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SCIENCE

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A revised landslide inventory of the Calabria Region (Italy)

Giuseppe Cianflone [a], Salvatore Larosa [b], Lisa Beccaro [c], Antonio Viscomi [a], Cristiano Tolomei [c], Giovanna Chiodo[d], Tiziana La Pietra[d], Sergio Leonetti[d], Luigi Mollica[d], Annamaria Pellegrino[e], Antonio Servidio[d], Salvatore Siviglia[d], Gianpietro Imbrogno [a], Fabio Ietto [a] and Rocco Dominici [a]

[a]Department of Biology, Ecology and Earth Sciences, University of Calabria, Arcavacata di Rende, Italy; [b]National Research Council of Italy, Institute of Methodologies for Environmental Analysis (CNR-IMAA), Tito Scalo, Italy; [c]National Earthquake Center, Istituto Nazionale di Geofisica e Vulcanologia, Rome, Italy; [d]Regione Calabria, Catanzaro, Italy; [e]Autorità di Bacino Distretto Appennino Meridionale, Sede Operativa Territoriale Calabria, Catanzaro, Italy

ABSTRACT
The Calabria region is prone to widespread landslides due to its unique geological and climatic conditions. Landslide risk is crucial for spatial planning, making an updated inventory essential. A revised landslide inventory for Calabria (CaLal) was created by processing previous inventories and new mapping, supported by local field surveys and A-InSAR Sentinel-1 data. The results were compiled in an atlas with four maps, featuring 16913 landslides, categorized as follows: 8081 slides, 5166 diffuse instability areas, 2065 complex landslides, 965 flows, 352 areas affected by erosion, 234 falls/topples, and 50 deep-seated gravitational slope deformations. Of the total, 9253 are active, and 760 are dormant/suspended. Additionally, a WebGIS platform was developed for quick visualization and continuous updating of the landslide inventor.

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Landslide; WebGIS; InSAR; persistent scatterer interferometry (PSI)

1. Introduction

Land-use planning is closely related to landslide hazards and risk assessment in disaster-prone areas, where landslides can cause serious injuries and often result in environmental and economic damage (Haque et al., 2016; Ietto et al., 2014; 2022). Landslide susceptibility and hazard maps are an important tool for mitigating and predicting natural disasters at both local and global scale (e.g. Bathrellos et al., 2024; Wilde et al., 2018; Youssef et al., 2024).

Landslides occur frequently throughout Italy and are mainly related to the climatic and geological conditions of the country (e.g. Guzzetti, 2000; Salvati et al., 2010; Solari et al., 2020). In addition, instability events in Italy are often associated with inappropriate land use. In the Calabria Region, southern Italy (Figure 1), instability events occur frequently, causing significant damage to urban areas and infrastructure and posing a serious threat to the population and economic activity (Cianflone et al., 2021; Filice et al., 2022; Ietto et al., 2022, 2023). Landslide hazard assessment is therefore an important tool for risk management, public safety and the implementation of engineering projects. Consequently, the creation of detailed landslide maps is a helpful tool for the proper use of the territory. For proper land use planning and management, an updated inventory of landslides at various scales, from local to regional scale (e.g. Conforti et al., 2013; Fusco et al., 2023; Guerrero et al., 2012; Lazzari et al., 2018; Lazzari & Gioia, 2015; Santangelo et al., 2014; Şandric & Chitu, 2009), supported also by InSAR data (e.g. Guerriero et al., 2019; Raspini et al., 2015), can be a valuable resource. In the Calabria region, the instrument used to manage the territory in terms of hydrogeological risks is the Hydrogeological Regulatory Plan, better known as 'PAI' (Piano stralcio di Assetto Idrogeologico). The latter became law in 2001 (Resolution of the Council of the Calabria Region no. 115 of 28/12/2001, Legislative Decree 180/1998 of the Italian Parliament and subsequent amendments) and its main purpose was to map and regulate the areas affected by landslides and/or hydraulic risks. Until 2011, landslide mapping and relative risk conditions were updated only in relation to the areas where public administrations had implemented mitigation and risk reclassification measures.

In 2016, the Regional Basin Authority (ABR) identified the need for a PAI update. The result was a new database called 'PAI2016', which was published but not adopted by the local authorities. For a further update of the database, the ABR signed an agreement with the Department of Biology, Ecology and Earth Sciences of the University of Calabria in 2019.

CONTACT Salvatore Larosa salvatore-larosa@cnr.it National Research Council of Italy, Institute of Methodologies for Environmental Analysis (CNR-IMAA), 85050, Tito Scalo (PZ), Italy

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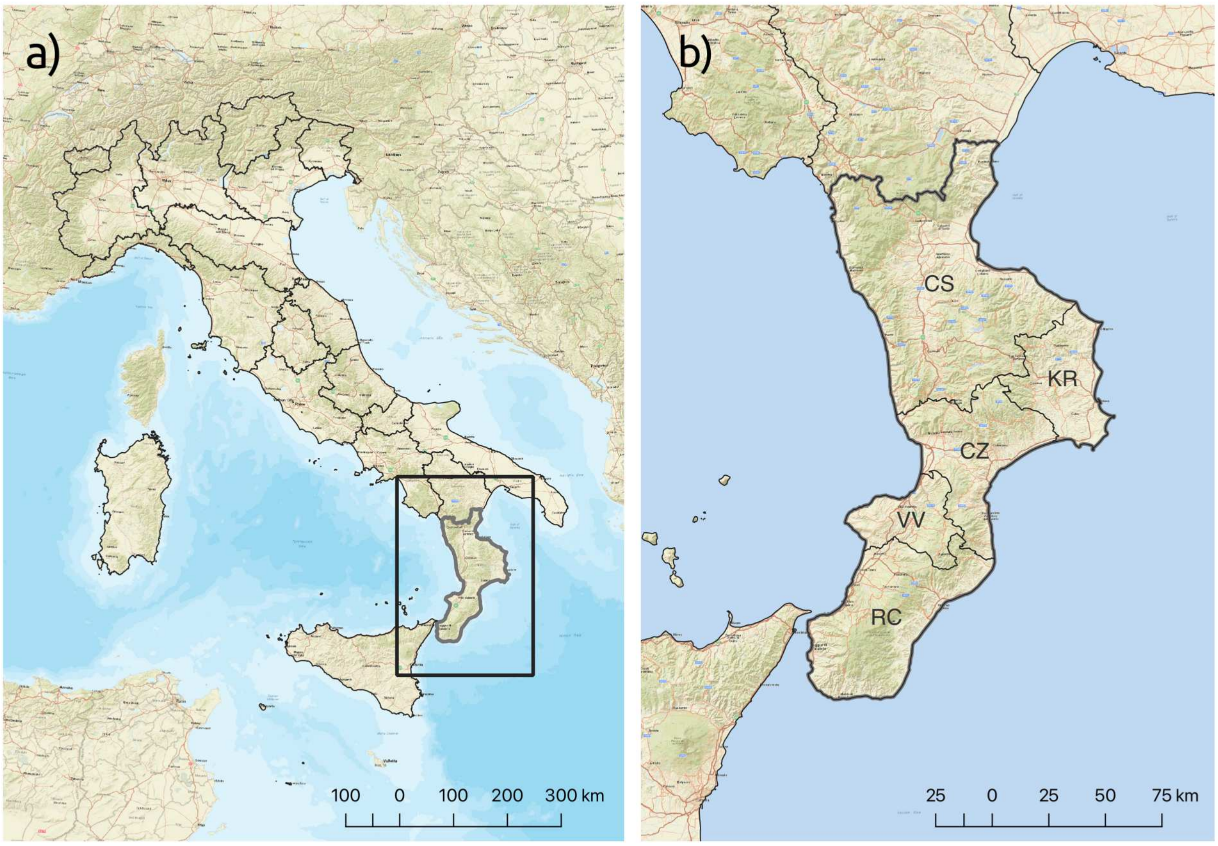

Figure 1. In a) a general map showing the area study and b) a detailed map showing the Calabria Region Provinces (CS = Cosenza; KR = Crotone; CZ = Catanzaro; VV = Vibo Valentia; RC = Reggio Calabria).

Our update consisted of creating an 'archive' inventory (sensu Guzzetti et al., 2012) starting from the 2011 and 2016 PAI and including a new landslide mapping based on literature data (mainly other available landslide databases) and a new field survey. The 2011 PAI and subsequent database integration were levelled; therefore, landslide geometries were redefined and a new 'archive' inventory called Calabria Landslides Inventory 'CaLaI' was created. This is not a traditional geomorphological mapping that contains information on the spatial characteristics (dimensions, slope, curvature, relief) of landforms (morphometry) (Dramis et al., 2011), but a valuable tool for territorial management that shows the distribution of landslides at a regional scale. The main objective of this paper is to provide an updated landslide inventory for the Calabria Region, useful for hazard analysis. Moreover, the use of a WebGIS will allow a continuous update of the inventory.

2. Materials and methods

2.1. Landslides archive inventory

The new inventory of the landslides archive (CaLaI) was created based on the 'PAI2016' archive (approved by an institutional committee appointed by the Calabria Region), which was never adopted.

Automatic GIS procedures, which also included information on the PAI2011 archive of origin, were used to transpose the information collected in PAI 2016 on each landslide. The conversion was based on the analysis of paper and digital archives to identify the source data for each landslide recorded (e.g. the institution or specialist who mapped the landslide). The result of this first step is a landslide archive called 'revised PAI2016', which includes 15714 landslides coming from three previous databases: PAI2001, Inventario dei Fenomeni Franosi in Italia (IFFI2006) and the new PAI2011 (update of PAI 2001) (Table 1).

The 'revised PAI2016' was analysed in detail with regard to the database content and the correct geometries of the shapefile polygons. The analysis of the database content was based on various documents available at the Calabria Region office, as follows:

- SAP2011 forms submitted by the municipalities containing landslide risk (related to phenomena not mapped in PAI);
- Urgent Work Plan 2010 of the Calabria Region;
- MDB file of the IFFI (Italian Register of Landslides);

Table 1. Databases included in revised PAI2016.

Database	Landslides number	Landslide surface (km^2)
PAI 201 (source)	8968	~700
IFFI 2006	9997	~883
PAI update 2011	9009	~703
PAI 2016	15714	~890

- General plan for soil protection works 1st phase (OCPM [Decree of the President of the Council of Ministers] 3741/2009);
- Detailed studies of the OPCM 2002/2014 carried out by civil protection competence centres;
- Map of landslides attached to the structural plan of the municipality;
- Database of the risk forecasting and prevention programme of the provinces of Cosenza and Reggio Calabria;
- Landslide consolidation projects, field survey reports and other similar documents available at the Calabria Region Office.

The review of the 'revised PAI2016' database made it possible to identify and correct numerous (about 35,000) and diverse errors. The main errors identified consisted of the following:

- Copy of landslides identification (ID and/or acronym);
- Polygons without identification (ID and/or acronym);
- alphanumeric strings associated with different polygons;
- Reuse of acronyms assigned to the original 'PAI2001' landslides that are not present in the revised database (e.g. a landslide body contained in a larger one). In order to preserve the database, the chronology of reused acronyms were modified;
- Syntax error in the relative table of attributes;
- non-unique compilation of the attribute table fields;
- topological errors (e.g. overlapping polygons).

The last step in the creation of the CaLaI landslide archive was to complete the 'revised PAI2016' database. The addition of new landslides was mainly based on the consultation of the previous databases (Table 2):

1. IFFI-ISPRA (agreement IFFI1);
2. The non – official database 'PAI Road 2001', which contains landslides along the main road networks mapped by photo-interpretation;
3. Detailed surveys on the northern side of the Ionian Sea and the southern side of the Tyrrhenian Sea (Agreement IFFI 2, 2006);
4. The field surveys were mainly carried out in correspondence with the municipalities that informed the Calabria Region Office of a landslide risk.

Table 2. Databases included in CaLaI.

Database	Landslides number	Landslide surface (km^2)
PAI 2001 (source)	8968	~700
IFFI 2006	9997	~883
PAI update 2011	9009	~703
PAI 2016	15714	~890
CaLaI	16913	~1130

For the landslides included in IFFI and 'PAI Strade 2001', the database field 'danger' was not filled in, as this is a large-scale landslide mapping.

For landslides contained in several databases, the most recent data were selected. All landslides were adjusted to a topographic map of the CTR (Regional Technical Map) at a scale of 1:5000 using aerial photographs.

2.2. Database architecture

The database consists of the following 5 fields: Municipality, Type, Code, Activity and Data Source. For each landslide, the field 'Municipality' is specified, which contains the municipality in which the landslide occurred.

The 'Type' field, which indicates the classification of the landslide mechanism. The latter includes the following types according to the original 'PAI2001' guide and the classification scheme of Cruden and Varnes (1996): Landslide, Earth flow, Rapid earth flow, Debris flow, Complex, Rock fall, Deep-seated gravitational slope deformation, Deep landslide zone, Shallow instability area. The PAI2001 database also includes areas affected by intense erosive processes (areas characterised by the diffuse presence of gullies). A code was assigned for each landslide type (Table 3).

In the new database, the status of each landslide activity ('Activity' field) was updated by aerial and/or satellite image observation, local authority investigations, InSAR data and several field inspections. So, landslide activity was classified as active or suspended/dormant.

Finally, each landslide was also reported with its source data ('Data source' field), which are available in a simplified form: (i) PAI2011 for the landslides of the current PAI, (ii) IFFI (for these landslides the 'ID_IFFI' is also reported), (iii) CaLaI for the new landslides.

2.3. InSAR data

The interpretation of the landslide activity state, previously pinpointed through of orthoimages analysis

Table 3. Landslide type and relative code enclosed in the CaLaI database.

Reclassified and grouped landslide movement	Type	Code
rotational slide, translational slide	slide	SLD
earth flow, fast earth flow, debris flow	flow	FLW
rock fall	fall, topple	FLL
complex	complex	CMX
deep seated gravitational slope deformation	deep seated gravitational slope deformation	DSGSD
Diffuse Instability Area	Slide, flow, fall, topple	DIA
Areas affected by intense erosive processes	Intense erosion zone	IEZ

and field observations, was updated using the Advanced – Synthetic Aperture Radar Interferometry (A-InSAR) products obtained from the processing of Sentinel-1 data available free of charge from the European Ground Motion Service (EGMS, https://egms.land.copernicus.eu/) (Costantini et al., 2021; Crosetto et al., 2020; Crosetto et al., 2021). In detail, we used the horizontal and vertical components of the ground motion, setting +/−2 mm/yr as the threshold to discriminate between ground motion and no motion. Such values were selected accordingly both with the consolidated A-InSAR theory (Hanssen, 2003; Manzo et al., 2012; Shanker et al., 2011) and the abundant literature about analysis of landslide activity (e.g. Balbi et al., 2021; Bianchini et al., 2012: Cianflone et al., 2018; Colesanti & Wasowski, 2006; Francioni et al., 2014; Ietto et al., 2022). A-InSAR outcomes were obtained using the Permanent Scatterers (PS) approach (Ferretti et al., 2001), covering the timespan 2016–2021.

The PS approach represented the first complete solution overcome the temporal and the geometrical decorrelation, and to estimate ground deformations, separating them from the Atmospheric Phase Screen (APS) contribution. This represented a major step forward with respect to the pre-existing DInSAR techniques, which increased dramatically their applicability, and it was a seminal work that provided a basis for further development. The major constraint of this approach is that it is limited to the scatterers that exhibit sufficiently high coherence, even at large baselines, which typically leads to low PS density in nonurban areas. By contrast, PSs are usually abundant on buildings, monuments, antennas, poles, conducts, exposed rocks or outcrops, among others. Then, the method was extended by implementing the PSInSAR™ algorithm (Ferretti et al., 2011) by jointly processing PSs and DSs (Distributed Scatterers), considering their statistical behaviour. The SqueeSAR™ algorithm is focused on pixels belonging to areas of moderate coherence, where neighbouring pixels share the same reflectivity values as they belong to the same object. The result of SqueeSAR™ is an improved density and quality of the PSI results, which is particularly remarkable in nonurban areas. The Permanent Scatterers (PS) technique is a sophisticated method used in Differential Interferometric Synthetic Aperture Radar (DInSAR) to monitor ground deformation with high accuracy. This technique identifies stable, radar-reflective points on the Earth's surface – known as Permanent Scatterers – that consistently reflect radar signals back to the satellite over long periods. By analyzing phase differences between multiple Synthetic Aperture Radar (SAR) images taken at different times, it is possible to detect even minute ground movements, down to a few millimetres (Ferretti et al., 2001). This method is particularly effective in urban environments and areas with scarce vegetation, where these stable scatterers are more abundant. In fact, the PS technique involves selecting a network of scatterers that remain stable over time, allowing for the detection of subtle changes in the ground's displacement that might not be visible with traditional methods. This ability to detect minute changes is crucial for monitoring infrastructure stability, such as bridges, roads, and buildings, especially in densely populated urban areas where ground movement could lead to significant structural damage. The technique is also highly valuable in natural hazard monitoring, such as detecting slow-moving landslides, subsidence, and volcanic deformation, providing essential data that can help mitigate risks associated with these phenomena (Hooper et al., 2004).

Moreover, the PS technique is highly adaptable, being applicable to various terrains and environmental conditions. Its effectiveness is enhanced when used in conjunction with other remote sensing data and ground-based observations, offering a more comprehensive view of the Earth's surface dynamics. The data acquired through PS techniques can be integrated into Geographic Information Systems (GIS), aiding in urban planning, land use management, and disaster preparedness strategies (Crosetto et al., 2010). The continuous advancements in satellite technology and processing algorithms further improve the accuracy and reliability of this technique, making it an indispensable tool in the field of geosciences and environmental monitoring.

The obtained data showed negative values when the ground motion is downward or westward oriented, and positive values when the surface is affected by uplift or its motion is eastward oriented. Because satellite SAR data are widely available, processing and analysing these data over vast areas using huge stacks of satellite images is more feasible. Currently, several active spaceborne SAR systems, working at medium and very high resolution, offer broad spatial coverage of the whole Earth's surface with short temporal revisiting time. The most important system among these is certainly the Sentinel-1 constellation, part of the Copernicus Programme operated by the European Space Agency. Advances in A-InSAR processing algorithms mainly concern the selection of the measurement points, phase unwrapping, estimation of the atmospheric components and modelling of the deformation time evolution. Finally, also the available computational resources (parallel computing, cloud computing, distributed computing architectures, etc.) have notably increased in the last decade, drastically reducing the costs.

PS from EGMS were used as support to update the state of activity of very/extremely slow-moving landslides (Cruden & Varnes, 1996).

2.4. Maps

In the map sheets we have used the terminology and a simplified classification scheme according to Cruden and Varnes (1996). Specifically, the type of movement (i.e. sliding, flowing) and the activity state (active, suspended/dormant) were indicated for each landslide in the map produced.

In the maps, we have indicated the active and dormant landslides in urban areas or parts of the infrastructure.

Each map sheet contains a shaded relief base map, the mechanism and activity of the landslides, PS with horizontal EW movements derived from EGMS, and administrative spatial data such as rivers, roads, cities, etc. The territory of the Calabria region was divided into 4 cartographic sheets referring to the provinces of the region: Sheet 1: CS, Sheet 2: CZ, Sheet 3: VV and KR and Sheet 4: RC.

A WebGIS (Figure 2) was built into this work to display all the collected geodata and to develop an

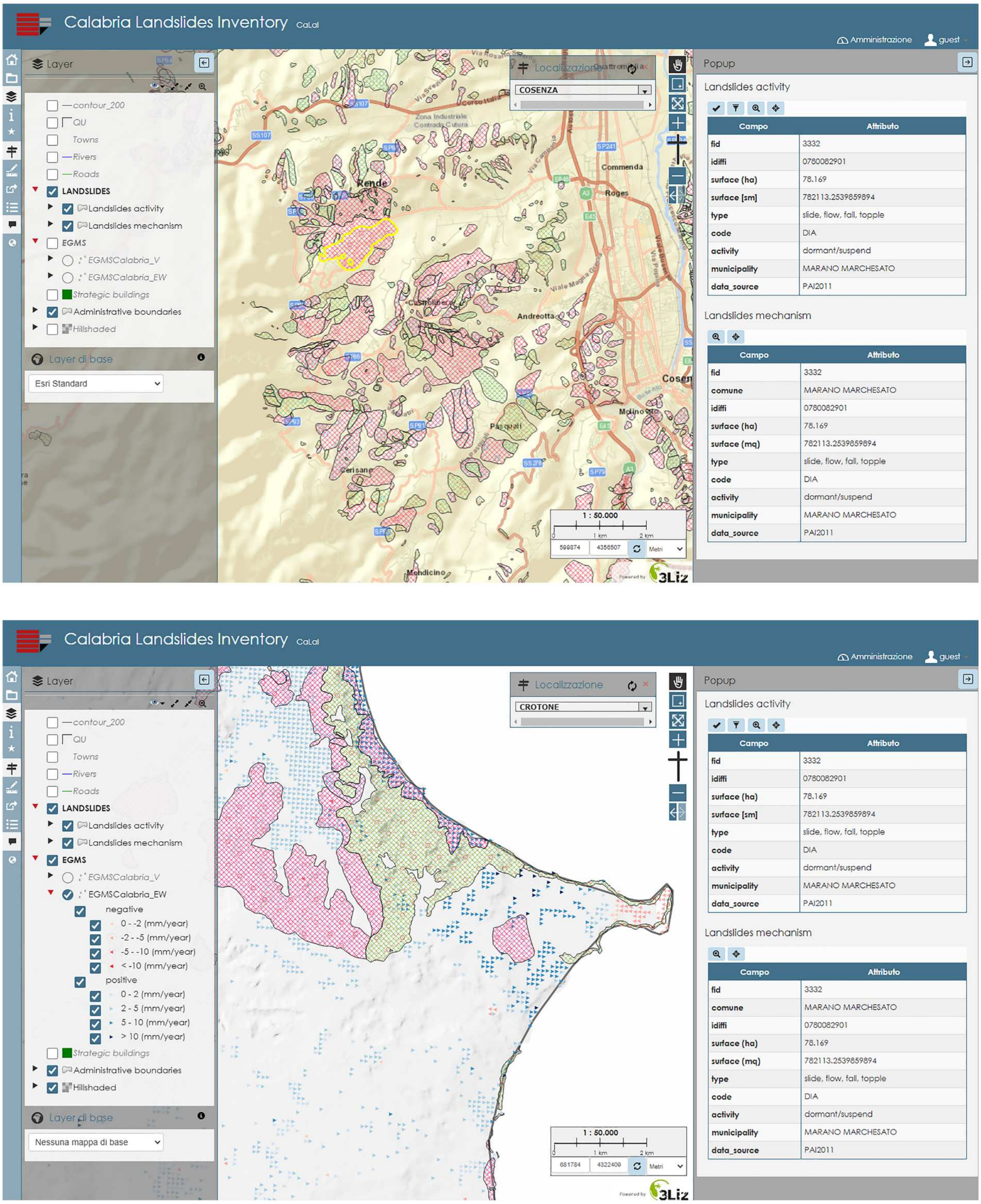

Figure 2. (top) WebGIS view of the landslides inventory. (bottom) WebGIS view of A-InSAR data from Sentinel-1.

efficient service that can be widely disseminated. An open-source web application based on Lizmap Web Client (LWC) and QGIS was developed to collect and manage the geospatial data. The WebGIS application was proposed to share spatial information and data and allow users with limited GIS skills to access the landslide inventory database of the entire Calabria region.

The GIS server is a QGIS server that provides a GIS engine and protocols for the delivery of georeferenced map images, i.e. Web Map Service (WMS) or Web Feature Service (WFS). It works in the backend of the system and the LWC framework provides the interface to the users.

The geodata is stored in GeoPackage format (GPKG). GeoPackage is an open and standardised, portable, platform-independent and compact format for the transmission of geodata. The format describes the rules for storing geodata (vector, raster, non-spatial data, etc.) in an SQLite database. All the data described above, which is available on each map sheet, is stored in the database in GPKG format and displayed in WebGIS.

3. Results

The inventory consists of a map atlas covering all five provinces (Cosenza, Catanzaro, Crotone, Vibo Valentia, Reggio Calabria) of the Calabria region. The inventory includes 16913 landslides covering an area of 15222 km^2.

In the province of Cosenza (CS), a total of 9376 landslides were recorded (Table 4); of these, 4996 were classified as slides (SLD), 617 as flows (FLW), 117 as falls/topples (FLL), 1049 as complex (CMX), 2436 as diffuse areas of instability (DIA), 23 as deep-seated gravitational slope deformations (DSGSD) and 138 as areas affected by intense erosive processes (IEZ). The number of active and dormant/suspended landslides is 5968 and 3408, respectively. The landslides cover an area of 552.4 km^2 (1.40 landslides/km^2) and are distributed as follows: 44.9%, 22.5% CMX, 20.7% SLD, 8.6% DSGSD, 2% FLW, 0.7% FLL and 0.6% IEZ.

In the province of Catanzaro (CZ), a total of 2526 landslides were recorded (Table 4), of these 1082 classified as SLD, 106 as FLW, 29 as FLL, 228 as CMX, 1024 as DIA, 10 as DSGSD and 47 as IEZ. The number of active and dormant/suspended landslides are 1417 and 1109 respectively. The landslides cover an area of 185.8 km^2 (1.05 landslides/km^2) and are divided as follows: 53.5% DIA, 21.1% SLD, 12.9% DSGSD, 7.5% CMX, 2.3% IEZ, 1.8% FLW and 0.9% FLL.

In the province of Crotone (KR), a total of 580 landslides were recorded, 161 classified as SLD, 18 as FLW, 21 as FLL, 90 as CMX, 264 as DIA and 26 as IEZ. The number of active and dormant/suspended landslides are 231 and 349 respectively. The landslides cover a surface of 71.8 km^2 (0.33 landslides/km^2) and are divided as follows: 66.6% DIA, 21.4% CMX, 8.8% SLD, 1.5% IEZ, 0.9% FLL and 0.8%FLW.

In the province of Vibo Valentia (VV), 1423 landslides were identified, 639 classified as SLD, 112 as FLW, 15 as FLL, 93 as CMX, 522 as DIA, 2 as DSGSD and 40 as IEZ. The number of active and dormant/suspended landslides are 641 and 782 respectively. The landslides cover a surface of 75.2 km^2 (1.24 landslides/km^2) and are divided as follows: 64.1% DIA, 22.8% SLD, 5% CMX, 2.9% IEZ, 2.8% DSGSD, 2.2 FLW and 0.2% FLL.

In the province of Reggio Calabria, a total of 3008 landslides were identified, 1203 classified as SLD, 112 as FLW, 52 as FLL, 605 as CMX, 920 as DIA, 15 as DSGSD and 101 as IEZ. The number of active and dormant/suspended landslides are 996 and 2012 respectively. The landslides cover a surface of 75.2 km^2 (0.94 landslides/km^2) and are divided as follows: 42.5% DIA, 27.7% CMX, 16.1% SLD, 7.6 IEZ, 3.3% DSGSD, 2.2% FLW and 0.7% FLL.

Table 4. Landslide inventory of the Calabria Region, showing types and number of landslides within each province.

	Landslide mechanism							
Province	CMX	DIA	DSGSD	FLL	FLW	IEZ	SLD	Total
CS	1049	2436	23	117	617	138	4996	9376
CZ	228	1024	10	29	106	47	1082	2526
KR	90	264	0	21	18	26	161	580
VV	93	522	2	15	112	40	639	1423
RC	605	920	15	52	112	101	1203	3008

Table 5. Landslide inventory of the Calabria Region, showing types and surface (km^2) of landslides within each province.

	Landslide mechanism							
Province	CMX	DIA	DSGSD	FLL	FLW	IEZ	SLD	Total
CS	124.2	247.9	47.5	3.7	10.9	3.6	114.5	552.4
CZ	13.9	99.4	24.0	1.7	3.3	4.3	39.3	185.8
KR	15.4	47.8	0.0	0.6	0.6	1.1	6.3	71.8
VV	3.8	48.2	2.1	0.2	1.7	2.2	17.2	75.2
RC	67.7	104.0	8.0	1.6	5.5	18.5	39.3	244.7

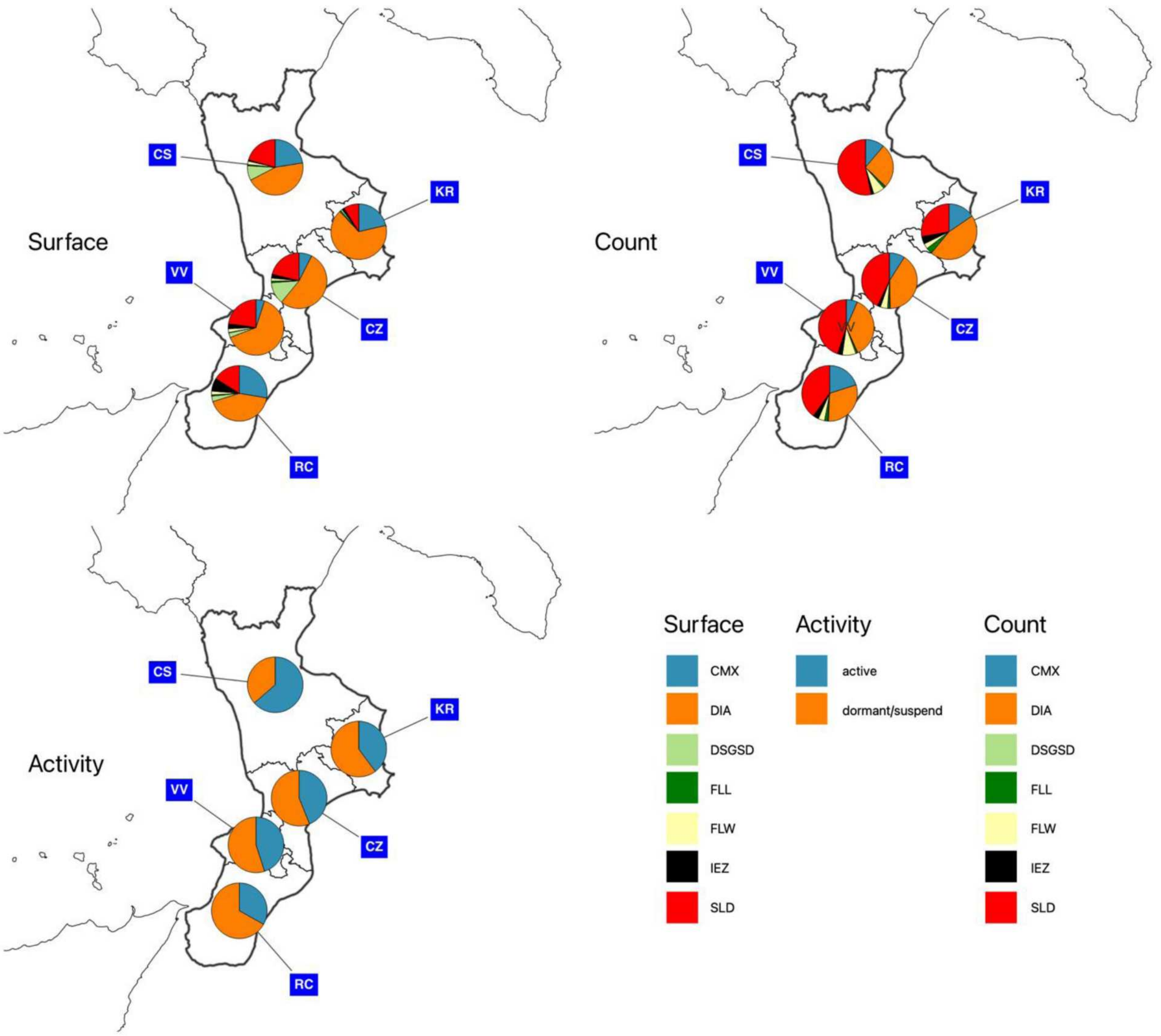

Figure 3. Pie diagrams of landslide inventory of the Calabria Region, showing surface, activity and count of landslides within each province.

The data in Table 5 indicates that Cosenza is the province most prone to landslides. The most common type of landslide in this area is the slide (Figure 3), which covers 8.2% of the province's surface. Following Cosenza, Reggio Calabria experiences the second highest number of landslides, with the slide-type being the most abundant (Figure 3). These landslides cover 7.6% of the entire province. Catanzaro and Vibo Valentia provinces have fewer landslides compared to the previous ones. In both these provinces, the slide-type is the most common (Figure 3), with mapped landslides covering 7.7% and 6.5% of the province surface, respectively. Finally, Crotone is the last province with landslides, where the most common landslide type is the diffuse instability area (Figure 3). The mapped landslides cover 4.1% of the province's surface.

4. Conclusion

The atlas created in this study includes the location, extent, and types of active and suspended/dormant landslides in the Calabria Region in southern Italy. This updated atlas aims to enhance understanding of landslide events affecting communities and certain infrastructures in the region. The main purpose of the WebGIS and Map Sheets, which are not geomorphological maps, is to support urban planning and the planning of mitigation measures.

In total, 16913 landslides were documented in the inventory, including 8081 slides, 5166 diffuse instability areas, 2065 complex landslides, 965 flows, 352 areas affected by intense erosive processes, 234 falls/topples, and 50 deep-seated gravitational slope deformations. Of these landslides, 9253 are active and 760 are dormant/suspended.

The use of PS ground deformation data from EGMS allows for: (i) monitoring possible recent changes in the identified landslides; (ii) supporting future analyses for selected areas with significant impact on society.

Future research could involve adding new landslide data and literature information where available to the WebGIS database. Moreover, the database will be implemented with more detailed road, railway networks, demographic and economic data to facilitate risk analysis.

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Data availability statement

The data is available via the interactive visualisation on the LizMap Web Client platform. The WebGIS platform is publicly accessible at http://geocube.unical.it/webgis/index.php. Access requires authentication by logging in with the username *guest* and the password *CaLaIguest24*.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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Software

All data and maps presented in this paper were created with the software QGIS version 3.28.10-Firenze (https://qgis.org). QGIS Server (version 3.28.10) LizMap Web Client version 3.7.2 (https://github.com/3liz/lizmap-web-client) and LizMap plugin (version 4.3.3) were used to publish the data on WebGIS. All software mentioned is open-source and freely accessible. QGIS and QGIS Server with GPL-3 license (General Public License 2.0) and LizMap Web Client with MPL-2 license (Mozilla public License 2.0).

ORCID

Giuseppe Cianflone http://orcid.org/0000-0002-2729-9415
Salvatore Larosa http://orcid.org/0000-0003-2588-6082
Lisa Beccaro http://orcid.org/0000-0002-4489-7871
Antonio Viscomi http://orcid.org/0000-0003-2792-1101
Cristiano Tolomei http://orcid.org/0000-0001-7378-0712
Gianpietro Imbrogno http://orcid.org/0009-0006-9257-2701
Fabio Ietto http://orcid.org/0000-0001-6517-7788
Rocco Dominici http://orcid.org/0000-0003-4223-1512

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