southern hillslope; c) top of the Soukbunar study area.

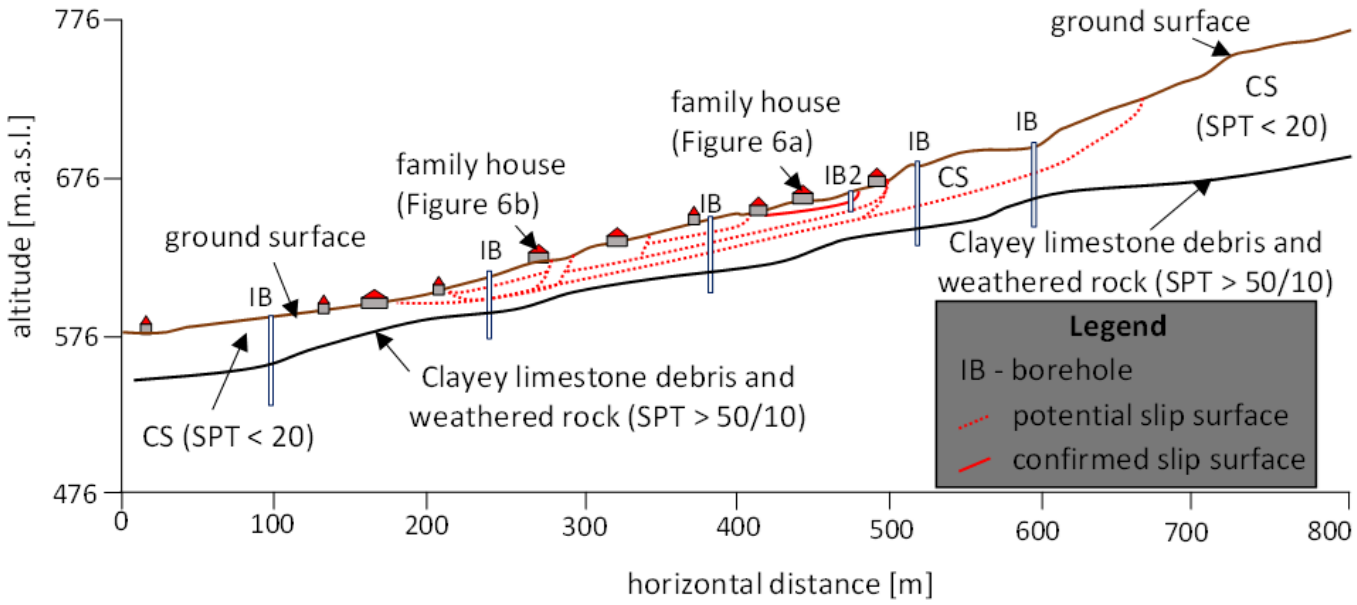


Figure 3

Slope cross-section along the profile trace outlined in Figure 4 (profile 1-1).

Overall, engineering–geological investigations conducted on the slopes beneath Mount Trebević revealed the absence of competent bedrock even beyond 20.0 m depth, complicating the delineation of potential slip surfaces and the assessment of long-term slope stability.



Figure 4

Overview of the Soukbunar area with indicated inclinometer measurement locations and slope direction. Basemap: Google Earth™ (Imagery © respective data providers), accessed on September 15, 2025.



a)



b)

Figure 5

The Soukbunar microlocation: a) the recent conditions of the family house nearby IB2; b) the recent conditions of the family houses nearby IB1.

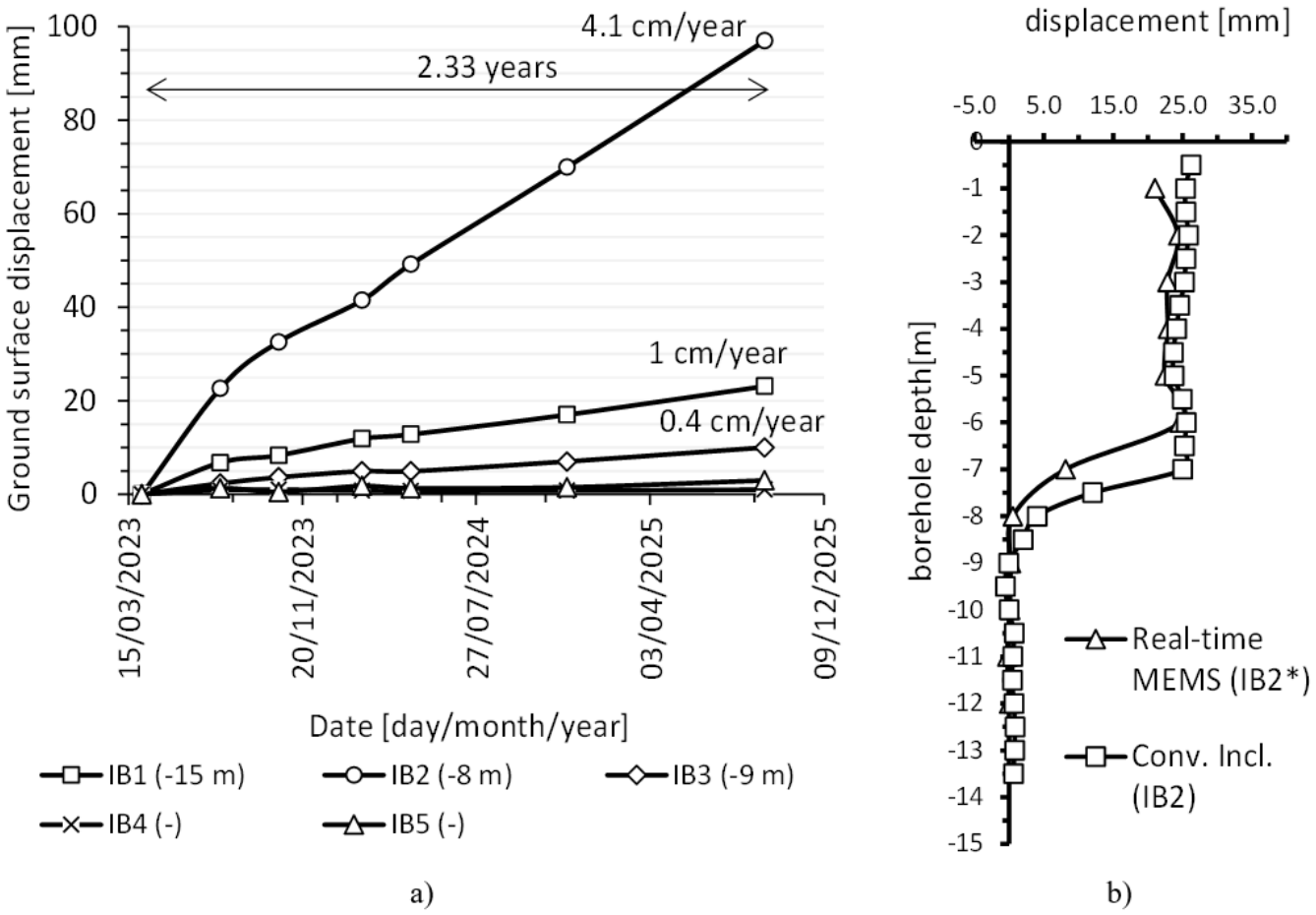


Figure 6

Conventional inclinometer results and comparison with real-time measurements: (a) Time-displacement series of ground-surface points from five conventional inclinometers; (b) horizontal displacements obtained from the conventional and real-time inclinometers at the IB2 and IB2* locations.

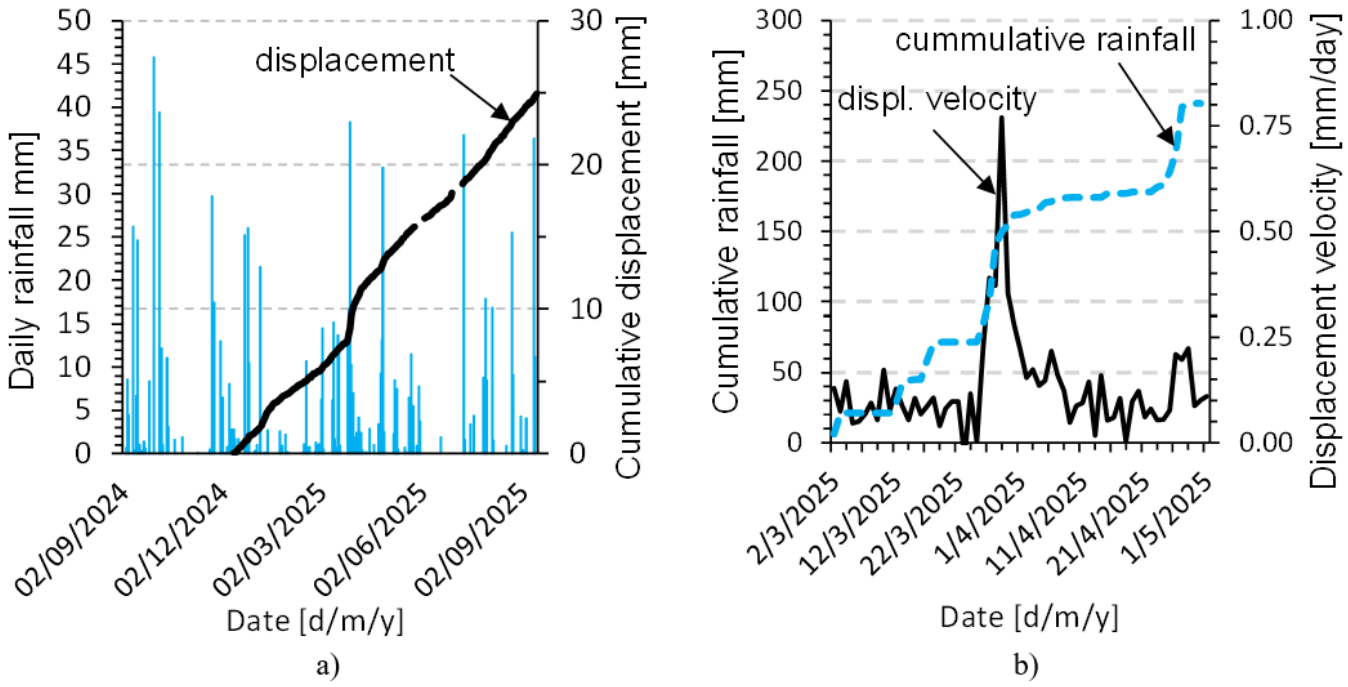


Figure 7

The ten-month real-time monitoring results: a) Ground surface cumulative displacements, showing accelerating creep from March to May 2025, compared with daily rainfall; b) Ground surface displacement velocity during the accelerating creep phase, recorded by real-time inclinometers (MEMS) between March 1 and May 1, 2025, compared with cumulative rainfall.

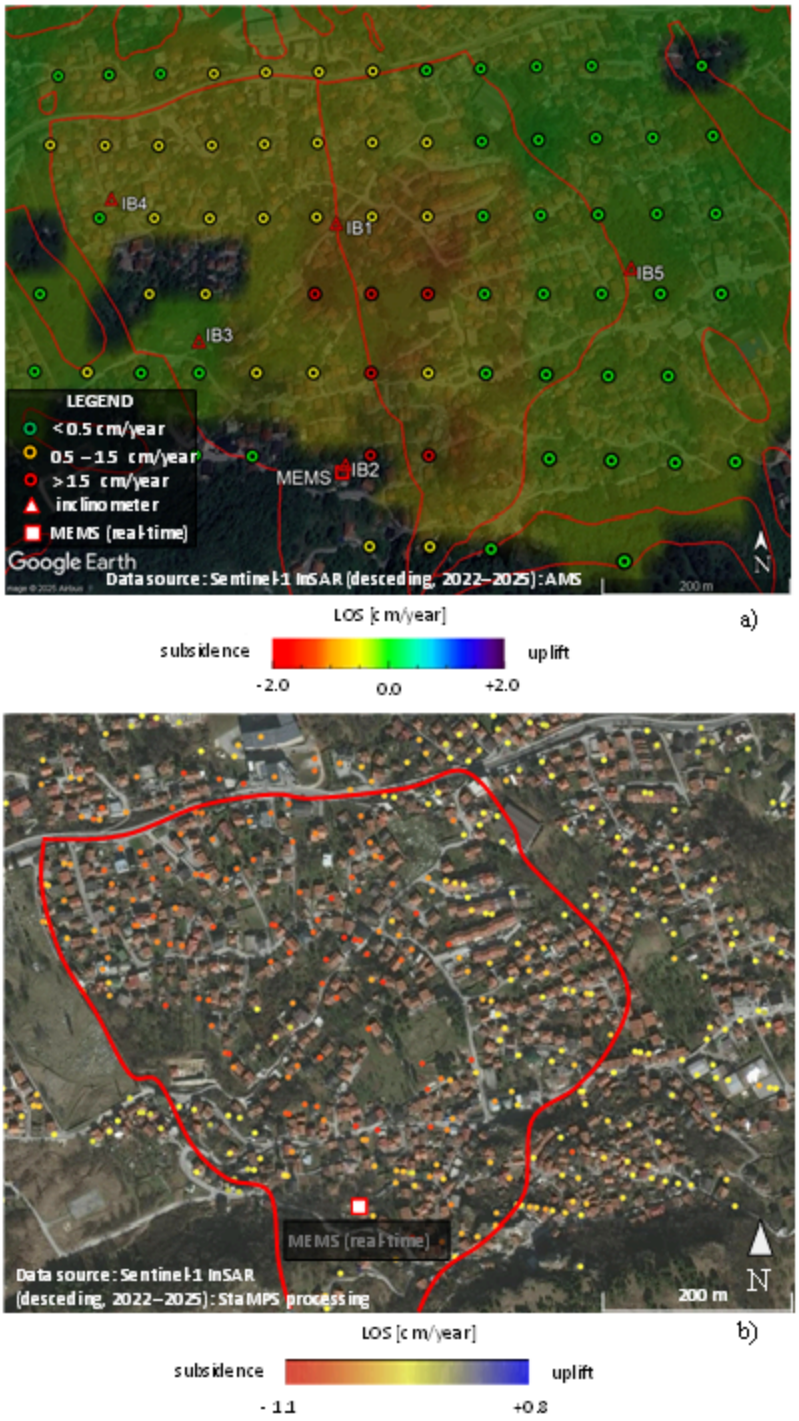


Figure 8

InSAR analysis results: a) Mean LOS velocity map of the Soukbunar Study area within the study area from the AMS P-SBAS service, inclinometer location, and high-susceptibility zones from Rokić et al. (2000); b) Map of the mean LOS velocity for the Soukbunar study area – StaMPS processing. Basemap: Google Earth™ (Imagery © respective data providers), accessed on September 15, 2025.

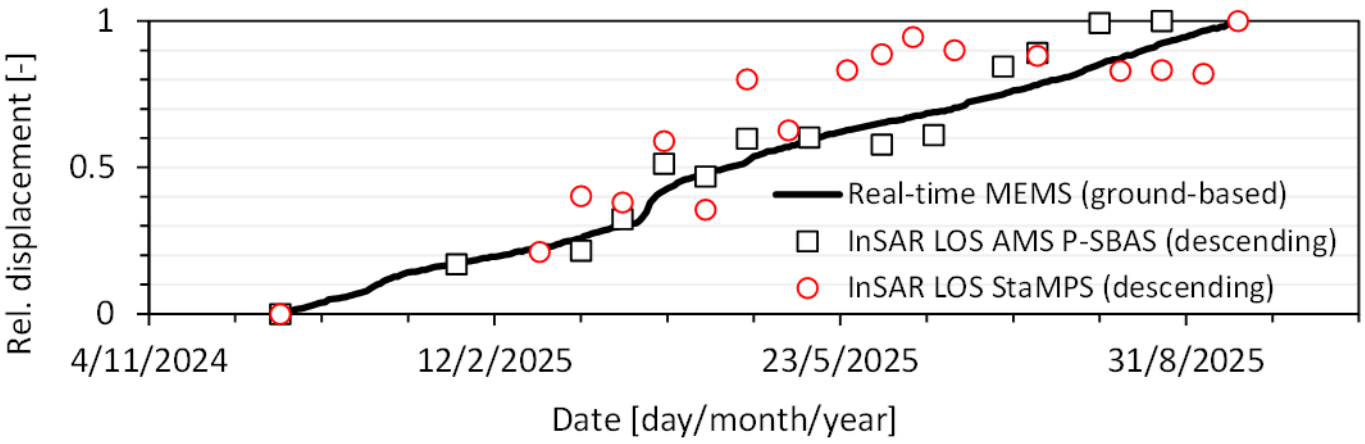


Figure 9

Comparison of Sentinel-1 descending LOS displacement time series with ground-surface relative displacements derived from real-time inclinometer readings, presented as relative values normalized to the maximum displacement (maximum LOS).

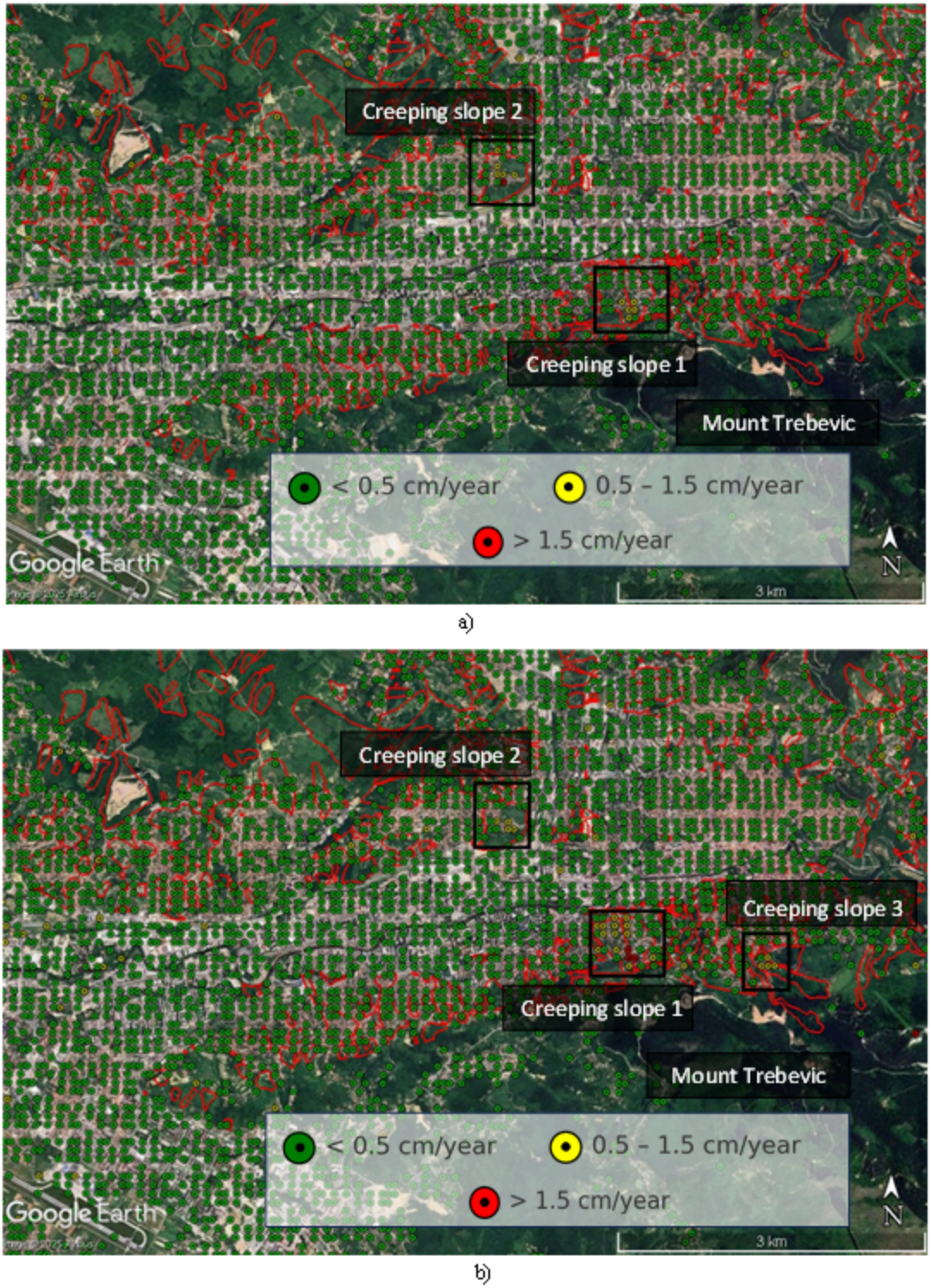


Figure 10

Line-of-sight (LOS) displacement velocities from Sentinel-1 InSAR (October 2022– June 2025) across the Sarajevo Basin, and comparison with red contours indicating zones classified as highly susceptible to landslides (Rokić et al., 2000): a) Comparison with InSAR data acquired in descending geometry; b) Comparison with InSAR data acquired in ascending geometry.

Supplementary Files

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- 3Highlights.docx