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VISIBILITY OF SINKHOLE AND SUBSIDENCE PROCESSES IN THE LAZIO REGION THROUGH COMBINED SPATIOTEMPORAL PS INTERFEROMETRIC ANALYSIS AND ANCILLARY DATA INTEGRATION

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EXTENDED ABSTRACT

La disponibilità di scansioni periodiche dell'intera regione Lazio attraverso l'*European Ground Motion Service*, rilascio EGMS, offre alle amministrazioni responsabili della gestione del territorio e della mitigazione dei rischi derivanti da processi di instabilità del suolo, l'opportunità di monitorare vaste aree, inventariare e caratterizzare i processi di deformazione del suolo attivi e classificare e dare priorità alle Aree di Interesse (AOI) dove dovrebbero essere adottati interventi di mitigazione. Partendo dall'esperienza acquisita nell'identificazione delle AOI candidate per le frane su tutto il territorio della regione Lazio (Marmoni *et alii*, 2025; Antonielli *et alii*, 2024), e nell'ambito dell'Accordo di Collaborazione tra l'amministrazione regionale e il CERI–Sapienza Università di Roma, l'analisi è stata estesa per includere processi di subsidenza lenta e potenziali *sinkhole* improvvisi, adottando tecniche di *clustering* spaziale di *Persistent Scatterers* (PS) ottenuti tramite interferometria SAR differenziale PSI da Sentinel-1 (EGMS) e analisi delle serie temporali. Questi *cluster* di subsidenza sono stati integrati con informazioni geologiche e idrogeologiche accessorie per aiutare nell'interpretazione dei plausibili processi generativi utilizzando alcune mappe sintetiche come la mappa di suscettibilità ai *sinkhole* a scala regionale proposta da Ciotoli *et alii* (2016). I più recenti rilasci EGMS, che coprono il periodo 2019–2023, hanno portato all'identificazione e alla classificazione di oltre 1.800 AOI caratterizzate da uno spostamento negativo lungo la linea di vista (LOS), coerente in entrambe le geometrie orbitali, indicativo di un abbassamento del suolo. Questi *cluster* di AOI sono spazialmente correlati con le principali piane alluvionali e intermontane della regione, dove affiorano depositi a grana fine compressibili o dove coincidono con i confini delle unità idrogeologiche dell'Appennino Centrale lungo le principali aree di recapito (ad es. sorgenti). Dall'ultimo dataset EGMS, un sottogruppo di AOI può essere considerato di nuova formazione rispetto a quelle identificate durante il precedente intervallo di monitoraggio (2015–2021). Tra queste, 78 nuove AOI mostrano una velocità assoluta superiore a 6 mm/anno e un'area inferiore a 5 km², con circa un terzo situato in aree classificate come aventi suscettibilità ai *sinkhole* alta o molto alta (Ciotoli *et alii*, 2016). Circa il 5% di queste si trova entro 500 m da *sinkhole* mappati.

In queste aree di deformazione del suolo, candidate a ospitare compattazione del sottosuolo o allargamento di cavità, sono state effettuate successive analisi sulle serie temporali di deformazione, evidenziando la presenza dei cosiddetti *Turning Points* (TPs – Ghaderpour *et alii*, 2024a e b), ovvero variazioni a lungo termine dei tassi di spostamento, e *Jumps* (Ghaderpour, 2021), che rappresentano spostamenti improvvisi e localizzati, sia episodici che multipli e sincroni in diversi PS all'interno di AOI suscettibili. Questi parametri si sono rivelati particolarmente efficaci nell'identificare *pattern* di subsidenza anomali, rendendoli preziosi per ulteriori indagini come potenziali *proxy* per l'occorrenza di *sinkhole* e come indicatori precoci di instabilità incipiente, come confermato preliminarmente applicando il metodo proposto a un evento già accaduto e documentato in letteratura (de ritis *et alii,* 2020). La metodologia proposta si dimostra efficace come strumento di *screening* a scala regionale per classificare e dare priorità ai potenziali fenomeni di instabilità. Mentre lo studio attuale si concentra sull'identificazione interferometrica e statistica di 78 nuove AOI, i futuri sviluppi comporteranno indagini sul campo specifiche sui *cluster* a più alta priorità per validare gli indicatori di telerilevamento e caratterizzare la geometria del sottosuolo comprendendo indagini topografiche e geoelettriche.

Il flusso di lavoro qui proposto mira a rappresentare il passaggio preliminare nello sviluppo di un sistema regionale integrato per il monitoraggio della subsidenza lenta del suolo e dei fenomeni di *sinkhole* rapidi.

ABSTRACT

The availability of periodic scans of the entire Lazio region through the European Ground Motion Service, EGMS release enables administrations to monitor vast areas, characterize ground deformation processes, classify Active Deformation Areas and prioritize Areas of Interest (AOIs). Within the framework of the agreement between the Lazio region and CERI–Sapienza, the analysis was extended to slow subsidence processes and potential sinkholes, integrating Sentinel-1 interferometric data provided by the European Ground Motion Service (EGMS, Copernicus) with geological and hydrogeological information. The 2019–2023 EGMS releases allowed the identification of 1,804 AOIs exhibiting coherent lowering along the Line of Sight, located mainly in alluvial and intermontane plains, associated in several sites with the presence of subsurface compressible deposits or hydrogeological discharge sectors, with approximately 5% situated within 500 m of known sinkholes. A subset of 1,369 AOIs is considered newly formed compared to the 2015–2021 interval: of these, 78 show velocities >6 mm/year and an area < 5 km², with one-third situated in zones with high sinkhole susceptibility. The analysis of deformation time series allowed for the identification of Turning Points and Jumps, effective indicators of subsidence anomalies, signatures of impulsive ground deformation processes, and potential precursor signals of instability. Ongoing activities include data integration with geophysical surveys and remote sensing surveys, as well as the analysis of dual-geometry COSMO-SkyMed datasets over wider-timescales. The objective is to consolidate an integrated system capable of monitoring both slow deformations and precursors of sinkhole occurrence.

Keywords: *sinkhole, Synthetic Aperture Radar Interferometry, persistent scatter, time series analysis*

INTRODUCTION

Synthetic Aperture Radar Interferometry (InSAR) techniques constitute established tools for the monitoring of slow-evolving ground deformations, thanks to their ability to detect millimetric displacements over large areas. The integration of free high-resolution data, global coverage, and reduced revisit times, combined with advancements in processing capabilities and computational algorithms, has significantly expanded the possibilities for analyzing ground movements (Medici *et alii*, 2025; Confuorto *et alii*, 2023; Festa *et alii*, 2022). In this context, one of the main markers of progress is represented by the development of the European Ground Motion Service (EGMS; https://egms.land.copernicus.eu/), an ambitious initiative of the Copernicus Land Monitoring Service (CLMS) implemented under the responsibility of the European Environment Agency (EEA). Since 2022, this service has been providing free Sentinel-1 data. The distributed data features millimetric precision and high reliability and are updated annually across the 29 Copernicus participating States (Costantini *et alii*, 2021; Crosetto *et alii*, 2020, 2021). The present work focuses on the post-processing of PS data derived from InSAR techniques, integrating them with ancillary geological and hydrogeological information, so as to identify subsiding areas and indications of rapid ground deformation, particularly sinkholes, extending and deepening. Such tentative approach was already reported by Medici *et alii* (2025) through the semi-automatic study of EGMS data on the Lazio region using the tool named ADAtool (Barra *et alii*, 2017; Navarro *et alii*, 2020; Monserrat *et alii*, 2024). Although InSAR techniques prove particularly effective in classifying slow and progressive processes, such as subsidence, they present limitations in detecting rapidly evolving phenomena, for which impact inventories are partial, the interferometric signal may result in missing or discontinuous signals, or due to the convergence between slow subsidence effects and rapid collapse (*e.g.*, Tivoli-Guidonia quarrying area). Being aware of technical criticalities in collapse prediction, this contribution has the scope of identifying diagnostic elements, satellite signatures, or potential interferometric precursors associated with sinkhole development aiming to improve early recognition strategies of such phenomena and related supporting risk assessment and mitigation activities. If detecting sudden collapse sinkholes using InSAR remains a challenge, as these events often lack long-term precursors detectable by satellite interferometry, given the image low resolution and satellite revisit times, conversely, the adopted method proposes a two-step, spatial and temporal statistical approach for the prioritization of territory, identifying 'Areas of Interest' (AOIs) where anomalous deformation trends (such as accelerations or sudden jumps) suggest active subsurface processes (Medici *et alii*, 2025; Tinagli *et alii*, 2025; Walczak *et alii*, 2025) . In this context, this work does not aim to provide a deterministic prediction of collapse events, for early detection and warning, but a regional scale screening of areas prone to experience slow-to-sudden ground instabilities where further direct investigations can be conducted. Through multitemporal analysis of ground deformation clusters and advanced time-series analysis (Ghaderpour, 2021), this method aimed to identify potential areas of evolution of sinkhole phenomena, defining the likelihood of AOIs in experiencing ground failures.

The present study was developed within the framework of a Collaboration Agreement with the Lazio region, aimed at updating the state of knowledge on subsidence and sinkhole processes by evaluating the applicability of interferometric techniques in large-scale knowledge monitoring approaches (Mazzanti *et alii*, 2017).

STUDY AREA

The Lazio region, located in central Italy, presents a complex geology deriving from the interaction of tectonic, volcanic, and sedimentary processes that have occurred successively from the Cenozoic up to the Quaternary. The territory is characterized by the Apennine belt, consisting mainly of Mesozoic sedimentary units and by Quaternary alluvial and lacustrine sedimentary basins occupying the plains and main river valleys (Tiber to the North, Aniene R. to the East of Rome, Liri and Sacco valleys to the South). The Quaternary alluvial deposits, which characterize the subsurface of the plains and valley floor, consist of gravels, sands, silts, and clays derived from the erosion of the surrounding reliefs. These areas are notoriously subject to ground instability, specifically subsidence and sinkholes (Bianchini *et alii*, 2022; Bozzano *et alii*, 2015; Stramondo *et alii*, 2008). Sinkholes are forms of ground sinking attributable to a plurality of genetic processes and can be distinguished into anthropogenic and non-anthropogenic. Anthropogenic sinkholes derive from induced alterations such as: intensive groundwater withdrawal, mining activities, excavations, and leakages from water and sewage infrastructures, which favor the deep erosion of sediments and the destabilization of rocks and cover soils. Non-anthropogenic sinkholes are instead linked to natural erosion and failure processes (cover-collapse, suffusion and piping) and dissolution typical of karst environments and recent alluvial sedimentary basins. The classification of these phenomena uses two terms to define each main type of sinkhole: the first describes the material affected by downward gravitational movements (cover, bedrock, or caprock), while the second indicates the main process involved (collapse, suffusion, or sagging) (Gutiérrez *et alii*, 2008;). In this study, particular interest was given to natural sinkholes, including cover collapse, suffusion and piping and sagging. They typical affect cohesive deposits and form through the sudden collapse of the roof of underground cavities, giving rise to surficial depressions ranging from couple of meters to tens of meters and with steep or sub-vertical walls (Fig. 1).

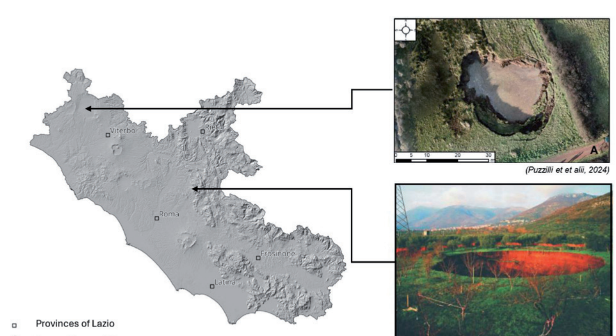

Fig. 1 - Study area of Lazio region, and detail of two sinkholes from literature

DATA AND METHODS

The adopted framework is based on the combination and data fusion of post-processed interferometric data with ancillary geological and morphological datasets. Multidisciplinary data, characterized by different spatial scales and resolutions, were used to carry out the analysis. In particular, the primary dataset employed includes:

- Satellite interferometric data from the Copernicus program, European Ground Motion Service (EGMS), covering the periods 2015–2021, 2018–2022, and 2019–2023, acquired in ascending and descending geometry.
- Digital Elevation Model (TINITALY DEM) with a 10 m spatial resolution of the Lazio region (Tarquini *et alii*, 2023);
- The Geological Map of the Lazio region at scale 1:25,000 available on the Lazio region Geoportal (https://dati.lazio.it/organization/regione-lazio);
- Hydrogeological Map of the Lazio region (Capelli *et alii*, 2013), including hydrogeological complexes, and mineral and thermo-mineral spring manifestations.

Which was complemented by an auxiliary dataset composed of:

- Sinkhole susceptibility map of the Lazio region (Ciotoli *et alii*, 2016);
- Subsidence susceptibility map (Herrera García *et alii*, 2021) tailored for the Lazio region;
- ISPRA sinkhole inventory integrated with data available at the Lazio region and subsequently updated through bibliographic analysis;
- Regional Technical Map of Lazio (CTR) at 1:5,000 scale available on the Lazio region Geoportal (https://dati.lazio.it/organization/regione-lazio).

The satellite interferometric data used in this study was downloaded from the EGMS Explorer platform. In particular, mean ground velocity data (PS) derived from Sentinel-1 (S-1) images, acquired in ascending and descending geometry, were employed, from which the relative Time Series (TS) referring to three-time intervals were analyzed: 2015–2021, 2018–2022, and 2019–2023. The overall number of PS identified in the three periods confirms a high availability of measurement points.

The method proposed in this study aimed to identify AOIs (Areas of Interest) of potential subsidence/sinkhole phenomena based on satellite data (Gentili *et alii*, 2025; Calligaris *et alii*, 2024; Esposito *et alii*, 2021). In this perspective, PS velocity values were spatialized through an interpolation process, in order to obtain a spatially continuous distribution of velocities. The interpolation was performed using the Heatmap tool based on the Inverse Distance Weighting (IDW) algorithm, implemented in the PS-Toolbox for the QGIS environment, developed by NHAZCA S.r.l., which simultaneously allows for the processing and filtering of PS cluster time series (Fig. 2a, b). The IDW algorithm calculates a velocity value for each point in space via a weighted average,

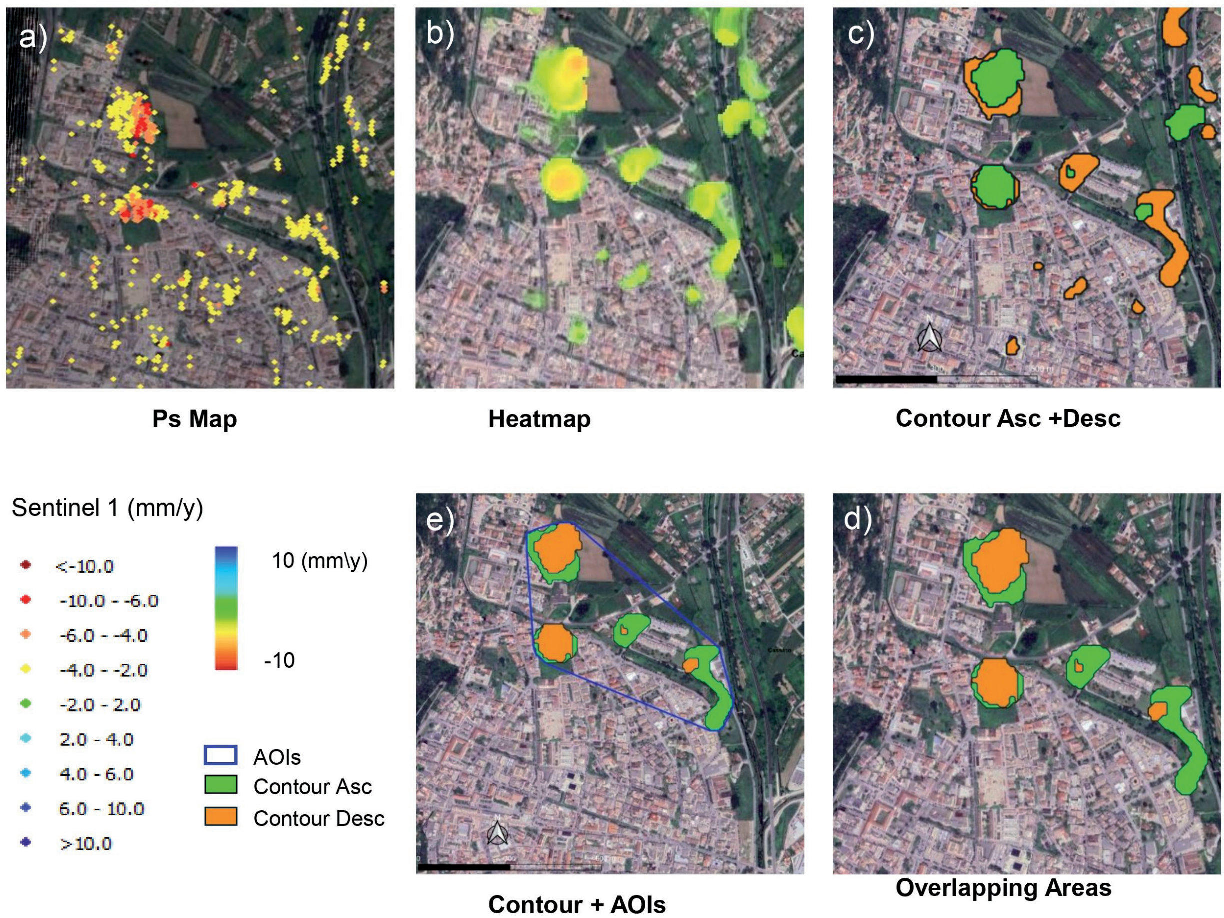

Fig. 2 - Processing Workflow for AOIs identification from Basic (Level 2-A) PS map. a) Distribution of PS acquired in ascending and descending geometries. b) PS interpolation via IDW algorithm, filtered for lowering greater than 2 mm/y. c, d) Selection of areas where ground lowering is detected in both spatially overlapping ascending and descending orbits. e) Clustering of the identified areas into AOIs using the DBSCAN tool in QGIS

where weights are defined as a function of the distance between the point of interest and the surrounding PS, also considering additional parameters, such as interferometric coherence. The interpolation parameters were selected iteratively to optimize the trade-off between reliability and precision, ensuring a correct spatialization of the individual point measurements. For the heatmap interpolation, the radius of influence was set to 50 m, with a minimum of 6 PS required within such radius. This threshold was adopted to filter the PS and reduce the noise present in the velocity map. Isolated PS points, defined as less than five within the specified radius, were excluded from the analysis. The resulting map is a raster file describing the continuous spatial distribution of ground displacement velocity. Two distinct heatmaps were generated, one for each of the two geometries (ascending and descending), and filtered for lowering greater than 2 mm/y. From the comparison of the filtered heatmaps for the two geometries, for each time interval, only those areas showing a spatial overlap, even partial, of the ground lowering detected in ascending and descending orbits were selected (Fig. 2c, d). Subsequently, through a clustering process of the selected areas (DBSCAN, QGIS), within a maximum radius of 200 m, the AOIs were obtained; these are areas where ground surface lowering phenomena are ongoing and are therefore candidates for hosting areal subsidence processes or localized sinkholes, for each time interval considered (Fig. 2e). The multitemporal analysis of EGMS releases allows, by comparison, further identification of persistent, new or vanished AOIs over the three time-intervals considered. Newly formed AOIs here highlighted in the 2019–2023 interval compared to the 2015–2021 interval, were filtered in terms of velocity and susceptibility level to conduct further analyses on PS time-series. On persistent AOIs further analyses on trend changes have been conducted.

The latter, focused attention on the temporal evolution of the ongoing phenomenon through the analysis of trends detected in the displacement time series of the PS included within the identified AOIs. In particular, the so-called Turning Points (TPs – GHADERPOUR *et alii*, 2024a, 2024b), understood as long-term variations in displacement rates, and Jumps -Js- (Ghaderpour, 2021), *i.e.*, sudden displacements observed simultaneously in multiple Persistent Scatterer time series within specific AOIs considered susceptible and coexisting in both acquisition geometries, were investigated. The analysis of these parameters was introduced with the aim of identifying anomalous trends in ground deformations over time, specifically acceleration phases presumably linked to external factors (subsurface fluid extraction; load imposition by structures and infrastructures), or to be interpreted as possible proxies for impulsive behavior associated with sinkhole formation and as potential early indicators of incipient instability conditions. Js are defined as abrupt changes in displacement time series caused by sudden ground motion. In PS-InSAR displacement time series, the presence of seasonal signals and measurement noise makes jump detection particularly challenging, especially when jump magnitudes are small relative to the signal-to-noise ratio. To address this issue, Ghaderpour (2021) proposed a modeling approach that simultaneously estimates trend and seasonal components while allowing for jump detection in unequally spaced time series. This characteristic makes the method particularly well suited for PS-InSAR applications, where observations are irregularly sampled and commonly exhibit annual and semi-annual periodicities. On the other hand, TPs refer to epochs in a displacement time series at which the velocity undergoes a significant change. In PS-InSAR time series, such turning points may indicate the reactivation of slow-moving landslides or long-term variations in land subsidence rates, as reported by Ghaderpour *et alii* (2024a, 2024b). In particular, Ghaderpour *et alii* (2024a) introduced a model termed Sequential Turning Point Detection (STPD), which automatically identifies trend turning points in PS-InSAR time series using a sequential least-squares fitting strategy. Extensive simulation experiments demonstrated that the proposed method is capable of detecting turning points with an accuracy of up to 83%. For the purpose of our study only negative Js or TPs have been considered. The interpretative phase of the acquired data involved the use of ancillary data available for the territory of the Lazio region. In particular, to provide a genetic attribution to the identified AOIs, the deformation analysis was integrated with regional ancillary data. Specifically, the interpretation relied on the Sinkhole Susceptibility Map of the Lazio Region (Ciotoli *et alii*, 2016). This thematic map was selected as the primary reference because it integrates and weights multiple predisposing factors, including outcropping lithology, alluvial cover thickness, proximity to fault lines, and hydrogeological settings. In addition, the local availability of DEM-LiDAR datasets allowed for the identification of morphologies associated with karst dolines or evolving sinkholes (*e.g.,* De Ritis *et alii*, 2020). Furthermore, DEM-based geomorphological expert analysis was integrated into the workflow to support the interpretation of InSAR-derived deformation patterns, allowing the identification of surface morphologies related to processes, such evolving sinkholes.

Concerning effect inventories, the sinkhole database used in this study derives from the "Sinkholes" project, launched by ISPRA in 2002. Within the territory of the Lazio region, the official database reports a total of 180 sinkhole points, accessible through the ISPRA portal (https://sgi2.isprambiente.it/viewersgi2/). In the course of this work, a systematic and in-depth bibliographic analysis was conducted starting from the 393 sinkhole events listed in the 2011 Unified Sinkhole Catalog of Lazio (Meloni *et alii*, 2013), aimed at identifying additional sinkhole phenomena documented in scientific literature but not included in the current database (*e.g.*, Ciotoli *et alii*, 2016; Nisio, 2008). This activity allowed for a significant integration of the existing inventory, bringing the total number of inventoried sinkholes to 509, for which localities, province, toponyms, and, when available, formation dates and other relevant characteristics are reported. This represents a substantial integration of the current ISPRA database of sinkhole phenomena (Fig. 3).

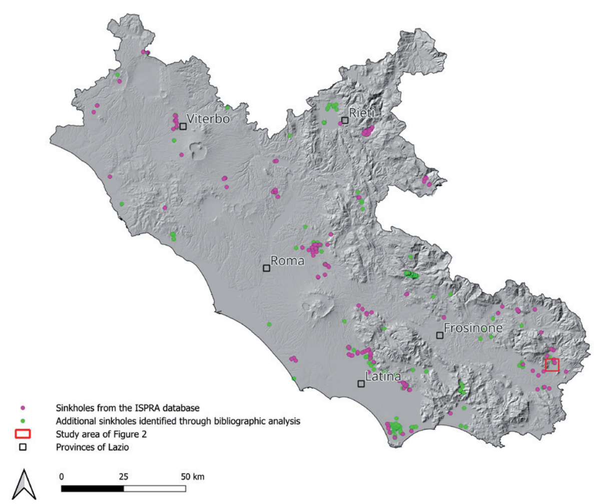

Fig. 3 - Distribution of sinkholes inventoried by the ISPRA Database and bibliographic analysis

RESULTS

The AOIs identified in this study were compared across the three available time intervals (Fig. 4) to select persistent ones and those newly appearing between successive periods (*e.g.*, 2018-2022 *vs*. 2015-2021), *i.e.*, areas where the mean velocity over the period exceeds the minimum lowering threshold of 2 mm/yr, associated with an intensification of the process. Given the increase in resolution and spatial density of PS in releases subsequent to 2015-2021, the number of AOIs increased linearly, following the linear increase of PSs.

It is observed that some particularly extensive AOIs fall and cluster within large subsidence zones already known in the literature, such as the urban center of Rome, the sub-urban areas of

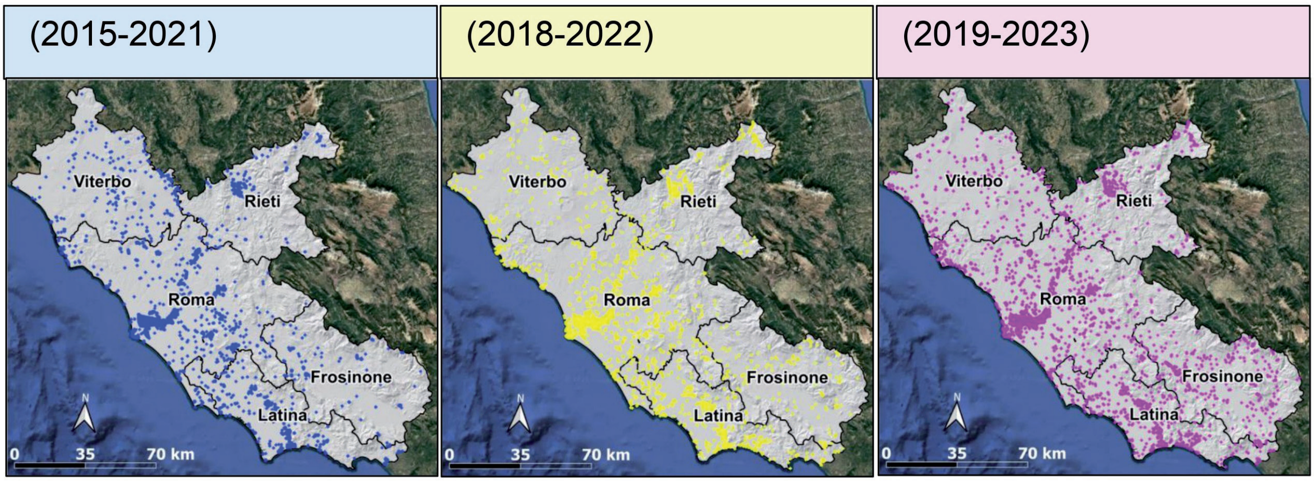

Fig. 4 - Distribution of the AOIs identified in the three time-intervals considered

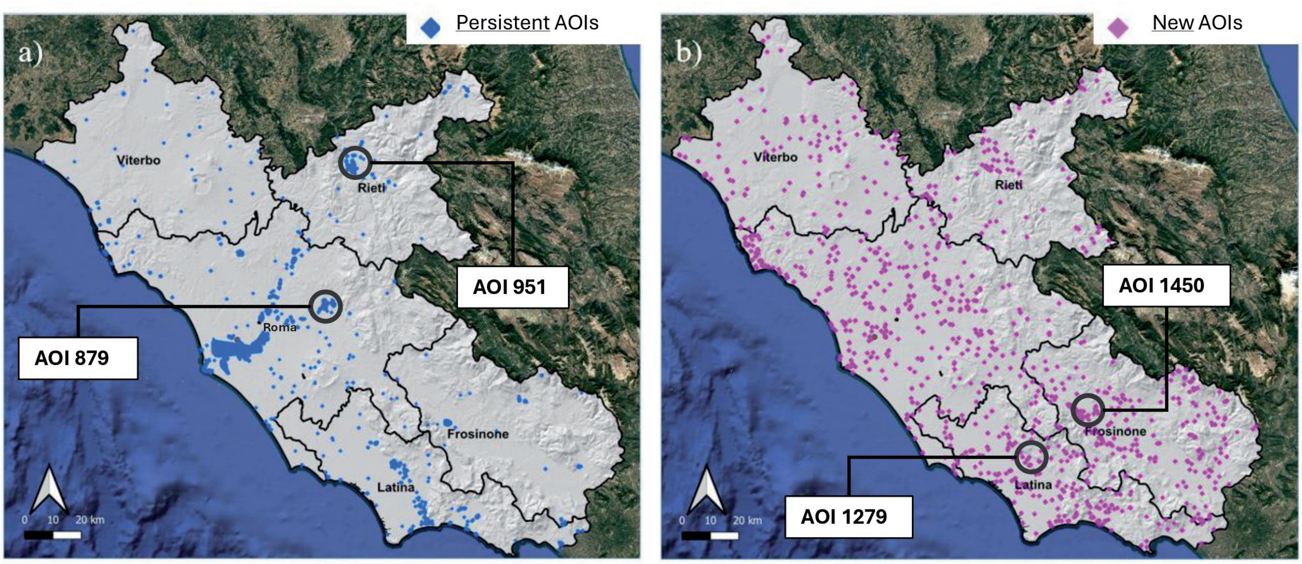

Fig. 5 - Distribution of new and persistent AOIs identified in the 2019–2023 period compared to the 2015–2021 period. The locations of the subsequently analyzed AOIs number 1279, 879, 1450, 951 are also shown in the figure

Interval	Number of AOIS	Comparison	Persistent	New	Vanished
2015-2021	1049	2015-2021 2018-2022	514	926	535
2018-2022	1440	2015-2021-2019-2023	435	1369	614
2019-2023	1804	2019-20232018-2022	831	973	609

Tab. 1 - Comparison of the total, persistent, new and vanished AOIs identified in the three time-intervals

Tivoli and Guidonia (Delgado Blasco *et alii*, 2015; Bozzano *et alii*, 2015; Stramondo *et alii*, 2008), or the northwestern portions of the Rieti province and the Valle Latina area in the Frosinone province. In particular, 1369 newly formed AOIs were highlighted in the 2019–2023 interval compared to the 2015–2021 interval (Tab. 1; Fig. 5), of which approximately 5% fall within 500 m of one or more sinkholes. Among the new AOIs, 78 exhibit a maximum velocity exceeding 6 mm/year and an area of less than 5 km². Of these, 24 are located in areas classified as having high or very high sinkhole susceptibility (Ciotoli *et alii*, 2016).

In these areas, through expert judgment, a subset of 9 AOIs were further selected, characterized by the presence of genuine localized ground surface lowering, *i.e.*, areas with clusters of subsiding PS nested within stable areas. This selection process allowed for the elimination of small-scale AOIs where apparent concentrated lowering resulted from a lack of surrounding scatterers. This ensured the selection of true subsidence hotspots, surrounded by interferometrically stable areas, where ground-based analysis and detailed investigations could be conducted. On these 9 newly selected AOIs, subsequent analyses focused on deformation time series were conducted to identify TPs or Js. Figure 6 shows an example of a time series relating to an AOI

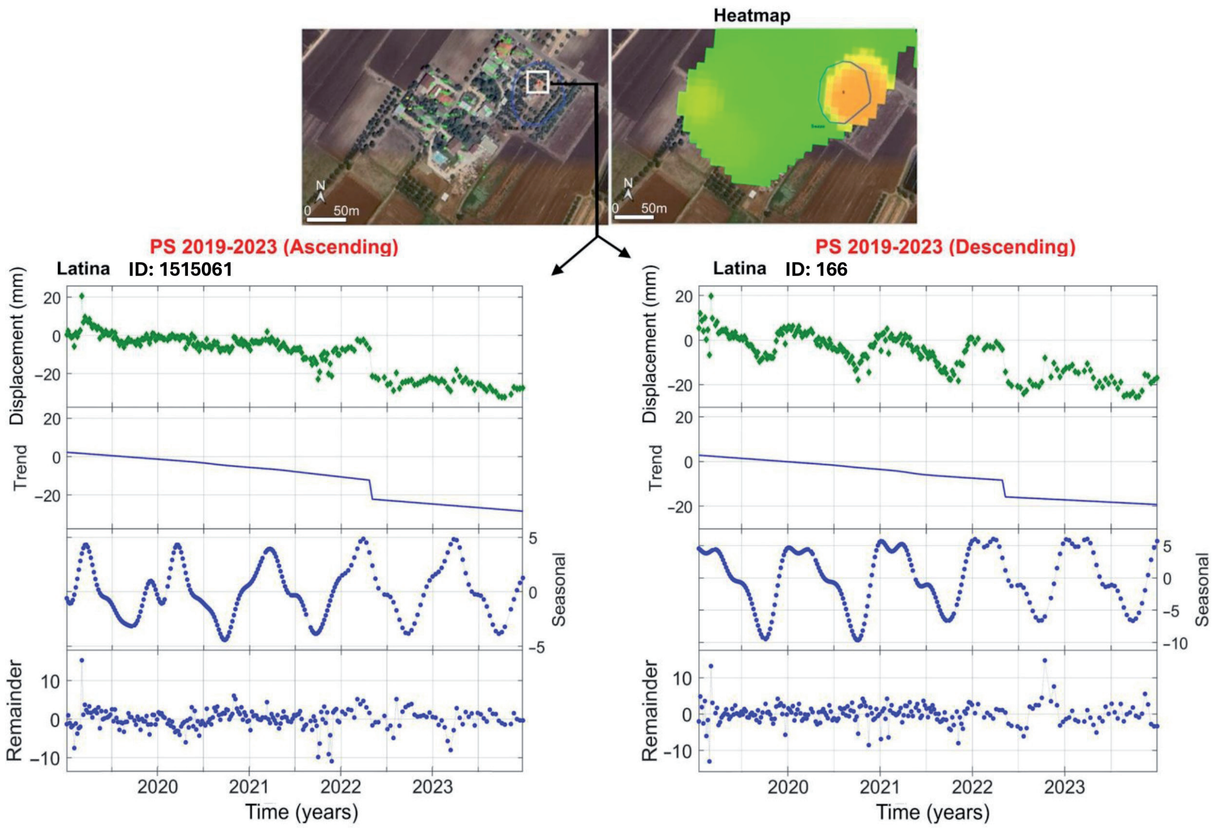

Fig. 6 - AOI number 1279, showing a jump in May 2022 in both ascending and descending PS time series. The localization of the AOI number 1279 is displayed in Figure 5

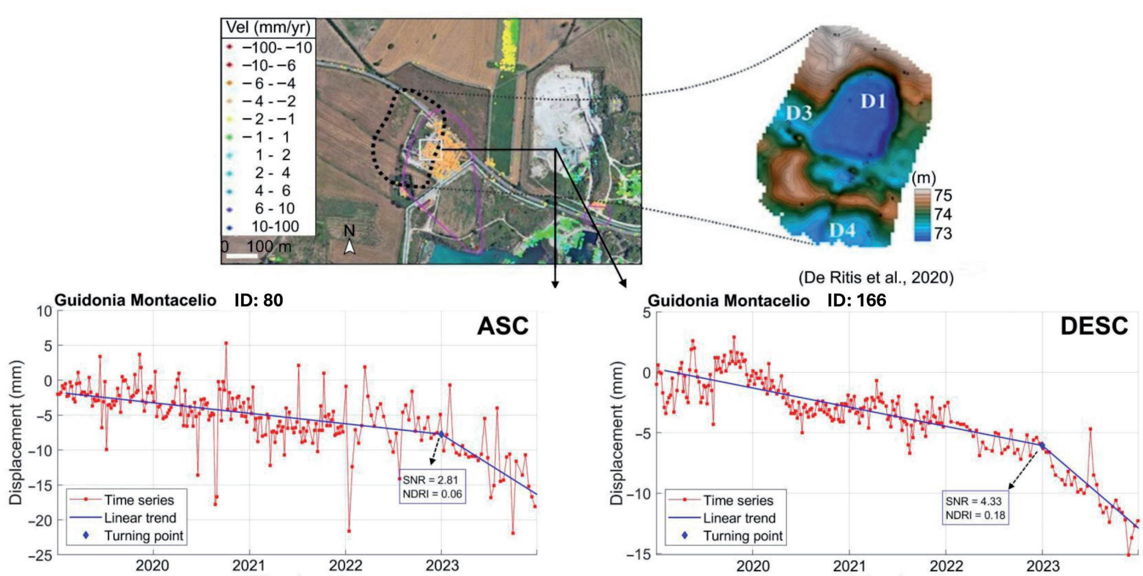

Fig. 7 - AOI number 879 with both ascending and descending time series showing a turning point. The PS time series highlights a distinct TP anomaly, confirming the surface response to the deep karst processes and buried paleo-forms characterizing the area. SNR and NDRI are short for signal-to-noise ratio and normalized difference residual index (see Ghaderpour *et alii, 2024 for their definitions). The localization of the AOI number 879 is displayed in Figure 5*

located about 750 m from a sinkhole recorded in the database, where a jump (with magnitude of approximately 10 mm estimated by the JUST software) is observed in the ascending and descending geometry in May 2022. This sudden variation in velocity over short time intervals can be interpreted as a sign of instability linked to sinkhole phenomena, representing a signal of an impulsive behavior. Ongoing field investigations are currently being conducted in the identified areas to assess the presence of geomorphological indicators or structural cracking patterns attributable to ground collapse.

Furthermore, we proceed with an application of the proposed methodology on a well-documented case study. A retrospective analysis was conducted on the sinkhole described by De Ritis *et alii* (2020). In this sector, characterized by active karst processes, the authors demonstrated, through the integration of remote sensing and geophysical data, how buried paleo-forms and dissolution chimneys drive vertical ground movements and surface topography modifications. Focusing on this well-documented context, the STPD analysis of the PS time series revealed a TP temporally coincident with the reported instability phase (Fig. 7). This correspondence is crucial as it links the surface kinematic signature detected by our algorithm to the deep-seated cavity evolution described by De Ritis *et alii* (2020), preliminary validating the TP as a reliable retrospective indicator for sinkhole-prone areas.

Furthermore, two representative displacement time series from the Lazio region are reported to demonstrate the performance of the Js and TPs detection model: one PS located in Frosinone (Fig. 8a, b) and one PS located in Rieti (Fig. 8c, d). The season–

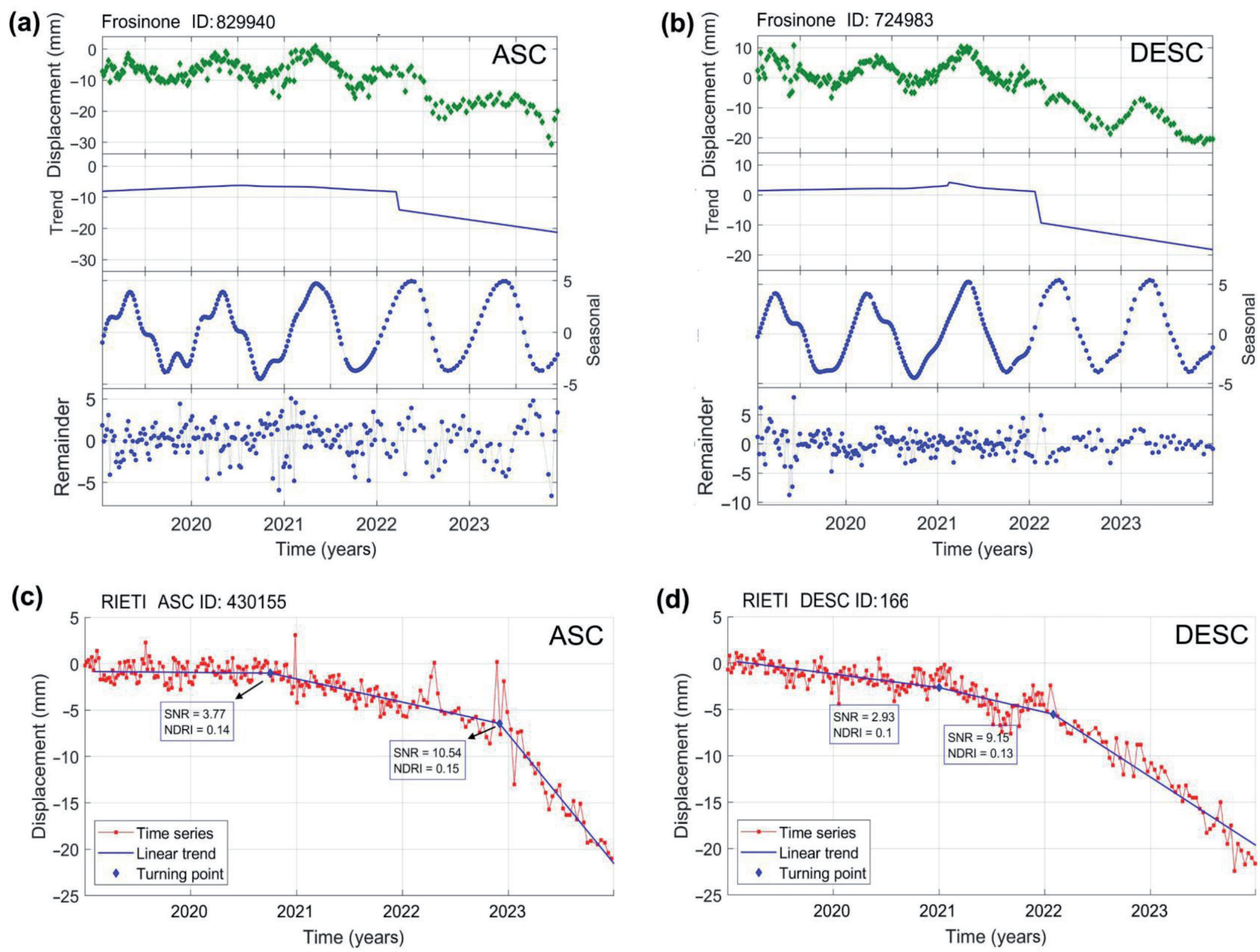

Fig. 8 - Examples of ascending (a) and descending (b) PS time series from AOI number 1450 and its decomposition using JUST algorithm (Ghaderpour, 2021). A significant negative Jump is observed in early 2022 within an AOI in the Frosinone province.) An example of a PS time series from ascending (c) and descending (d) geometry with two Turning Points in the province of Rieti from AOI 951, showing an acceleration of the process. Signal-to-Noise Ratio (SNR) and Normalized Difference Residual Index (NDRI) are also reported (see Ghaderpour et alii, 2024 for their definitions). The localization of the AOIs number 1450 and 951 is displayed in Figure 5

trend decomposition of the Frosinone time series, obtained using the JUST algorithm (Ghaderpour, 2021). In addition, the results of STPD applied to the Rieti PS time series are illustrated in Fig. 8c and 8d, where two distinct turning points are identified.

DISCUSSION

Today, InSAR techniques are confirmed as being among the most effective tools for the multitemporal monitoring of ground deformations, thanks to their ability to provide high-resolution information with millimetric precision. However, the evolution of satellite technologies has led to an exponential increase in the quantity of available data, making the development of semi-automatic methodological approaches necessary. These approaches must be capable of extracting signals useful for geohazard assessment within timeframes compatible with territorial planning needs, with a view to supporting risk assessment affecting structures, transport infrastructures, and service networks. In sinkhole risk analysis, a fundamental step is the creation of a cartographic inventory that is reliable, updated, and as complete as possible. Having a constantly updated sinkhole database represents, in fact, an essential tool for this type of analysis, as it allows for the integration of information on the localization of phenomena and the training of advanced susceptibility models, which contemplate spatial predictions and indicators on their evolution over time, as well as classifications regarding their genesis (Gutiérrez *et alii*, 2008). In this study, the analysis was based on an updated database of sinkholes already mapped and available in the literature and institutional archives, considering occurrences as point data. The approach utilized ancillary data, considering inventory and susceptibility products, with overlap and distance criteria, in order to guide the selection of areas on which to conduct in-depth studies and to assign a genetic attribution to the identified AOIs. The integration of InSAR data allowed for the identification of ground deformations, specifically lowering, across the entire region. As highlighted by recent studies in natural and anthropic contexts (Medici *et alii*, 2025; Tinagli *et alii*, 2025; Walczak *et alii*, 2025; Esposito *et alii*, 2021) identifying sudden collapse sinkholes remains a challenge due to the fast evolution linked to the brittle nature of the failure mechanism. Therefore, the proposed workflow acts as a regional screening tool aimed at identifying characteristic signals, such as subsidence rate change, *i.e.* turning points, or time-series ‘jumps’, that may indicate active subsurface processes (*e.g.*, suffusion or plastic deformation of the cavity roof). The detection of Js and TPs in the deformation time series highlights these non-linear behaviors. While a ‘Jump’ does not automatically imply an imminent collapse, it indicates a sudden variation in the displacement regime requiring verification. In addition, TPs in PS-InSAR displacement time series may indicate reactivation processes that can lead to sudden acceleration and eventual sinkhole formation; therefore, careful detection and monitoring of such events are crucial for mitigation and prevention. Currently, the proposed method acts as a methodological workflow to filter candidate areas from the entire regional territory to specific clusters, prioritizing AOIs for further direct investigations. In particular, the analysis of the time series (Figs. 6 and 8) suggests that the sudden variation in velocity over short time intervals is not an isolated phenomenon but may reflect the response of the aquifer-soil system to external stresses, such as intense rainfall or groundwater level variations due to intense pumping. Such processes can accelerate sub-surface erosion processes, bringing the system closer to collapse conditions. It is therefore fundamental to integrate satellite monitoring with the examination of pluviometric data and piezometric levels (when available) to discriminate between seasonal trends and signals of incipient structural instability. From a methodological perspective, this work stands in continuity with other literature experiences on the topic of landslides, for which knowledge and impact inventories are richer and more complete, aiming to provide a cognitive contribution to the study of sinking phenomena. In particular, the adopted approach serves as a tool for territorial monitoring and planning in deferred time. Such a database, in continuous evolution, contributes to constituting a dataset of potentially critical areas on which to conduct site-specific in-depth studies via geognostic and geophysical investigations, as well as serving as an orientation tool to define intervention priorities and for the allocation of economic resources aimed at risk mitigation. In terms of impact, although less frequent and widespread than landslides, sinkholes can generate both direct and indirect losses such as, respectively, harm to people and affected structures or infrastructures, or significant impacts from an economic and social point of view due to the temporary loss of functionality of infrastructures and services. The spatial convergence between sinkhole phenomena and discharge zones of water springs from large carbonate ridges poses relevant risk conditions for the aqueduct network and catchment plants, and by extension, to issues of drinking water supply.

REMARKS AND FUTURE PERSPECTIVES

This investigation highlights how fusing differential SAR interferometry (DInSAR) from the European Ground Motion Service (EGMS) with local hydrogeological frameworks provides a robust mechanism for tracking multitemporal ground stability. By bridging the gap between broad satellite datasets and site-specific geological conditions, the proposed methodology establishes a dynamic lens through which deformation processes across the Lazio region can be interpreted. The identification of 1,804 AOIs during the 2019–2023 interval, including 1,369 newly identified clusters, validates the strategic use of Sentinel-1 for persistent, wide-area surveillance. The mapping of New and Persistent AOIs reveals that these subsidence hotspots are not randomly distributed; rather, their spatial density in alluvial plains and hydrogeological discharge zones confirms that lithological composition and aquifer stress are the primary drivers of regional ground lowering. Moving beyond linear trend analysis, the adopted integration of TP and jump into time-series evaluation represents a significant diagnostic leap. These metrics proved capable of pinpointing abrupt rate fluctuations. Even when observed within presumably slow-onset processes, such shifts act as vital proxies or early signals for high-magnitude, localized failures, specifically cover-collapse sinkholes.

The workflow presented here serves as the frame for a more comprehensive, integrated regional monitoring architecture. Future phases of this research will lean on the higher resolution of COSMO-SkyMed data, paired with in-situ geophysical survey and real-time piezometric monitoring. Such granularity is required to successfully untangle cyclical seasonal noise from the true signals of incipient structural collapse.

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