Updating landslide inventory maps in mountain areas by means of Persistent Scatterer Interferometry (PSI) and photo-interpretation: Central Calabria (Italy) case study

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ABSTRACT: Conventional methods used to detect slope instability and map geomorphologic processes, especially in mountain areas, can benefit from remote sensing analyses, e.g. optical and radar satellite data. We illustrate the contribution of Persistent Scatterer Interferometry (PSI) analyses and photo-interpretation for the updating of pre-existing landslide inventory maps in mountain areas, through the case study of Central Calabria, located in southern Italy with an extension of 4,470 km². We used 108 ENVISAT ascending images (20 m ground resolution) acquired in 2003-2009 and processed with the PSP (Persistent Scatterer Pairs) technique, 1 optical image acquired by SPOT satellite (2.5 m resolution), and digital orthophotos with 1 m resolution covering the whole investigated area. All these data were integrated and combined with additional ancillary information (e.g. topographic, geological and land use maps), 980 landslides (23.9% of pre-existing inventory) were updated by means of PSI information and 64 new landslides were also detected. The state of activity and the intensity of these landslides were also updated and/or evaluated, showing that 22% and 2% of the updated inventory include active (919 landslides) and reactivated (93 landslides) phenomena respectively. The outcomes of the integrated radar-interpretation and photo-interpretation methodology for Central Calabria and its operative usefulness for civil protection authorities represented a valuable proof of the reliability of this approach for updating landslide inventory maps in mountain areas at regional scale.

1 INTRODUCTION

Many urban settlements in mountain regions are developed without taking into account landslide hazards and their potential consequences on local population (Schuster & Fleming 1986). Proper identification and mapping of such phenomena, together with a good urban planning, facilitate the mitigation of geological risks and the reduction of damages and economic impacts.

In mountain regions, the use of ground-based instrumentation is not always economically and practically suitable to perform a systematic control of natural phenomena, because of both huge extension and inaccessibility of the investigated areas. Radar and optical remote sensing techniques represent therefore a valuable tool for landslide identification and mapping, which are fundamental activities for landslide hazard and risk assessment.

In the last years, many different InSAR (Synthetic Aperture Radar Interferometry) techniques for measuring ground deformations have been developed and experimented to analyze different geological processes and dynamics, such as land subsidence, slow moving landslides, tectonic motions, and volcanic activity (Massonnet & Feigl 1998, Singhroy et al. 1998, Ferretti et al. 2001, Hilley et al. 2004, Salvi et al. 2004, Bürgmann et al. 2006). Multi-temporal InSAR analyses (e.g. Persistent Scatterer Interferometry, PSI), integrated and coupled with in situ investigations and surveys together with photo-interpretation, can successfully support conventional landslide studies at local and regional scale, thanks to the measurement and monitoring of ground deformations with millimeter accuracy and also the reconstruction of the history of deformations of the investigated areas (Farina et al. 2008, Casagli et al. 2009, Cigna et al. in press).

We present an integrated methodology for the updating of pre-existing landslide inventory maps in mountain areas, based on the combination of thematic maps (e.g. topographic, geological, land use maps) and optical (e.g. orthophotos and optical satellite images) data with multi-temporal ground deformation measures extracted by means of multi-pass InSAR. We discuss potentials and limitations of this approach through an application to the test site of Central Calabria, located in southern Italy. This region is extensively affected by slow landslides threatening urban settlements and consequently fits very well the potentials of radar analyses.

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2 CENTRAL CALABRIA (ITALY)

2.1 Geological and geomorphologic background

The investigated area is the central part of the Calabria peninsula in Italy and includes part of the provinces of Cosenza, Catanzaro, Crotone and Vibo Valentia, with a total area of 4,470 km² (Fig. 1).

Most of the outcropping basement is composed of Hercynian and Alpine crystalline and metamorphic allochthonous complexes, with associated Eocene and Lower Neogene sedimentary sequences (Van Dijk et al. 2000). Along the internal side of the Calabrian Arc, Mesozoic carbonate rocks – similar to the Apennine allochthonous units – crop out in windows below this basement. The contact between the basement units is overlapped at a low angle, obliterated by successive high-angle faults. Terrigenous Tertiary sequences are present as remains along the over-thrust contacts between these basement units and also as tectonic wedges along the fault zones at a higher angle. All these rocks are crossed by a complex group of high-angle faults, which can be organized in major systems and patterns, partly correlated to transcurrent faulting (Van Dijk et al. 2000). The geological structure is characterized by low-angle thrusts, dissected by high-angle faults with oblique movement components (Guerricchio 2004).

The geomorphologic setting is characterized by widespread slope movements. In particular, several slow moving slides and complex slide-flows can be recognized and, secondarily, severe erosion and superficial rapid slope movements. Earth slides involve metamorphic rocks and earth flows affect Pliocene deposits. Moreover, landslides generally show recent morphologies, indicative of new activations. Along the eastern border of the Coastal Chain, large-scale and deep-seated gravitational landslides can also be recognized (Iovine et al. 2006).

2.2 Pre-existing landslide inventory map

The official landslide inventory map available for Central Calabria is part of the Hydrogeological Setting Plan (PAI - Piano di Assetto Idrogeologico) of Calabria Region, published in 2006 and distributed by the Regional River Basin Authority. Inside the investigated area, a total of 4,102 landslides are mapped, 861 (21%) of which are classified as active, 3,220 (78%) as dormant and 21 (1%) as stabilized (the reference year is 2006). Landslides cover an area of 325 km², corresponding to 7.3% of the whole territory (Fig. 1), and the main landslide typologies are represented by rotational slides and flows.

The inventory of the PAI can be integrated also with the information from the IFFI (Inventario dei Fenomeni Franosi in Italia, Landslide Inventory in Italy) inventory, a national landslide database published in 2007. Both these sources of information (PAI and IFFI) are based on aerial photo-interpretation, field surveys and collection of local databases mapped on a reference scale of 1:10,000.

![Figure 1. Pre-existing landslide inventory for the area of Central Calabria (Italy) displayed on a Google Earth map (top). Main statistics for the pre-existing inventory are summarized inside the pie charts (bottom).](image)

3 LANDSLIDE INVENTORY MAP UPDATING

3.1 Methodological approach

The methodology relies on the updating of a pre-existing landslide inventory database by means of the integration of very high resolution optical images (e.g. orthophotos and IKONOS, SPOT, QuickBird satellite images) with other thematic data (e.g. topographic, geological, land use maps), combined with ground displacement measurements provided by Persistent Scatterer Interferometry (PSI) analysis. In particular, the methodological approach uses the ‘radar-interpretation’ (Farina et al. 2008) and photo-interpretation methods and it is based on the possibility of extending and assigning a spatial meaning to the point-wise ground displacement measurements provided by the PSI technique, through the interpretation of aerial and satellite optical imagery and other ancillary data.

The contributions of this integrated analysis to the updating of pre-existing inventories consist in the following facets: i) detection of geomorphologic
phenomena not emerged from conventional analyses, field surveys or bibliographic studies; ii) verification or modification of landslide boundaries; iii) assessment of representative ground deformation rate for each phenomenon; iv) definition of state of activity; v) assessment of main direction of displacements (reconstruction of vertical and horizontal EW deformation components, combining ascending and descending data – if available).

3.2 Input data

The different types of input data that are necessary to perform the updating of a pre-existing landslide inventory map through this integrated analysis, can be grouped in two categories: ancillary and PSI data.

3.2.1 Ancillary data

Ancillary data generally include thematic maps (e.g. topographic, geomorphologic, geological and land use maps) and optical images (both aerial and satellite data).

In particular, for the Central Calabria test site we collected the following ancillary data:
- 1:25,000 topographic map distributed by IGM (Military Geographic Institute) and 1:10,000 map from the Regional Cartographic Center;
- Digital Terrain Model (DTM) with 20 m spatial resolution;
- Regional geological map at 1:25,000 scale, distributed by the Regional Cartographic Center;
- Digital color orthophotos from Volo Italia 2000 (not stereo), with 1 m resolution;
- SPOT multispectral image acquired in 2005 with 2.5 m resolution;
- CORINE Land Cover map (Perdigao & Annoni 1997) at 1:50,000 scale (the 3rd classification level was used), published in 2000 and distributed by ISPRA (Istituto Superiore PROtezione Ambiente).

3.2.2 PSI data

Today many archives of SAR images are available, including both historical data acquired since the early ’90s (e.g. ERS1/2 images) and images from currently operating SAR satellites (e.g. ENVISAT, RADARSAT1/2), spanning a time interval of more than 17 years. However, the choice of the best radar data stacks for a given test site is mainly driven by the spatial and temporal coverage of these data in the investigated area. As well as for SAR data, many different PSI techniques are available today to process multi-temporal SAR data stacks; among which, the Permanent Scatterers (PSInSAR; Ferretti et al. 2001), the PSP (Persistent Scatterer Pairs; Constantini et al. 2000) and the SBAS (Small Baseline Subset; Berardino et al. 2002) approach.

For the Central Calabria test site we used 108 ENVISAT ASAR (Advanced SAR) images acquired along ascending orbits in 2003-2009 and distributed in 3 different frames. SAR data were processed by e-GEOS (an ASI/Telespazio Company) by means of the PSP technique, providing 348,874 Persistent Scatterers (PS) in the whole area, with a mean target distribution of 78 PS/km². For each PS, the following measures were extracted:
- geographic coordinates (latitude, longitude and elevation), with meter precision;
- average LOS (Line Of Sight) displacement rate in 2003-2009, with a precision of about 1 mm/yr (depending on the number of available images, the phase stability of each PS and its distance from the reference point);
- 2003-2009 displacement time series (i.e. LOS displacement at each acquisition), with millimeter (mm) precision.

3.3 Updating procedure

Following our methodology, the updating of the pre-existing landslide inventory database is obtained through the integration of traditional photo-interpretation with the radar-interpretation approach. This methodology has been recently developed and validated by the scientific community (PREVIEW and Terrafirma projects; Casagli et al. 2008, Pancioli et al. 2008, Righini et al. 2008, Herrera et al. 2009). The entire process, including the analysis and interpretation of all the available data, is carried out in a Geographic Information System (GIS) environment.

In general, the updating of a pre-existing landslide inventory can lead to the identification of new landslides, the modification of boundaries of pre-mapped phenomena and the assessment (or updating) of their state of activity (WP/WLI 1993) and landslide intensity (Cruden & Varnes 1996), integrating qualitative (state of activity) and quantitative information (intensity; here defined in terms of movement velocity) of each phenomenon.

Monoscopic and stereoscopic photo-interpretation of aerial photos and satellite optical images are the conventional tools for the identification and mapping of ground instabilities, allowing the recognition of geomorphologic evidences and indicators of movement (e.g. anomalies in vegetation coverage) and the shape of unstable areas (Soeters & van Westen 1996). For the Central Calabria, we interpreted one color orthophoto (Volo Italia) and one satellite image (SPOT) using the monoscopic photo-interpretation approach and the multispectral analysis respectively.

In order to evaluate the state of activity and intensity of the phenomena covered by the PSI data, we used an activity matrix and an intensity scale (Fig. 2), defined in terms of PS average yearly velocity and based on the information coming from the pre-existing inventory map of the investigated area (i.e. PAI, 2006) and from ENVISAT ascending PSI data (2003-2009). Representative ground displacement
values in 2003-2009 for each landslide are determined through the analysis of spatial distribution and frequency of PSI data inside its boundaries. These values are then compared to some deformation thresholds (e.g. 2 and 10 mm/yr in the LOS direction, away or towards the satellite) and combined with the landslide information extracted from the pre-existing inventory in order to determine the state of activity (reactivated, active, dormant, stabilized) and intensity (negligible, extremely slow, very slow) of each phenomenon (Fig. 2). The deformation thresholds used inside the activity matrix and intensity scale are site-specific values and they are empirically determined taking into account the characteristics of each application, e.g. typology of landslides affecting the investigated area, PSI data, LOS direction, measurement accuracy, distance from the reference point. Generally, the use of the activity matrix is performed through a conservative approach; in other words, the previous state of activity of dormant or active landslides is not lowered (to stabilized or dormant, respectively) even if PSI data register slow movement rates (lower than 2 mm/yr, away or towards the satellite), unless field evidences and in situ monitoring data confirm an actual lowering of activity (Fig. 2).

The interpretation of PSI information, supported by the analysis of the geomorphologic evidences through photo-interpretation, generally can lead to two main conditions (Fig. 3):

- Presence of PS data outside the previous mapped areas, resulting in:
  - new landslide detection, when significant PS velocities, and also geological and geomorphologic evidences suggest the presence of a landslide;
  - no additional landslide detection, when geomorphologic and geological setting and/or the PS velocity distribution do not confirm the presence of a landslide (other geological processes such subsidence or erosion, may also induce significant deformations).

- Presence of PS data within the already mapped landslides, resulting in:
  - confirmation of the state of activity when the inventory information is in agreement with PS data;
  - change of the state of activity when the inventory information is not in agreement with PS data;
  - change of landslide boundaries, when PS data suggests the enlargement (or reduction) of the already mapped area.

3.4 Results

An overview of the updated landslide inventory map for the Central Calabria test site is shown in Figure 4. The updated landslide inventory provides not only the spatial distribution of slow moving landslides – represented as polygons – but also their temporal characteristics (i.e. state of activity and intensity).

The radar-interpretation of ENVISAT PSI data gave spatial and temporal information for 980 landslides (23.9%) of the pre-existing inventory (PAI), updating the boundaries and/or state of activity of 144 phenomena and confirming the spatial and temporal characteristics of 836 phenomena (Table 1). The analysis also allowed us to map 64 new landslides, corresponding to 1.5% of the updated inventory (Table 2). The updated map totally includes 4,166 phenomena, corresponding to an area of 334 km² (Fig. 4). The distribution of the state of activity and intensity in the updated inventory (Fig. 4) highlights that 229 and 93 of the updated phenomena were active or reactivated in 2009 respectively, for a total of 919 active (continuous) landslides in the whole updated inventory (corresponding to 60.3 km²; 18%) and a total of 93 reactivated phenomena (i.e. 22.6 km²; 7%). Dormant and stabilized landslides are 3,136 (i.e. 248.7 km²; 74%) and 18 (i.e. 2.2 km²; 1%) respectively (Fig. 4).

<table>
<thead>
<tr>
<th>Activity Matrix</th>
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<tbody>
<tr>
<td>V &lt; 2 mm/yr</td>
</tr>
<tr>
<td>Stabilized</td>
</tr>
<tr>
<td>Dormant</td>
</tr>
<tr>
<td>Active</td>
</tr>
<tr>
<td>New Landslide</td>
</tr>
</tbody>
</table>

<table>
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<tr>
<th>Intensity Scale</th>
</tr>
</thead>
<tbody>
<tr>
<td>V &lt; 2 mm/yr</td>
</tr>
<tr>
<td>Negligible</td>
</tr>
</tbody>
</table>

Figure 2. Activity matrix and intensity scale based on ENVISAT PSI measures and the information from the pre-existing landslide inventory of Central Calabria (Italy).

4 DISCUSSION

In the application for Central Calabria, the use of photo-interpretation turned out to be a useful contribution for landslide mapping in particular in hilly and mountainous environments, where a low density of radar targets was identified. On the other hand,
radar-interpretation contribution was more suitable for most of the landslides involving urban areas and the road network, for which the reliability of PSI was higher but photo-interpretation was strongly limited by the dense urban fabric.

The presence of highly vegetated areas frequently led to a lack of PSI measures (due to the absence of good radar reflectors). Thus, PSI data did not give any additional information on 321 landslides (7.8% of the PAI) due to an insufficient number of PS (N.C.), and on 2,801 landslides (68.3% of the PAI) due to the complete absence of PS within the already mapped landslides (NO INFO; Tables 1, 2). In these cases, we did not change the spatial and temporal information of the original inventory.

By using ENVISAT PSI data, or other data with similar acquisition frequency (i.e. 1 image per month), the applicability of this integrated approach for the investigation of landslide processes is limited to extremely slow ($v < 16$ mm/yr) and very slow phenomena ($16$ mm/yr $< v < 1.6$ m/yr), as defined by Cruden & Varnes in 1996. However, the availability of new SAR missions with higher temporal frequency, such as TerraSAR-X and COSMO-SkyMed (i.e. 3-4 acquisitions per month), allows today the opening of new perspectives and scenarios also for the analysis of faster phenomena.

<table>
<thead>
<tr>
<th>Landslides</th>
<th>N°</th>
<th>Pre-existing Inventory</th>
</tr>
</thead>
<tbody>
<tr>
<td>Updated</td>
<td>980</td>
<td>23.9</td>
</tr>
<tr>
<td>N.C.*</td>
<td>321</td>
<td>7.8</td>
</tr>
<tr>
<td>NO INFO*</td>
<td>2,801</td>
<td>68.3</td>
</tr>
<tr>
<td>Total</td>
<td>4,102</td>
<td>100</td>
</tr>
</tbody>
</table>

* Insufficient number (N.C.) or complete absence (NO INFO) of PS within the already mapped landslide.

<table>
<thead>
<tr>
<th>Landslides</th>
<th>N°</th>
<th>Pre-existing Inventory</th>
</tr>
</thead>
<tbody>
<tr>
<td>Updated</td>
<td>980</td>
<td>23.5</td>
</tr>
<tr>
<td>New</td>
<td>64</td>
<td>1.5</td>
</tr>
<tr>
<td>N.C. + NO INFO*</td>
<td>3,122</td>
<td>74.9</td>
</tr>
<tr>
<td>Total</td>
<td>4,166</td>
<td>100</td>
</tr>
</tbody>
</table>

* Insufficient number (N.C.) or complete absence (NO INFO) of PS within the already mapped landslide.

![Figure 3](image3.png)

Figure 3. Updating of the pre-existing landslide inventory map for the Central Calabria (Italy): example for the area of Catanzano. PSI data (2003-2009), pre-existing (2006) and updated (2009) inventories are displayed on the 2000 orthophoto. N.C. and NO INFO designate, respectively, landslides with insufficient number or complete absence of PS within the already mapped area.

Table 1. Landslide distribution for the pre-existing inventory map (2006).

Table 2. Landslide distribution for the updated inventory map (2009).

![Figure 4](image4.png)

Figure 4. Updated landslide inventory map for the area of Central Calabria (Italy) overlapped on a Google Earth map (top). Main statistics for the updated inventory are summarized inside the pie charts (bottom).
5 CONCLUSIONS

The outcomes of this study for the test site of Central Calabria provided valuable results, demonstrating the suitability of this integrated method for the updating of landslide inventory maps using radar remotely sensed data for detection and mapping of slow-moving landslides. Its operational usefulness for civil protection authorities represents a valuable proof of the reliability of this approach for application in mountain areas and at regional or local scale. However, vegetated areas often prevent reflective targets to be identified as PS; moreover, fast-moving phenomena usually decrease or even compromise also the functioning of PSI analyses.

The analysis for Central Calabria opens new perspectives for the future exportability of this methodology in different and various geomorphologic environments (e.g. tropical, high mountains etc.), as an effective tool to improve risk management activities and focus planning resources according to distribution and intensity of landslide hazard.

ACKNOWLEDGEMENTS

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WP/WLI (Working Party for World Landslide Inventory)