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CORRELATION OF MULTIPLATFORM SAR-DATA FOR MULTITEMPORAL SLOPE INSTABILITY ANALYSIS: THE PAUPISI CASE STUDY (BENEVENTO PROVINCE, SOUTHERN ITALY)

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EXTENDED ABSTRACT

Le tecniche di telerilevamento, in particolare le tecniche di interferometria SAR differenziale avanzata (A-DInSAR) sono ampiamente utilizzate nello studio delle frane, specialmente per identificare e mappare nuovi processi deformativi e aggiornare, qualora siano disponibili, inventari dei fenomeni franosi. Queste tecniche si basano su stack di serie temporali (di lunghezza variabile da giorni a mesi) di immagini SAR (almeno 20 immagini) per una medesima stessa area. In tal modo, è possibile analizzare un determinato areale da un punto di vista delle deformazioni multitemporali e per differenti scale. Tra le tecniche A-DInSAR troviamo le procedure PSInSAR e ISBAS. La tecnica Persistent Scatterers InSAR (PSInSAR™; Ferretti *et alii*, 2001) studia l'informazione di fase su oggetti caratterizzati da un'elevata stabilità di coerenza nel tempo. L'Intermittent Small Baseline (ISBAS; Sowter *et alii*, 2013) si basa sull'approccio small baseline e si riferisce al metodo di formazione dell'interferogramma piuttosto che ai criteri di selezione dei pixel, considerando anche quelli a coerenza intermittente. A differenza della prima, inoltre, fornisce una maggiore copertura di dati in aree non-urbane (es. terreni agricoli, foreste, aree vegetate, ecc.).

La provincia di Benevento è una delle aree geologicamente più complesse dell'Appennino meridionale. Infatti, a causa del suo assetto litostrutturale e morfologico, è stata storicamente intensamente interessata da processi deformativi pluvioindotti e sismoindotti spesso responsabili del danneggiamento di strade principali e aree urbane.

Lo scopo di questo lavoro è definire lo stato di attività di frane a cinematica lenta che interessano alcune aree urbane della provincia di Benevento, mediante la combinazione di risultati derivanti da un'analisi multitemporale di dati interferometrici SAR derivati sia con tecnica PSInSAR che ISBAS. Tale metodologia, applicata a scala provinciale e di dettaglio (con risoluzione della griglia a terra 20×20 m) ha previsto tre fasi consequenziali: (i) approccio basato su griglia, per l'omogeneizzazione dei dati ERS 1&2 (1992-2000), ENVISAT (2002-2010) e RADARSAT (2003-2007) PS e Sentinel-1 (2017-2020) ISBAS; (ii) approccio multipiattaforma, per la definizione di mappe di velocità media ponderata (VWA) rispetto all'estensione dell'area con disponibilità del dato; (iii) approccio a matrice, per la definizione dello stato di attività, sulla base di classi di velocità definite a partire dalle mappe VWA. In particolare, sulla base delle mappe VWA con scala di rappresentazione omogenea, è stata identificata una soglia di attività (stimata pari a ± 3 mm/y), che ha permesso di discriminare, per ogni cella della griglia di analisi: i) aree stabili (velocità compresa tra ± 3 mm/y), ii) aree instabili (velocità maggiori di ± 3 mm/y), iii) aree caratterizzate dall'assenza del dato. A partire dalle classi discretizzate sulla base della soglia di attività, è stata condotta, a scala provinciale, un'analisi del dato interferometrico mediante matrici, sia a due che a tre fattori, per la definizione dello stato di attività dei fenomeni deformativi. Sono state, quindi, generate diverse mappe dello stato di attività della provincia di Benevento per l'intero arco temporale coperto dai dati ERS 1&2, ENVISAT e RADARSAT e Sentinel-1 (1992-2020), che ha portato all'individuazione di fenomeni deformativi al suolo nella forma di hotspot di potenziale movimento a scala di sito (o locale). Tra questi siti, di particolarmente interesse è l'hotspot ricadente nel comune di Paupisi (BN), a causa dei processi deformativi attualmente attivi che interessano aree edificate e alcune infrastrutture (ad esempio, la strada provinciale SP108). L'area è stata selezionata come caso studio per cui lo stato e la distribuzione di attività dei fenomeni franosi sono stati identificati mediante l'applicazione della suddetta metodologia di correlazione multipla del dato interferometrico. Successivamente, l'analisi di distribuzione dei PS e quella dei loro spostamenti in relazione alle precipitazioni hanno permesso una ricostruzione del trend deformativo dell'area.

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ABSTRACT

The Benevento Province (southern Italy) has been historically affected by soil erosion and ground deformation (i.e. landslides; REVELLINO *et alii*, 2019), as testified by documents and reports which describe damage scenario, social effects, surveys and measures carried out. REVELLINO *et alii* (2010) highlighted as the landslide index, defined as the ratio of areas affected by landslides over total areas, reaches up to 90%. Earth flows make up about 46% of these landslides, involving structurally complex geologic formations and often responsible for damaging human infrastructures (e.g. roads and service lines; GUERRIERO *et alii*, 2016; MARESCA *et alii*, 2022). As a result, the province has widespread problems in management of the landslide hazard, due to the activation (and reactivation) of phenomena connected to both rainfall and seismic events.

In order to reconstruct state of activity maps for the Benevento Province, a multitemporal analysis of multiplatform satellite data was carried out, with a resolution of cells of 20×20 m. In particular, PSInSAR (ERS 1&2 for the time-span 1992-2000, ENVISAT for 2002-2010, and RADARSAT for 2003-2007) and ISBAS data (Sentinel-1 for 2017-2020), were first treated by a grid-based approach to uniform the PS data and subsequently, by a multiplatform approach defining weighted average velocity (VWA) maps on the base of the extent of the area with data availability. Finally, a multiplatform activity-matrix approach allowed the definition of landslide activity maps based on a velocity threshold of ± 3 mm/y, derived by VWA maps. Specifically, velocity threshold allowed to discriminate for each cell of the analyzed area i) stable cells (velocities between ± 3 mm/y), ii) unstable cells (velocities greater than ± 3 mm/y), iii) cells with no data (unclassified).

The multiplatform activity-matrix approach at provincial scale was used to identify and analyze unstable area (hotspots), currently involved in active deformation processes. Among them, the Paupisi municipality (Benevento Province) was identified as critical for the involvement of built-up areas and infrastructures in landslide deformation processes. For that reason, Paupisi area was selected as study case and a detailed analysis of the PS distribution as well as reconstruction and evaluation of deformation trend were carried out. Finally, a relation between land deformation and rainfall events was also investigated.

KEYWORDS: *PSInSAR data, slow-moving landslide, remote sensing techniques, state of activity map*

INTRODUCTION

In some cases, slope instabilities are difficult to recognize by means of in-situ surveys, especially in hilly and mountainous areas, due to the scale of survey, the area accessibility, and the economic and time constraints. Such problems are experienced also in monitoring activities, essential for the understanding of the dynamic of the process, its ongoing evolution and designing mitigation measures. With the development of interferometric techniques (e.g. A-DInSAR) for the analysis of large image datasets and the possibility of integrating them into GIS environment, most of problems linked to the recognizing and monitoring of land deformation have been overcome. As a result, many authors have used A-DInSAR techniques for analysing the activity status of known landslides as well as updating landslide inventories, thought different data analysis methods. For example, FARINA *et alii* (2006) used an approach based on the combination of PS data, photointerpretation and optical imagery at regional scale, to recognize landslides, and at a local scale to monitor known slope movements. MEISINA *et alii* (2006, 2008) also used PS data at both regional and sub-regional scale, obtained by processing images from ERS 1&2 satellites, to identify unstable areas and update their activity status through a comparison with the existing maps. Validation was then conducted through photointerpretation. Starting form RIGHINI *et alii* (2008, 2011), the state of activity analysis of an area has been performed by applying matrices considering different types of input data. This approach presents the advantage of being able to scan large areas and identify unstable hotspots. Subsequently, BIANCHINI *et alii* (2012, 2013) introduced a key step in the matrix approach for landslide state of activity estimation, consisting in a definition of a deformation threshold based on the averaging of all velocity data available for an unstable area. The comparison between the average velocity and the established threshold is fundamental to distinguish “moving” from “non-moving” areas. However, the matrix development is based on the comparison of average velocity of a single PS dataset with a pre-existing landslide inventory. In the case of an information lack about past events in terms of their activity status, CIGNA *et alii* (2013) introduced a matrix that takes into account both historical and recent multi-platform PS datasets. OLIVEIRA *et alii* (2015) proposed a PSI-based matrix which combines field estimations of landslide state of activity and deformation results obtained through the application of the PSInSAR technique to TerraSAR-X data. It is worth noting that this approach requires to manage a large amount of data, derived from different techniques and therefore with significant differences between them. To overcome this limitation, BONÌ *et alii* (2018) developed the LAMBDA method. From an established deformation threshold, a code was used to distinguish three classes of activity (stable, unstable and unclassified) in the case of three different satellite datasets. These classes allow the Authors to define a multidimensional matrix, useful to estimate the landslide activity status, covering a period of 22 years.

All the above-mentioned studies used data derived from PSI techniques in the different matrices. In this work instead, a multiplatform activity-matrix approach is proposed using four different satellite data derived from PSInSAR and ISBAS techniques and covering a 30 year-interval (i.e. ERS 1 and 2 for the time-span 1992-2000, ENVISAT for 2002-2010, RADARSAT for 2003-2007 and Sentinel-1 for 2017-2020), to map the state of activity of slow-moving landslides affecting several urban areas of the Benevento Province (Campania, southern Italy). The analysis was carried out by using three sequential approaches: (i) a grid-based approach; (ii) a multi-platform approach; (iii) a state of activity-matrix approach.

Different matrices (2- and 3-factors) were developed on the base of a deformation threshold estimated through the analysis of weighted average velocity maps (VWA).

Results at provincial scale provide state of activity maps, whose comparison with the existing landslide inventory for the Benevento Province (Guadagno *et alii*, 2006), allowed to identify hotspots of land deformation interested by current activity. One of such area corresponds to the municipality of Paupisi, here selected as study case. In particular, average velocity and state of activity maps with a resolution of cells of 20×20 m, were produced for the case study to reconstruct its deformation history. A detailed analysis of the PS distribution and of the deformation trend were then carried out, as well as an analysis of the relation between land deformation and rainfall events.

DATA AND METHODS

For the Benevento Province landslide activity analysis, four multitemporal and multiplatform satellite datasets, derived from both PSInSAR and ISBAS techniques, were used. Considering their wide territorial coverage, just the data in ascending geometry were considered. In particular, PS data, available for different time-span are: i) ERS 1 & 2 (1992-2000), ii) ENVISAT (2002-2010) and iii) RADARSAT (2003-2007); while iv) Sentinel-1 data, elaborated by Terra Motion algorithm using ISBAS technique, are available for the time span 2017-2020. Available data cover then a 30 year-interval.

Starting from these data, the proposed method was performed at two different scale (provincial and local) considering three sequential phases (steps in Fig. 1): (i) grid-based approach; (ii) multiplatform approach; (iii) activity-matrix approach.

In the grid-based approach, a vector grid with a resolution of 20×20 m was generated using the open source software QGIS (V.3.16.3). PS and ISBAS data were homogenized on the base of such grids in the same vectorial format. Subsequently, a statistic analysis was executed on the ascending velocity along the LOS (Line of Sight) for each dataset estimating the mean deformation velocity. To avoid overestimation, deformation velocity was weighted on the area actually covered by the available data computing Weighted Average Velocity (VWA) maps. By the multiplatform approach, the resulted VWA maps were represented with a single-scale velocity representation, allowing a better multitemporal observation of the land deformation affecting the Benevento Province. Moreover, such representation enables to individually analyse and compare each other the VWA maps. A deformation threshold was then defined to distinguish moving from non-moving areas. Usually, for velocity along LOS, a value of ±2 mm/y is adopted as a representative velocity threshold (Colesanti & Wasowski, 2006). However, for the analysis of deformation evolution on urban areas and infrastructure, it is possible to increase up to ± 1 mm/y the established threshold as suggested by several authors (e.g. Nappo *et alii*, 2019).

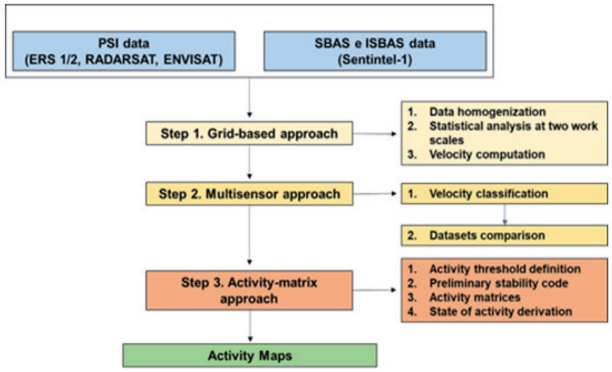
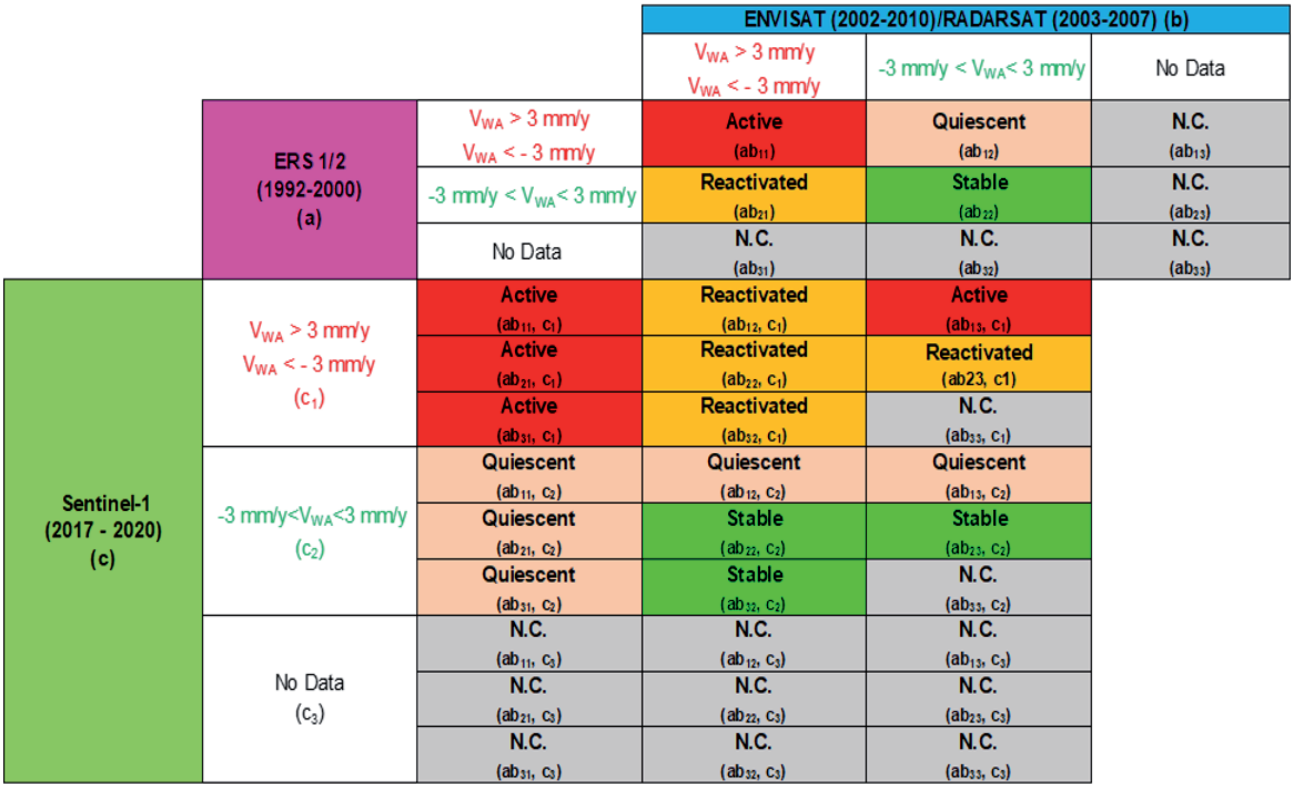


Fig. 1 - Synthetic flowchart of the proposed method

For this reason, by the VWA maps a deformation threshold of ± 3 mm/y was established, allowing to discriminate i) stable if the velocity range is ± 3 mm/y (code = '0'), ii) unstable when the velocity is <-3 or > 3 mm/y (code = '1') and iii) unclassified area (code = 'no data'), by executing a preliminary stability code. Cell discrimination is necessary to apply the activity matrix-based approach. In particular, in this phase four two-factor matrices were built by combining pairs of temporally consecutive satellite data (e.g. ERS-ENVISAT data), obtaining four activity maps. Although such step already provides potential hotspots at provincial scale, 2- and 3-factor matrices were also processed in order to achieve a complete deformation overview of the area. Due to the temporal overlap of the ENVISAT (2002-2010) and RADARSAT (2003-2007) data, the two matrices were performed including ENVISAT or RADARSAT as central data. Assuming therefore that ERS=A, ENVISAT (or RADARSAT)=B and Sentinel-1=C, and always considering the classifications of the individual datasets in '0', '1' and 'No data' (ND), the matrix of activity status was constructed for each cell (Fig. 2). Activity states were defined following the simplification of the Multilingual Landslide Glossary (WP/WLI 1993) as reported by Bonì *et alii* (2018):

- active: currently moving;
- reactivated: in motion after having been inactive;
- quiescent: inactive, but potentially reactivated;
- stable: no longer affected by the original causes through natural or artificial stabilisation;
- not classified: there is insufficient information to define the current state of activity.



		ENVISAT (2002-2010)/RADARSAT (2003-2007) (b)		
		$V_{WA} > 3$ mm/y $V_{WA} < -3$ mm/y	-3 mm/y $< V_{WA} < 3$ mm/y	No Data
ERS 1/2 (1992-2000) (a)	$V_{WA} > 3$ mm/y $V_{WA} < -3$ mm/y	**Active** (ab$_{11}$)	**Quiescent** (ab$_{12}$)	**N.C.** (ab$_{13}$)
	-3 mm/y $< V_{WA} < 3$ mm/y	**Reactivated** (ab$_{21}$)	**Stable** (ab$_{22}$)	**N.C.** (ab$_{23}$)
	No Data	**N.C.** (ab$_{31}$)	**N.C.** (ab$_{32}$)	**N.C.** (ab$_{33}$)

Sentinel-1 (2017 - 2020) (c)	$V_{WA} > 3$ mm/y $V_{WA} < -3$ mm/y (c_1)	**Active** (ab$_{11}$, c$_1$)	**Reactivated** (ab$_{12}$, c$_1$)	**Active** (ab$_{13}$, c$_1$)
		Active (ab$_{21}$, c$_1$)	**Reactivated** (ab$_{22}$, c$_1$)	**Reactivated** (ab23, c1)
		Active (ab$_{31}$, c$_1$)	**Reactivated** (ab$_{32}$, c$_1$)	**N.C.** (ab$_{33}$, c$_1$)
	-3 mm/y$<V_{WA}<3$ mm/y (c_2)	**Quiescent** (ab$_{11}$, c$_2$)	**Quiescent** (ab$_{12}$, c$_2$)	**Quiescent** (ab$_{13}$, c$_2$)
		Quiescent (ab$_{21}$, c$_2$)	**Stable** (ab$_{22}$, c$_2$)	**Stable** (ab$_{23}$, c$_2$)
		Quiescent (ab$_{31}$, c$_2$)	**Stable** (ab$_{32}$, c$_2$)	**N.C.** (ab$_{33}$, c$_2$)
	No Data (c_3)	**N.C.** (ab$_{11}$, c$_3$)	**N.C.** (ab$_{12}$, c$_3$)	**N.C.** (ab$_{13}$, c$_3$)
		N.C. (ab$_{21}$, c$_3$)	**N.C.** (ab$_{22}$, c$_3$)	**N.C.** (ab$_{23}$, c$_3$)
		N.C. (ab$_{31}$, c$_3$)	**N.C.** (ab$_{32}$, c$_3$)	**N.C.** (ab$_{33}$, c$_3$)

Fig. 2 - Multiplatform Activity Matrix processed from ERS (1992-2000), ENVISAT (2002-2010) /RADARSAT (2003-2007) and Sentinel-1 (2017-2020) data (modified from Bonì *et alii, 2018)*

Two maps of activity status for the entire time-span considered (1992-2020) were thus generated.

The examination of VWA and state of activity maps and their comparison with the already existing landslide database of the Benevento Province (Guadagno *et alii*, 2006), has allowed to identify specific hotspots interested by currently deformation processes, paying particular attention on the built-up areas and infrastructures. Among such area, the significant case study of Paupisi Municipality was recognized. For this site, a detailed analysis was carried out. The average velocity, obtained using the statistical mean value, and state of activity maps were then examined to reconstruct the deformation history of this case study.

The PS distribution was also analysed. In this step, some representative PSs were selected and used for the examination of the ground deformation trend. Also, a correlation between the displacement (mm) of each PS and the monthly precipitation (mm) for the corresponding time-span was conducted. Finally, results were compared to the landslide map for the Benevento Province (Guadagno *et alii*, 2006) and literature results (Guerriero *et alii*, 2019).

The rainfall data used were derived from four rain gauges located in Paupisi Municipality and in surrounding areas (i.e., Paupisi, Telese, Solopaca, and Torrecuso rain gauges).

PAUPISI CASE STUDY

Geological and geomorphological setting

The municipality of Paupisi includes the northern slope of the Taburno-Camposauro Massif up to the alluvial plain of the Calore River to the north. The geological setting is characterised by the presence of a Mesozoic limestone and dolomite ridge, on which the town of Paupisi is partially built. The limestone slopes are covered by fossil talus and soil alteration deposits, intersected with palaeosoils and pyroclastic materials deposited by the eruptions of Somma-Vesuvius (Grelle *et alii*, 2019). The successions outcropping belong to the Matese-Taburno-Camposauro Unit and the San Giorgio Formation of the Fortore Tectonic Unit, which are covered by slope, eluvial and colluvial deposits. In terms of lithotechnical characterisation, the urban area is located in the outcrop zone of i) fractured limestone successions, ii) uncemented detrital successions and iii) clayey-marly successions (Fig. 3). This sector corresponds to slopes with medium steepness (slope between 15 and 30%), affected by erosive phenomena due to runoff (Donnarumma *et alii*, 2013).

The geomorphological context is therefore strongly influenced by the lithological conditions, together with the hydrographic setting. The effects of this combination can be seen in the instabilities that affect the built-up area and related infrastructures (such as the provincial road SP108). Such instabilities can be attributed to an articulated, translational movement with conspicuous plastic deformations detectable in the surrounding areas.

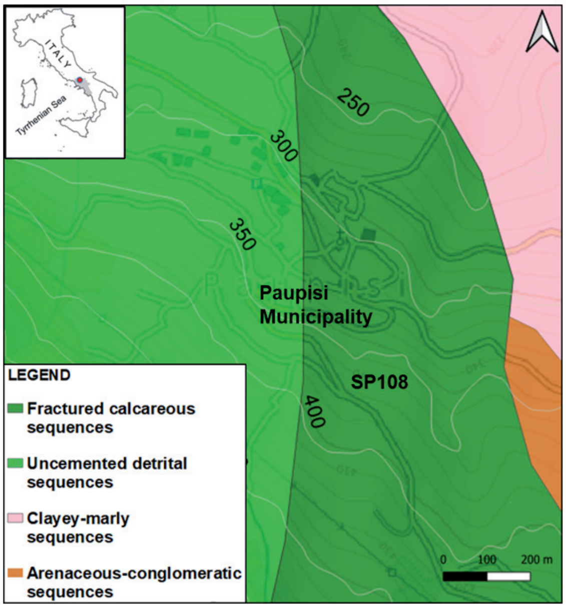


Fig. 3 - Extract of the litho-technical sequences map of the Province of Benevento (modified from Revellino *et alii, 2010) for Paupisi*

Average velocity maps

The average velocity maps (resolution of cells 20×20 m; Fig. 4) show that the deformation process was already underway in the 1992-2000 time span (ERS data) and was particularly concentrated in the northern part of the municipality, below the SP108 provincial road (Fig. 4a). Two distinct deformation zones are evident: the first along the central part of the built-up area with deformation rates mainly from -3 to -5 mm/y; the second in the northern part of the built-up area with a greater deformation rates (from -5 to -15 mm/y).

From 2002 to 2010 (ENVISAT and RADARSAT data) an expansion and retrogression of the deformation and an acceleration of the movement in the central area are recognized (Fig. 4b, c). In particular, ENVISAT dataset (Fig. 4b) shows the presence of movements in the south-western part of the settlement, with deformation rates from -3 to -5 mm/y. In proximity of the two areas highlighted by the ERS dataset, ENVISAT data show a single unstable area with deformation values ranging from -5 to -15 mm/y. Probably, from 2002 to 2010, the deformation process underwent stresses that caused an acceleration, as well as a general expansion and a retrogression of the source area. The RADARSAT average velocity map (Fig. 4c), which partially covers the ENVISAT dataset area, shows a lateral expansion of the area affected by the landslide movement with a higher deformation rate (from -5 to -10 mm/y), in the northern part of the built-up area. Conversely, the upper part of the built-up area shows deformation rates of up to -10 mm/y and greater lateral expansions.

The Sentinel-1 data produced with the ISBAS technique (2017-2020) show a greater extension of the movement (Fig. 4d), if compared to previous data, with higher deformation rates (mainly from -5 to -15 mm/y) in the central-northern sector of the settlements, suggesting a progression and expansion of the deformation process. Only a part of the central-southern area of the Paupisi Municipality shows low deformation rates (from -3 to -5 mm/y). This aspect, together with the extension of the movement towards the southern part of the settlement, suggests a progression of the deformation process.

State of activity maps from 2-factor matrices analysis

The state of activity maps (Fig. 5) derived by the 2-factor matrices, allows to observe the deformation of the study area through pairs of satellite data and consecutive time-spans.

The ERS-RADARSAT map (1992-2007; Fig. 5a) shows a continuous movement in the central sector of the built-up area, parallel to a section of the SP108. Such an area can be classified as active, while the central-southern area of the settlement, as reactivated. This suggests that in the period from 2003 to 2007, the deformation process also involved that portion of the territory, thus undergoing a retrogression with respect to the 1992-2000 period. The ERS-ENVISAT map (1992-2010; Fig. 5b) confirms what observed with the previous satellite data pair. However, a greater extension of both the area classified as active, towards the northern part of the built-up area, and reactivated, towards the upper part of the latter, could be observed. This is consistent with retrogression and expansion processes of the deformation. Comparison with landslide databases (Guadagno *et alii*, 2006 and Guerriero *et alii*, 2019) of both state of activity maps, reveals correspondence, in particular, for landslide n.4 (Guerriero *et alii*, 2019) and the left flank area of landslide no.1 (Guadagno *et alii*, 2006). In addition, the ERS-RADARSAT map shows active areas corresponding to the source area of landslide n.2 (Guadagno *et alii*, 2006) and the accumulation zone of landslide no.3 (Guerriero *et alii*, 2019).

In the RADARSAT-Sentinel-1 map (2003-2020; Fig. 5c), the active area is larger and wider than the ERS-RADARSAT pair. Furthermore, the previously-named reactivated area are now classified as active; this implies a continuity of the deformation process in the period from 2003 to 2020. Another aspect to note is that part of the southern area and of the north-western area of the settlement, are in a quiescent state (for the period 1992-2003 the lack of PS ERS data has generated cells defined as Not Classified - N.C.).

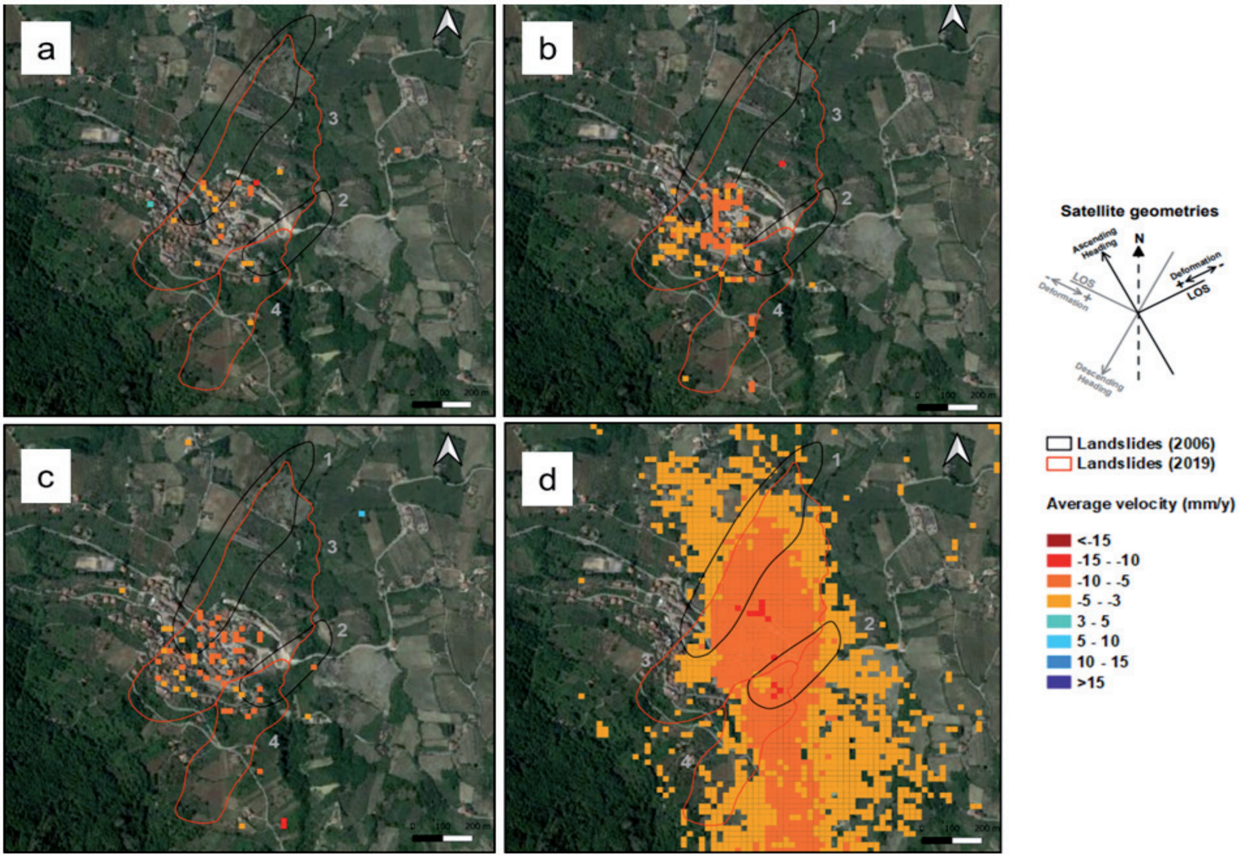


Fig. 4 - Average velocity maps (resolution cells 20×20) for Paupisi Municipality: a) ERS; b) ENVISAT; c) RADARSAT; d) Sentinel-1

The ENVISAT-Sentinel-1 map (2002-2020; fig. 5d) also reveals an expansion of the active area from the southern to the northern part of the settlement. In particular, with respect to the ERS-ENVISAT map, some areas that were previously classified as reactivated are active, confirming a continuity of the deformation process over the time-span considered.

The southern area of the built-up area is instead quiescent, indicating a stability if compared to the ENVISAT dataset (2002-2010). Once again, this area was not highlighted by the ERS dataset due to a lack of data and is therefore N.C..

With respect to the landslide map inventories, for both state of activity maps including Sentinel-1 data (Fig. 5c, d), the active area is mostly located between and above the boundaries of the landslide n.1 and n.2 (Guadagno *et alii*, 2006). In particular, there is correspondence with a part of the left flank of landslide n.1 and of the source area of landslide n. 2. A positive match for the central part of landslide n.3 and the accumulation zone of landslide n.4 (Guerriero *et alii*, 2019) is recognized. However, the presence of the area classified as stable and quiescent and the concentration of the active area below the source area of landslide n.3 could suggest a progression of the latter. Finally, given the distribution of the active area, it could be said that the deformation process expanded in recent years compared to previous decades.

State of activity maps from 3-factor matrices analysis

In order to get a broader view of the deformation state of the Paupisi, two 3-factor matrix maps are shown in Figure 6, thus covering a time span from 1992 to 2020 (ERS 1/2, ENVISAT/RADARSAT, and Sentinel-1). Both maps show a continuity in the deformation process during the time in the central built-up area, up to the northern area. The involvement of a large part of the provincial road SP108 is also visible. In particular, for the map including the RADARSAT dataset (Fig. 6a), the area classified as active is distributed mainly in the central-northern part of the built-up area and in a confined portion of the aforementioned provincial road. Only a few areas are reactivated, which indicates the presence of movement in the period 2017-2020. The upper part of the Paupisi Municipality is both stable and quiescent.

In the map including the ENVISAT dataset (Fig. 6b), the active area has the same distribution of the RADARSAT map, but a higher coverage density. The reactivated areas are

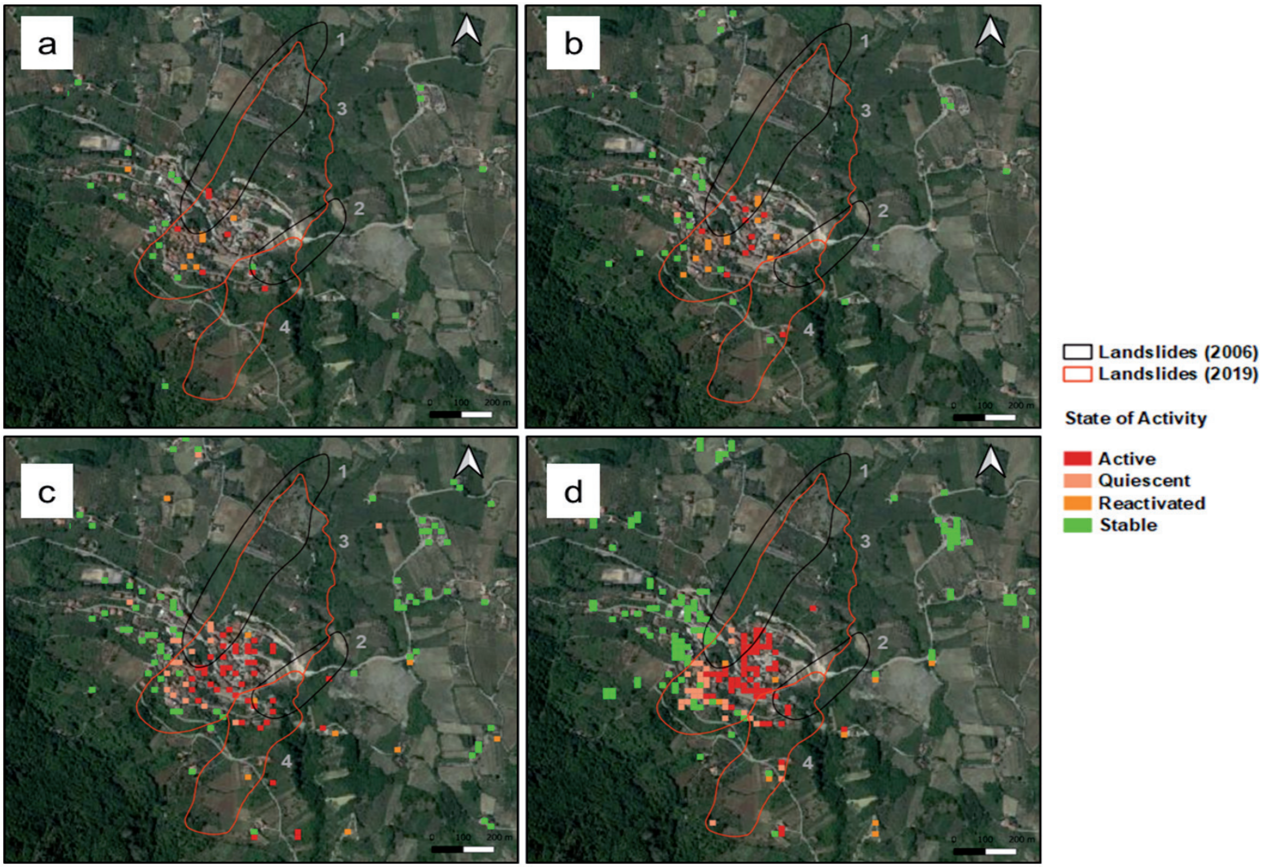


Fig. 5 - State of activity maps from 2-factor matrices analysis: a) ERS-RADARSAT; b) ERS-ENVISAT; c) RADARSAT-Sentinel-1; d) ENVISAT-Sentinel-1

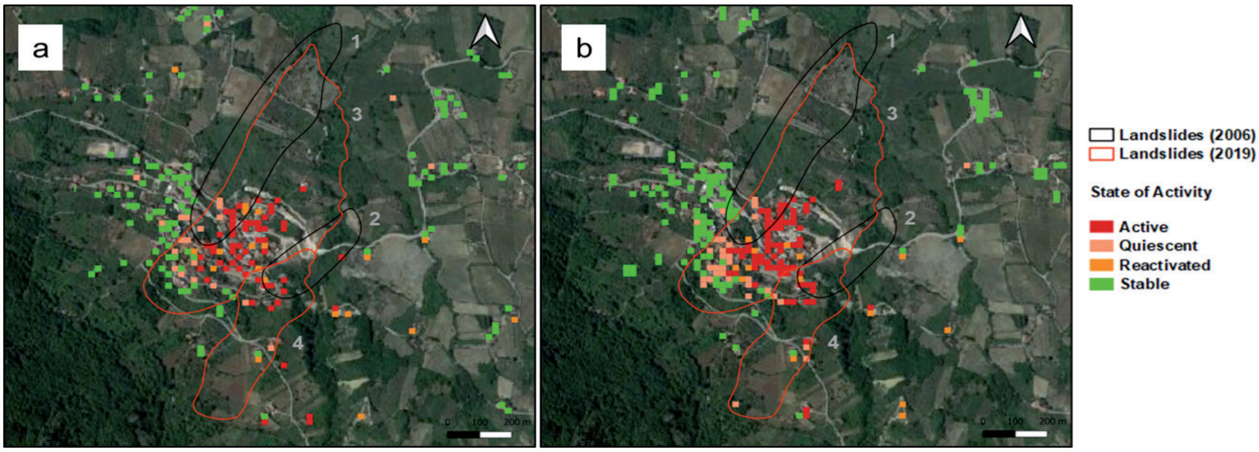


Fig. 6 - State of activity maps from 3-factor matrices analysis: a) ERS-RADARSAT-Sentinel-1; b) ERS-ENVISAT-Sentinel-1

reduced, while the upper part of the built-up area is again stable and quiescent. This could indicate a progression of the source area in the deformation process over the last two decades.

In relation to the landslides mapped by Guadagno *et alii* (2006), it should be emphasised once again that the boundaries of these ones only show a small part of the movement that has occurred. On the contrary, there is correspondence with landslide body n. 3 (Guerriero *et alii*, 2019), except for the source area. There is also a further positive match with the accumulation area of landslide n.3.

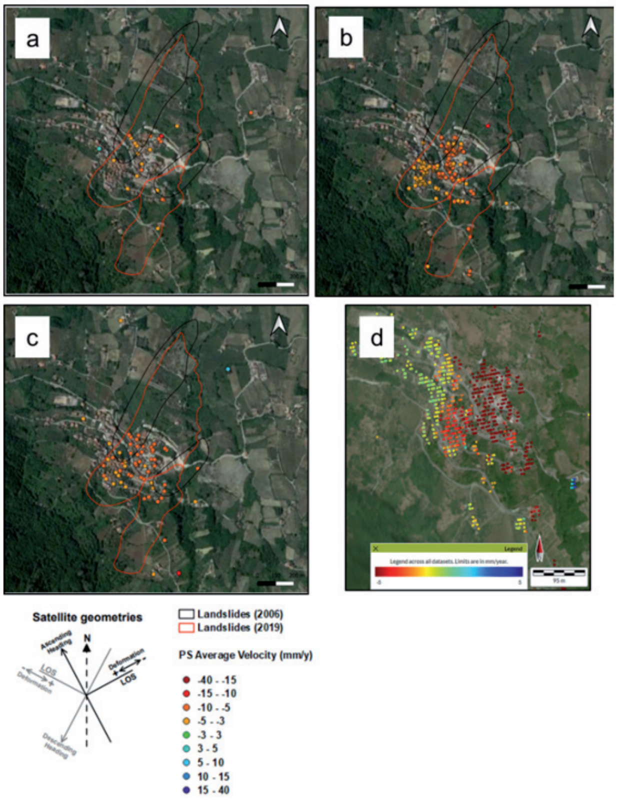


Fig. 7 - PS data distribution on Paupisi area

Analysis of PS distribution and deformation trend

The considered PS datasets (Fig. 7) shows homogeneity of spatial distribution over time, confirming evidence of movement in the area throughout the considered time span (1992-2020). PSs of the ERS dataset (Fig. 7a), show that ground deformation are particularly concentrated in the northern sector of the built-up area, below the provincial road SP108; few PSs are instead in the southern sector, above the aforementioned road. Most of these PS are characterised by a velocity from -3 to -5 mm/y and only a few from -5 to -10 mm/y. Consequently, it can be said that the deformation process was already active in the reference time span for the ERS 1 & 2 satellite sensor (1992-2000).

PSs of the ENVISAT dataset are homogeneously distributed over the entire built-up area and present a greater spatial coverage and a higher deformation rate (from -5 to -10 mm/y; Fig. 7b). This indicates an acceleration of the movement affecting the municipality of Paupisi in the time span considered (2002-2010) with respect to the ERS time-span. Also, for the RADARSAT PSs, the distribution is uniform over the entire built-up area (Fig. 7c). The deformation rates equals that of ENVISAT in terms of range, in particular for the central-northern sector. The acceleration of the deformation process is confirmed with respect to the displacements measured by ERS dataset.

The Sentinel-1 data, available for the period 2015-2020, confirm the presence of a ground deformation (i.e. landslides) that affects the entire built-up area. In particular, the south-western part of the Paupisi Municipality, above the provincial road SP 108, interfaces with deformation rates between -3 and -5 mm/y, while the northern part is characterised by a velocity range of -5 to -10 mm/y. This is consistent with that observed by the RADARSAT and ENVISAT data, thus suggesting that the development of the deformation process has remained constant over the last 20 years.

In order to get a more precise idea of the evolution of the deformation trend over time, four PS representative of the deformation process were selected (one per dataset) in the central sector of the Paupisi Municipality. Their deformation trend presents values between -30 and -40 mm for each dataset considered, thus constant over the entire observation period (1992-2020), from which is recognizable a seasonal pattern. Increase of displacement can be traced mainly to precipitation occurring from January to April and secondarily, from September to December, as confirmed by the correlation between absolute displacement values and the rainfall (in form of daily and cumulative; Fig. 8). A time-lag of the deformation of about four months respect to the rainfall can be observable. It is perfectly consistent with the slow-moving cinematics of such landslides.

Table 1 shows good correlation coefficients and the R2 for the relationship between displacement and rainfall. The lower values are for the RADARSAT PS data probably due to the variable displacement trend over the time span considered (2003-2007).

PS	Cumulative Rainfall - Absolute Displacement Correlation Coefficient	Progressive Cumulative Rainfall (time lag= 4 months) - Absolute Displacement R^2 Factor
ERS	0.90	0.83
ENVISAT	0.89	0.78
RADARSAT	0.49	0.24
Sentinel-1	0.98	0.94

Tab. 1 - Correlation Coefficient and R2 factor between cumulative rainfall and displacement for each selected PS

CONCLUSION

Benevento province experiences with several slow-moving earth flow involving human infrastructures (e.g. roads and railroads) and for which different monitoring activities have been conducted over the years (e.g. *Guerriero et alii*, 2017; *Maresca et alii*, 2020). An accurate identification and monitoring of the landslide activity is crucial in designing mitigation measures. In order to identify new potential hotspot and to define the state of activity of recognized processes, in this study a multitemporal analysis of multiplatform satellite data was carried out.

The analysis was performed for the municipality of Paupisi showing a complex deformation history, characterised by

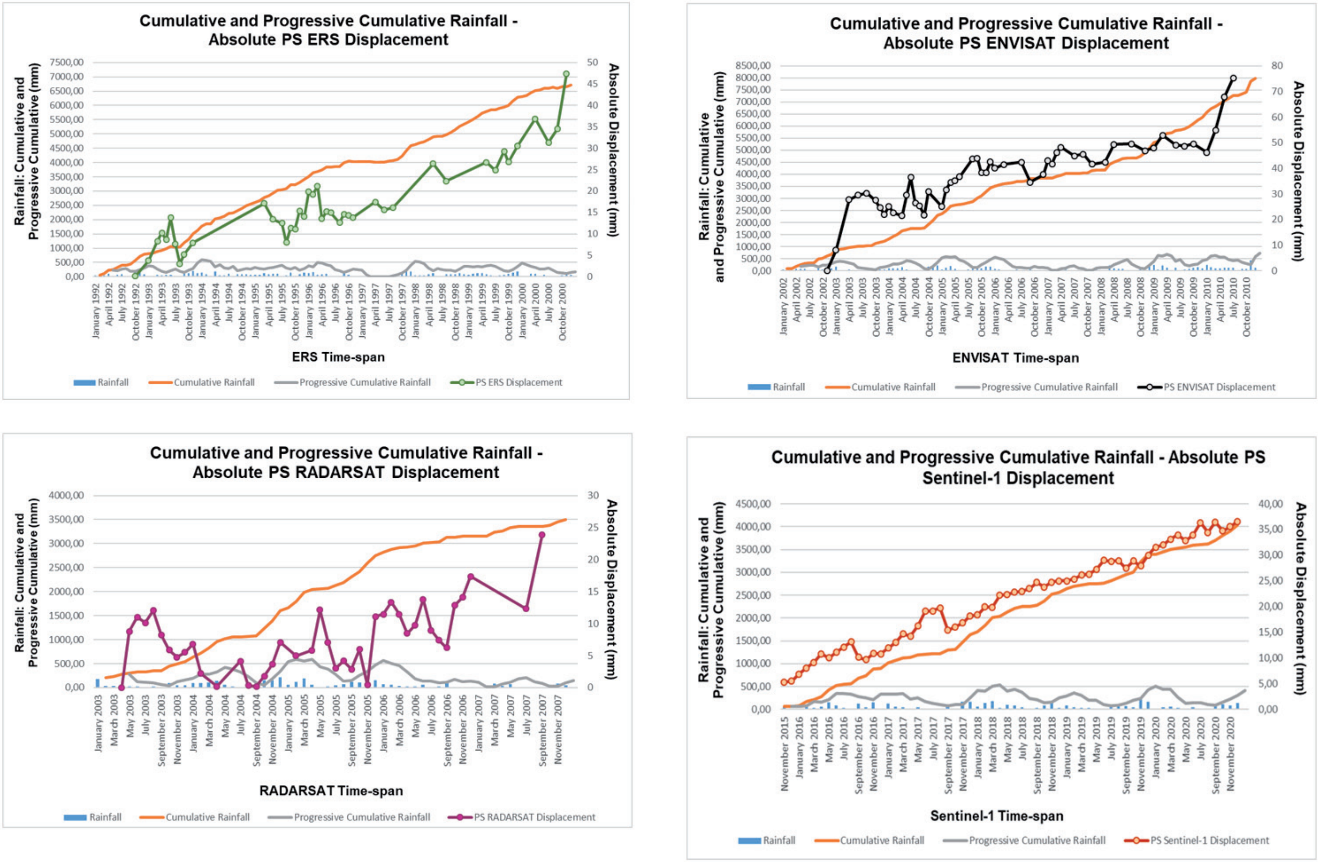


Fig. 8 - Charts showing the displacement in absolute values of the four PS in relation to cumulative and cumulative progressive rainfall, with a time lag of 4 months

evidence of movement throughout the time-span considered. The deformation process presents a generally homogeneous spatial distribution, concentrated mainly in the central area of the built-up area. However, it underwent initial phases of expansion and retrogression (2002-2010), the latter coinciding with the source area of landslide n.3 mapped by *Guerriero et alii* (2019). Subsequently, in the 2015-2020 time-span, a progressive phase occurred that probably brought the deformation initiation zone back to the same altitude as shown by the movement detected by the ERS dataset (1992-2000).

The methodology applied demonstrates how the availability of multi-temporal satellite data allows interpretation at different spatial scale. The results achieved can be conceived as proper management tool for the assessment of slow-moving landslides, enabling the study of deformation processes, in terms of both state and distribution of activity.

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