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Multitemporal landslides inventory map updating using spaceborne SAR analysis

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ABSTRACT

Deep seated gravitational slope deformation and slow moving landslides on large areas were analyzed by spaceborne SAR interferometry: a test site in the Italian Alps of about 300 km^2 was selected for updating pre-existing landslide inventory maps based on the advanced interferometric processing technique (A-DInSAR).

SAR images from ERS-1/2 satellites (1995–2000) and from Envisat satellite (2002–2009) have been used, allowing the deferred-time analysis of past movements and the record of recent slope movements. In the multi-temporal updated landslide inventory database, the characteristics of the landslides were highlighted: geometry, state of activity, typology, monitoring systems, interventions, source of information and the updating time and actions. Furthermore, for each landslide area, the occurrence of persistent scatterers points and the statistical description of their velocities were reported. This methodology may allow the systematic updating of landslides inventory maps keeping all information on each landslide, becoming the basic tool for the realization and updating of thematic maps such as the landslide susceptibility map.

1. Introduction

The cost necessary to meet the hydrogeological disasters is one of the major items of expenditure for the civil protection authorities. Therefore, in order to reduce costs, it is essential to work for a proper land management and planning. The assessment of the spatial distribution and state of activity of landslide processes is crucial for landslide hazard and risk analysis on a regional scale, aimed at proper urban planning.

Numerous applications of Synthetic Aperture Radar (SAR) data to ground displacement detection have demonstrated that it is a useful technique for slow-moving landslide characterization and mapping and it permits to reconstruct the landslide activity with a millimetre precision (Rott et al., 1999; Ferretti et al., 2001; Massonnet and Feigl, 1998; Hilley et al., 2004; Strozzi et al., 2005; Prati et al., 2010; Lauknes et al., 2010; Herrera et al., 2013; Bianchini et al., 2012b). Coupled with pre-existing landslide inventory maps and thematic data, SAR interferometry leads to an efficient methods to make or update landslides inventory especially at basin scale (Colesanti and Wasowski, 2006; Hilley et al., 2004; Meisina et al., 2008; Cascini et al., 2009; Herrera et al., 2009; Notti et al., 2010; Righini et al., 2012; Bianchini et al., 2012a; Liu et al., 2013; Bianchini et al., 2013; Tofani et al., 2014). SAR techniques are suitable tools in checking/updating inventory maps dealing with mass movement phenomena whose typical velocity values range from few millimeters/year up to 1.6 m/y, i.e., extremely slow landslides according to the classification of Cruden and Varnes (1996). Indeed, the conventional methods for slope instability analysis, as field campaigns, in situ measurements or aerial photo interpretation, are not always practically suitable for systematic investigations of landslide phenomena at such scale and the quality and accuracy of the maps are strongly relater on the scale resolution (Guzzetti, 2004). Furthermore, thanks to more than 15 years covered by radar images, this remote sensing technique enables a spatially and temporally detailed characterization of displacement rates.

In this paper we present the results obtained by the interpretation of A-DInSAR satellite dataset and their integration with geological and geomorphological data to obtain a multi-temporal updating of landslide inventory map. The activities here described were carried out in the framework of two European funded project: (1) Prevention, Information and Early Warning – PREVIEW

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Table 1
Matrix of activity used to update landslide inventory map.

a) Activity matrix used when only with ERS dataset are available			
		ERS < 1.5 mm/y	ERS > 1.5 mm/y
Original landslides inventory	Active	Dormant	Active
	Dormant	Dormant	Active
	Relict	Relict	Active
b) Activity matrix used when both ERS and Envisat data are available			
		ERS < 1.5 mm/y	ERS > 1.5 mm/y
Envisat < 1.5 mm/y		Relict	Dormant
Envisat > 1.5 mm/y		Active (reactivated)	Active (continuous)
c) Activity matrix used to update a pre-existing landslide inventory map when both ERS and Envisat data are available			
		ENVISAT < 1.5 mm/y	ENVISAT > 1.5 mm/y
2008 landslides inventory	Active	Dormant	Active
	Dormant	Dormant	Active
	Relict	Relict	Active

Landslides Platform (Sixth Framework Programme) and (2) Landslide Modelling and Tools for vulnerability assessment Preparedness and recovery management – LAMPRE (Seventh Framework Programme).

In particular this work presents one of the outcomes in monitoring the deep-seated and slow-moving landslides using remote-sensing interferometric techniques and the integration of diverse information sources and preoperational functions to obtain a multi-temporal updated landslide inventory maps useful to estimate landslide risk assessment and to perform hazard zonation. The test site is located in Valfurva, east of Bormio, in the Rhaetian Alps of the Lombardia Region (Fig. 1). Lombardia Region is one of the most populated and urbanized region in Italy and it is also very prone to landsliding so the risk is high for human life and infrastructures. The Valfurva area is characterized by high density of significant rock-slides and deep-seated gravitational slope deformations that could be involved many citizens (Agliardi et al., 2001; Crosta and Agliardi, 2003; Del Ventisette et al., 2012).

In the Valfurva area landslides affect pre-Permian metapelites, metabasites and marbles, as well as Late Pleistocene and Holocene glacial and rock glacier deposits. The deformation started after the Late-Wurmian age (15,000 ± 11,000 years B.P.), and continued until few centuries ago, not excluding a present-day low-rate activity (Agliardi et al., 2001). The evolution of fault systems, resulting in asymmetric trenches, led in some cases to the progressive failure of the slope during the last 10,000 years, as testified by large paleo-landslide accumulations, and it is still in progress (Agliardi et al., 2001).

2. Methodology

Slow moving landslides on a basin scale can be detected and analysed through the integration of spaceborne SAR interferometry data with thematic maps, field campaigns and in situ monitoring (Farina et al., 2004; Colesanti and Wasowski, 2006; Liu et al., 2013; Righini et al., 2012; Bianchini et al., 2012; Herrera et al., 2009; Meisina et al., 2006; Farina et al., 2006; Cascini et al., 2010; Cigna et al., 2010, 2012; Bovenga et al., 2013; Del Ventisette et al., 2013; Tofani et al., 2014). The workflow (Fig. 2) used in this work started from radar images processing. The radar images (in this paper ERS and Envisat dataset) are processed using the persistent scatterers pairs PSP-DIFSAR technique developed by Telespazio/e-GEOS (Costantini and Rosen, 1999; Costantini et al., 2002, 2008, 2009). Compared to the other persistent scatterer interferometry (PSI) techniques, one of the peculiarities of the PSP-DIFSAR method is to use only the properties of the signal relating to pairs of neighboring points to identify and to analyze the PS. Indeed, two neighbors points are equally affected by atmospheric artifacts and consider the spatiality of data. This approach allows to better identify the PS optimizing the capacity of the PSI analysis especially in vegetated areas (were generally PS are not dense) and when the movements are or non-linear with the time. Like other advanced InSAR techniques, PSP-DIFSAR estimates the intensity of deformation along the Line of Sight (LOS) and not along the real direction of movements. Furthermore new (and more recent) Envisat dataset derived from the Persistent Scatterers Interferometry Project (PSIP) from the Italian National Geoportal (ING) of the Italian Ministry of Environment, Land and Sea (http://www.pcn.minambiente.it/viewer/) was analyzed to update the landslides inventory up to 2009.

The results of radar images processing have been integrated using a Geographical Information System (GIS) with ancillary data (such as geological and topographical maps), field surveys and, where available, in situ measurements. In the case study presented in this paper we started from a pre-existing landslide inventory (produced by Regional Civil Protection of the Lombardia Region in 1998) in which some characteristics of the landslides were highlighted in the database (such as geometry, state of activity and typology).

The main criteria used to define the state of activity (SoA) were related to the mean velocities derived from the A-DInSAR processing. To identify the unstable PS, a threshold mean velocity has been chosen; e.g., ±1.5 mm/y (away or towards the satellite) in LOS direction. The PS that shows different average speed value (greater than 1.5 mm/y or less than −1.5 mm/y) are classified as unstable. To estimate the state of activity of each landslides an “activity matrix” that consider the average speed of PS is applied.

To overcome a limitation of PS approach, such as the loss of the point due to a sudden increasing in deformation rate, and starting from a pre-existing landslide inventory map, three different updated maps were produced. The first one is made using only the ERS dataset and applying the activity matrix in Table 1a and the second update (for 2008 update) is implemented using both ERS and Envisat data and applied Table 1b (Table 2).

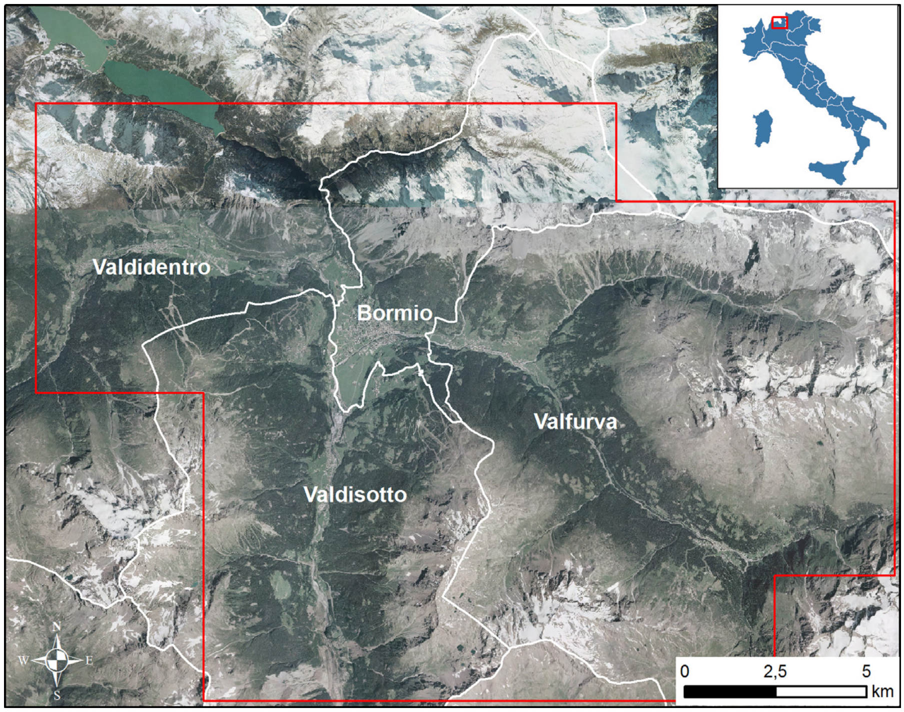

Fig. 1. Localization of the study area.

Following Table 1a, the update landslide state of activity starts from the classification in the inventory map and, if the PSPs in landslide area are unstable the new SoA is always "active". Inversely if the original SoA is "active" or "dormant" and unstable points are not present on the landslide, than in the updated inventory map the landslide is classified as "dormant". When both ERS and Envisat are available the updating was carried out through the integration between the two datasets (Table 1b). To update the inventory up to 2009 the activity matrix in Table 1c was applied starting from the data derived from 2008 updating. In this approach when unstable Envisat PSs are present the landslide was defined as "active"; reactivate or continuous in relation to the velocity derived from ERS data.

The meaning of "dormant" is here quite different from standard definition: in this paper a "dormant" landslide represents the state of activity of a landslide that has not shown evidence of movements from 1992 to 2000, i.e., the timing covered by ERS data, or that from 2002 to 2009, i.e., the time span covered by available Envisat

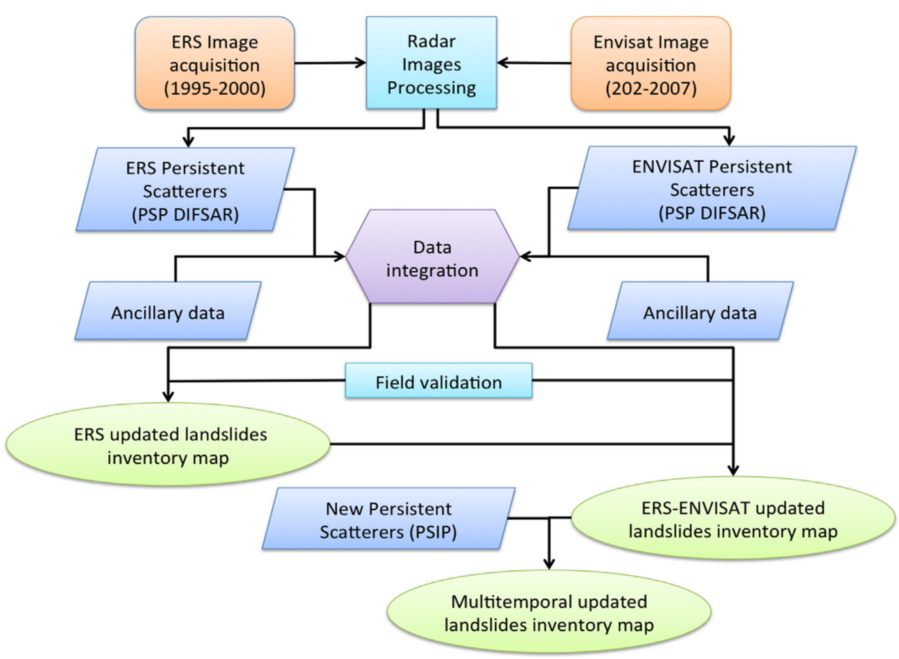

Fig. 2. Proposed workflow to create and/or update a multitemporal landslide inventory maps. PSP DIFSAR: PSP-DIFSAR technique developed by Telespazio/e-GEOS; PSIP: Persistent Scatterers Interferometry Project of the Italian Ministry of Environment and Land and Sea Protection.

Table 2
Number of landsides and affected area derived from OLIM classified in relation to the State of activity.

State of activity (number)	Landside type	Landslide number	Interested area (km^2)
Active (292)	Complex	84	3.8
	Debris flow	119	1.7
	Flow	1	0.1
	Rotational slide	86	1.8
	Topple	2	0.1
Dormant (425)	Complex	16	4.3
	Debris flow	7	0.2
	Rotational slide	402	22.8
Relict (88)	Complex	11	3.3
	Rotational slide	77	22.9
"n.d." (56)	Toople	33	1.3
	Debris flow	18	0.05
	n.d.	5	0.2

data. Obviously, following this approach, any type of SoA change is possible if no (or few and not representative) PSs are in the landslide perimeter.

Furthermore integration between the results derived from A-DInSAR processing and available ancillary data and in situ measurements were made before applied each change to elaborate an integrated geomorphological map (Ciampalini et al., 2012). To validate the updated inventory map and to confirm the made change, field campaigns were organized. In particular on July 2007, a field survey on the Ruinon landslide was carried out, in the framework of an exercise regarding landslide organized with users (National Civil Protection Agency, Civil Protection of Regione Lombardia, ARPA Lombardia); the objective of field survey is to obtain an overview of the recent evolution of the debris flows and outcrops, and to check the status of the in situ instruments. Several findings of terrain movements were detected on the slope corresponding to the main landslide body such as cracks, topped trees, and structural damages on buildings. Moreover, evidences of few local disruptions were identified in the monitoring instrumentation

2.1. Methods limitation

Though the adopted methodology has many advantages in relation to conventional techniques, that generally are extremely expensive in term of cost and time, there are two types of limitations that are worth considering before used this approach for the landslides detection. The first one is related to SAR interferometry approach and concerns the underestimation of the real movement magnitude due to the direction of measurements (LOS direction) that differs from the real movement direction. Furthermore, considering the direction of satellite movements, some directions of movement are not detectable (N-S direction). The second ones regard the workflow and the use of a Persistent Scatterers as main indicator for landslide detection and activity. Indeed, if the sliding is sudden, PSs are lost in that area. So, as expected by workflow, any type of change in inventory is possible, but that landslide is moving! For these reason we use the datasets independently and proceed with consecutive updating. When a sliding acceleration is recognized a subset of processed image can be desirable even if in this way the accuracy of this method diminish. For these reasons a field survey must be carried out to resolve the ambiguous interpretation and to validate the updates of the landslide inventories.

3. Available data

3.1. Ancillary data

In this paper we integrated the results of A-DInSAR with different thematic maps (ancillary data). Maps on geology, geomorphology, tectonics were collected. Topographic maps at 1:10,000 scale were given us by the Regional Cartographic Office while a Digital Elevation Model (DEM) at 20 m spatial resolution was available at our premises. Digital color orthophotos (Volo Italia 2000), with 1 m of resolution in monoscopic configuration was accessible for the entire area. Corine Land Cover 2006 map at 1:100,000 (EEA, 2007) was analyzed using the 3rd classification rank.

3.2. Original landslide inventory map

The original landslide inventory map of the study area was produced by Regional Civil Protection of the Lombardia Region in 1998. It is part of the landslide inventory of the alpine areas that is a large database with more than 60,000 phenomena, among which 13,863 slides, 802 complex landslides, 1000 large rock-falls, 276 earthflows, 43,600 debris flows. The vulnerability of the area is thus an issue as more than 23 km^2 of urbanized areas in the Lombardy Alps are located on landslides, other 6 km^2 lie on alluvial fans recognized as active and hazardous and, several dams are located in proximity to landslides.

In the study area, that covered about 318 km^2, 866 landslide (more than 62 km^2) and 13 (about 59 km^2) deep-seated gravitational slope deformation (DSGSD) have been recognized (Fig. 3). The state of activity of the 866 landslides was classified as follows in Table 2; all DSGSD are classified as "Relict".

3.3. SAR data

The PSP-DIFSAR processing was applied by Telespazio on a set of 63 images (5 image are discarded for their low radiometric characteristics) acquired in descending mode by the sensors ERS1/2 in the period April 1995 – April 2001 (Track 437; Frame 2673) and on a set of 30 images (the August 8, 2002 image was discarded) acquired in descending mode by the sensors Envisat in the period August 2002 – March 2008 (Track 437; Frame 2673). Considering the characteristics of the image the March 26, 1998 for ERS data and the December 2004 image were selected as master image. The reference point has been chosen in the center of the Bormio village.

From ERS Images 26,345 PSPs (with a density of 82.8 points/km^2) were extracted (Fig. 4a); instead from Envisat images were obtained 10624 PSP (33.4 points/km^2; Fig. 4b).

Furthermore the Persistent Scatterers Interferometry Project (PSIP) of the Italian Ministry of Environment Land and Sea dataset, acquired both in ascending and in descending orbits (http://www.pcn.minambiente.it/; Fig. 5) obtained and integrated in GIS through the WMS services, was analyzed to update the landslide inventory map up to 2009.

Considering the available data in the PREVIEW project only a restricted number of coherent points are located on the landslides and on DSGSD polygons of the OLIM (Fig. 6). The landslides characterized by the presence of coherent points (ERS and/or Envisat) are 151 of the total 861 (interested area 27.83 km^2 of 62.76 km^2, more than 40% of landslide area). The DSGSD characterized by the presence of coherent points (ERS and/or Envisat) are 10 of the total 13 (interested area 49.49 km^2 of 59.2 km^2).

4. Results

Three updated landslide inventory maps were produced using the A-DInSAR technique. The first update is based on ERS1/2 data;

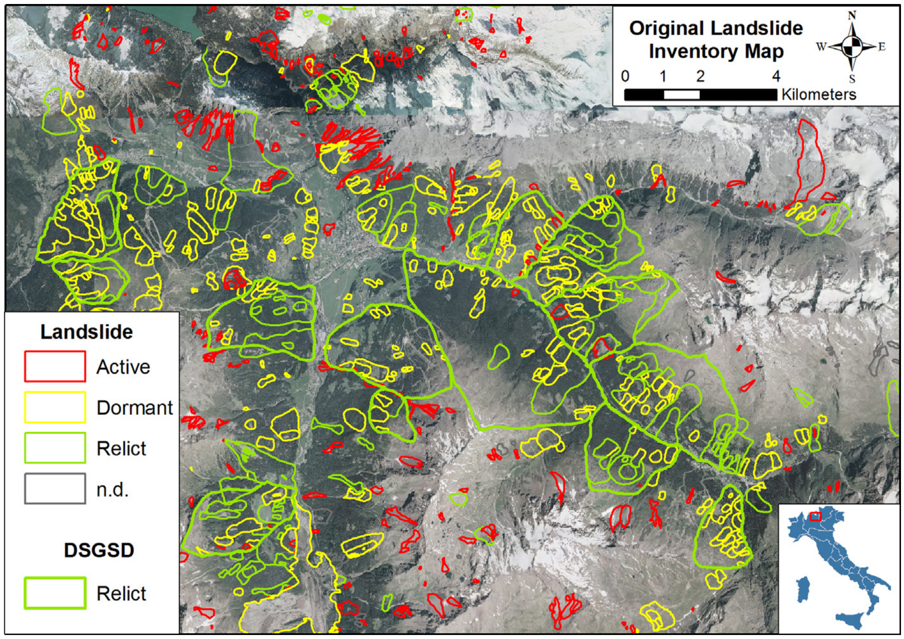

Fig. 3. Original landslide inventory map (OLIM; Regione Lombardia, 1998).

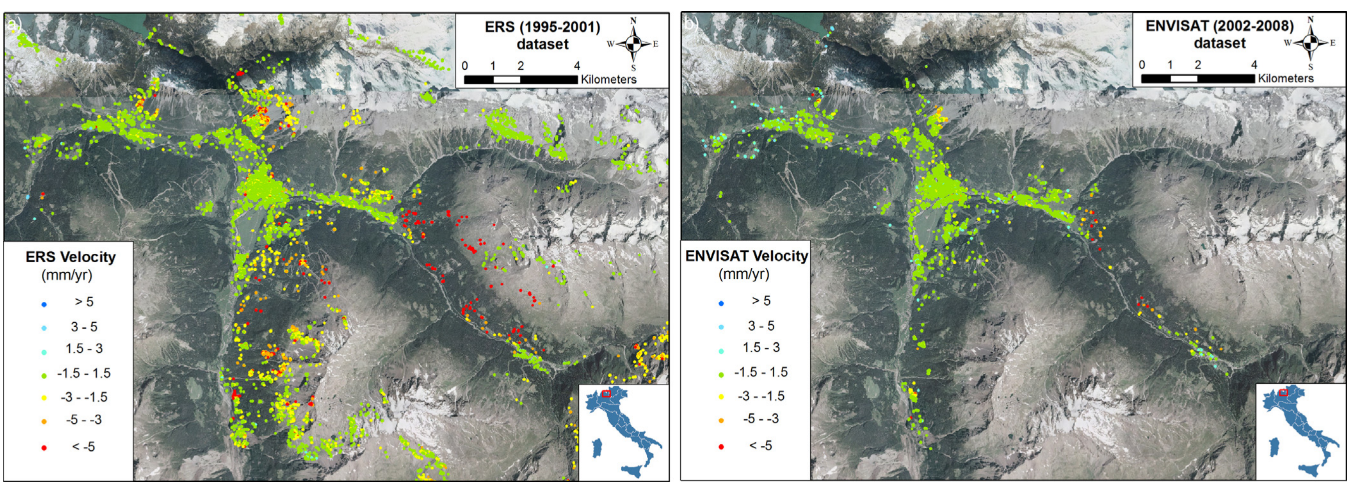

Fig. 4. Spatial distribution of coherent points extracted from ERS-1 and ERS-2 images (a) and from Envisat images (b) processed in the framework of PREVIEW Project.

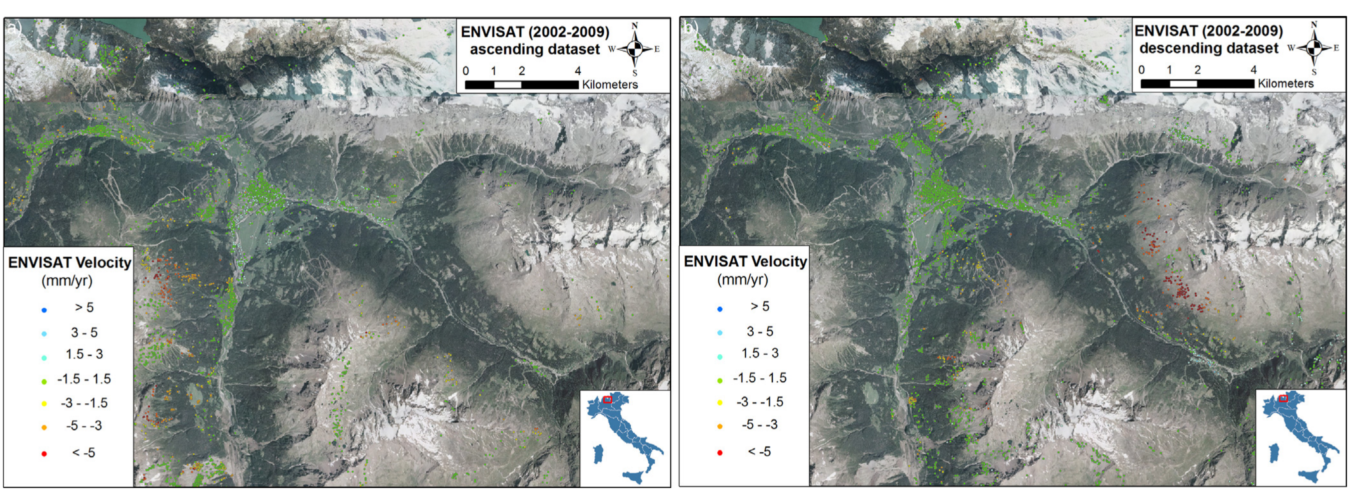

Fig. 5. Spatial distribution of Persistent Scatters derived from Envisat images (2002–2009) of the Persistent Scatterers Interferometry of the (http://www.pcn.minambiente.it/) in ascending (a) and in descending (b) orbit.

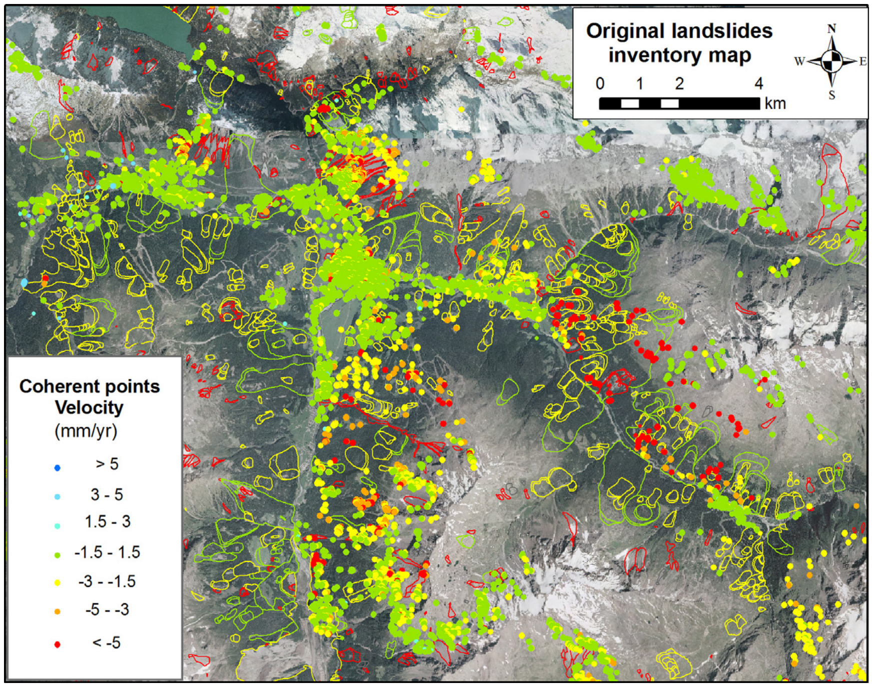

Fig. 6. Overlap between original landslide inventory map and available coherent point.

the second starts from the ERS updated landslide inventory and was made using Envisat dataset up to 2008. A further update of landslide inventory was carried out by considering the Envisat persistent scatterers updated to 2009 derived from PSIP.

4.1. Landslide inventory updates using ERS1/2 data (ERS updated landslide inventory map)

Among all the ERS1/2 PSPs (26345) only a restrict number are located in areas mapped as mass movement in the OLIM; 5018 (19.04% of all ERS coherent points) in landslides and 3200 (12.14%) in DSGSD. The landslides characterized only by ERS coherent points are 65 (7.21 km^2), while only two DSGSD (3.39 km^2) are characterized by the ERS1/2 PSPs. These data, applying the activity matrix in Table 1a, have enabled a first update of the available inventory. ERS PSPs allowed to change the state of activity of 7 landslides (4 rotational and 3 topple) and to identify 4 landslides. Regarding the DSGSD, the state of activity of 1 DSGSD was changed from relict to active.

4.2. Landslide inventory updates using ERS and Envisat data (2008 update and 2009 update)

The PSPs extracted from Envisat image updated to 2008 are 10,624; only 1814 (17.07%) and 1437 (15.53%) are located on landslides and DSGSD respectively. In 75 (20.35 km^2) landslides Envisat PSPs are present. Changes occurred in 42 landslides (Fig. 7a); in 35 of which the state of activity was changed.

The new (until 2009) ascending and descending Envisat dataset allowed to update/verify 139 landslide (28.7 km^2) and to update the inventory up to 2009 (Fig. 7b).

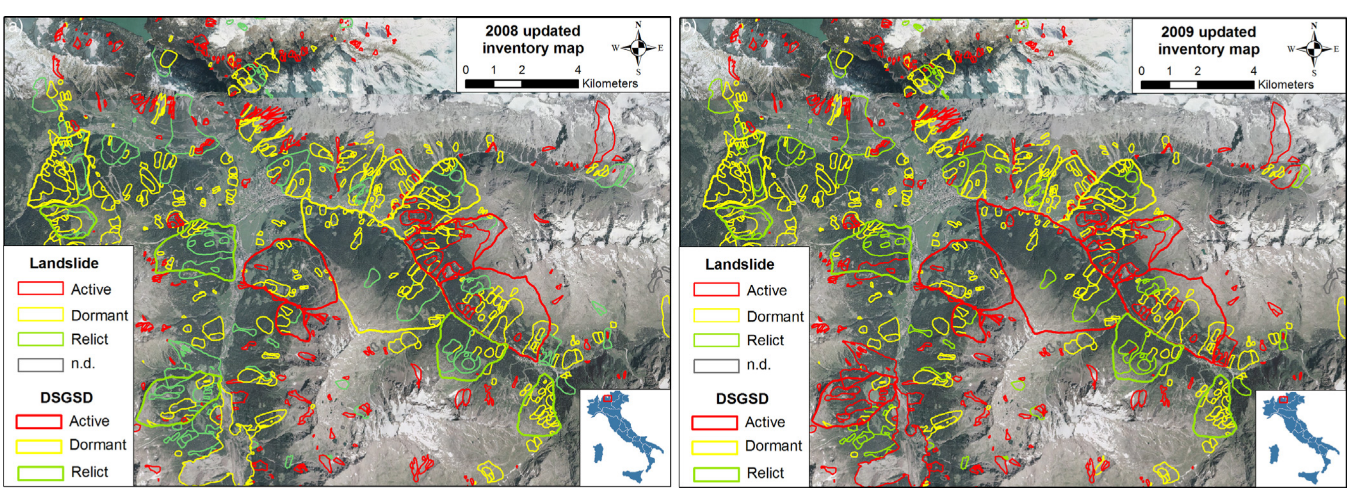

Fig. 7. (a) 2008 updated landslide inventory map using both ERS1/2 and Envisat PSPs derived from PREVIEW Project. (b) 2009 updated landslide inventory map using dataset derived from PSIP and analyzed in the framework of LAMPRE project. Landslides are in thin line while DSGSD are in thick line. Different color show the state of activity: red: Active; yellow: dormant and green: relict. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

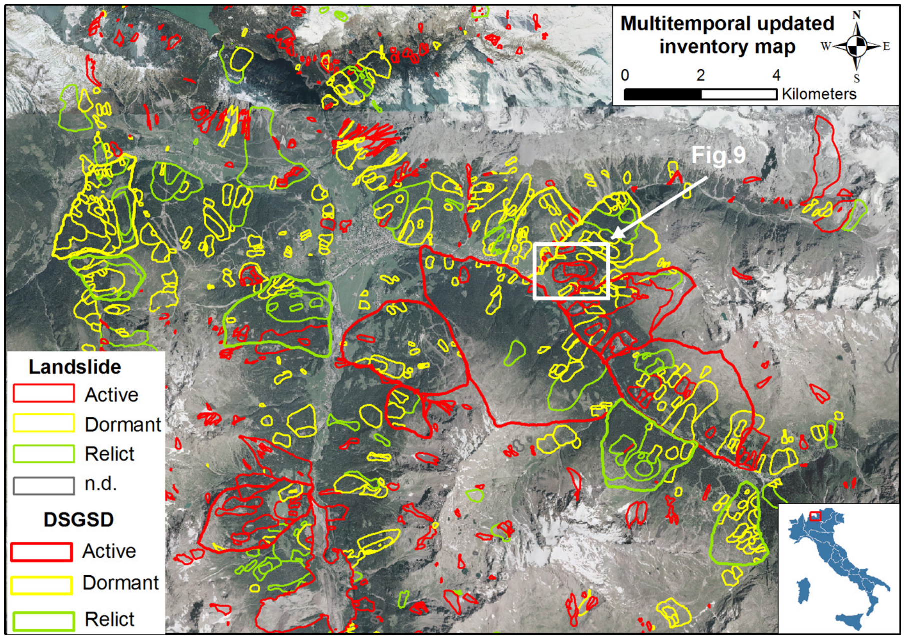

Fig. 8. Comparison between OLIM (a) and multi-temporal (b) updated landslide inventory map.

Table 3
Results derived from the application of proposed methodology (comparison between OLIM and 2009 inventory).

	By number	By area (km^2)	By tipology: number/affected area			
			Rotational	Complex	Topple	Debris
New landslides	5	0.4	N.V.	N.V.	N.V.	N.V.
State of activity	62	14.4	50 (13.5)	3 (0.2)	6 (0.4)	3 (0.3)
State of activity Geometry	3	0.2	3 (0.2)	–	–	–
Geometry	6	0.4	1 (0.1)	2 (0.1)	–	3 (0.2)
Confirmed	135	17.8	100 (12.8)	18 (4.5)	2 (0.3)	15 (0.2)

N.V. = not validated.

Envisat PSPs located into 9 DSGSD (48.3 km^2) allow updating the state of activity of 7 DSGSD from relict to active (Fig. 7).

5. Discussion and conclusion

More than half of the mapped landslides in the original landslide inventory map have been updated applying the proposed method (Fig. 8). The updates of the OLIM give evidence of the importance of the detection and mapping of slope unstable areas using the ground deformation rates from PSI data. Each type of variation are reported in Table 3. In more than 8 km^2 (65 landslide), representing just under half of the entire surface in landslide, the updating regards the state of activity (Table 3; Fig. 9). Main change concern the attribution of an active state to 37 landslides, involving several

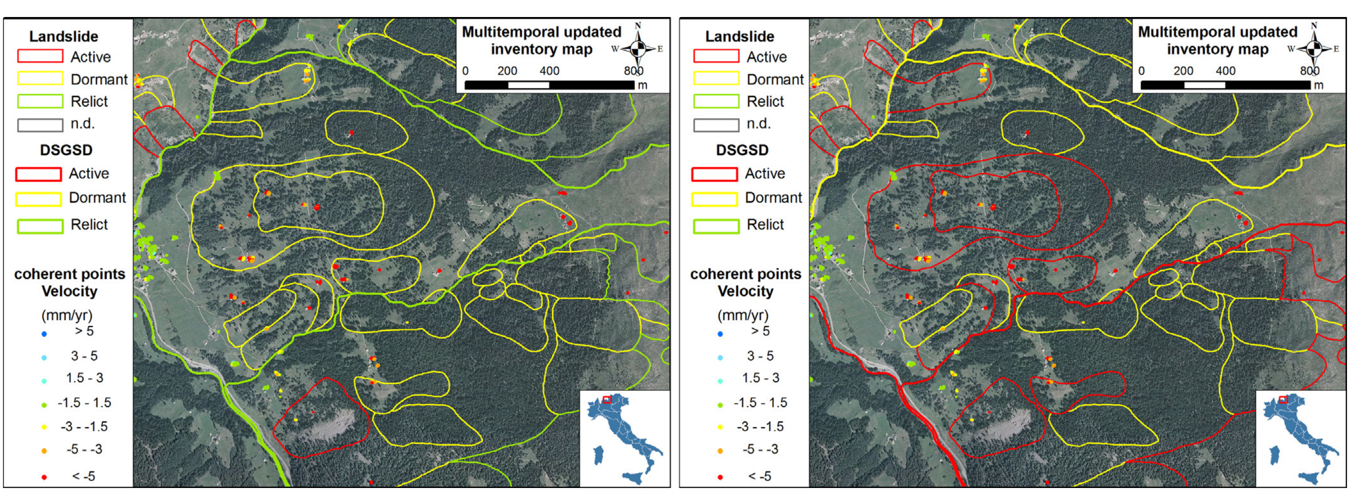

Fig. 9. Examples of changes in landslide activity applying the proposed methods (location is in Fig. 8) between the original landslide inventory map (on the left) and multitemporal updated inventory (on the right).

Table 4
Proposed changes in landslide activity (comparison between OLIM and 2009 inventory).

Original state of activity	Updated state of activity	Number of landslides	Landslides interested area (km^2)
n.d.	Active	1	0.2
n.d.	Relict	3	0.1
Relict	Active	13	6.4
Relict	Dormant	10	3.4
Dormant	Relict	6	0.4
Dormant	Active	24	2.1
Active	Dormant	5	0.4

Table 5
Proposed changes for mapped DSGSD.

	Number of DSGSD	DSGSD interested area (km^2)
Confirmed	4	12.6
State of activity changed (from "stabilized" to "Active")	6	33.83
State of activity changed (from "stabilized" to "Dormant")	3	9.5

squared kilometers, already mapped in OLIM as dormant or relict and of a dormant state to 10 landslide previously classified as relict (Table 4). These updates provide crucial information to end-users and stakeholders for the proper risk mitigation actions planning, considering also the fact that higher density of PS is retrieved where the presence of urban fabric and road network reveals many good radar reflectors. Indeed, further implementations of the applied methodology could rely on the integration of the updated landslide inventory map with a detailed dataset of survey-recorded damages to facilities that may represent indicators of movements (Cascini et al., 2013).

On the other hand, the state of activity was downgraded for 5 landslides only, from active to dormant, also because the use of the activity matrix is carried out using a 'conservative' approach and the activity of such phenomena is not lowered, unless field evidences and in situ data confirm clearly this modification of the activity.

As concern the DSGSD mapped in the inventory, in eleven of them PSPs directly connected to DSGSD activity are detected. The proposed changes in state of activity are shown in Table 5; no update regarding geometry has been possible due to the lack of a sufficient number of PSP.

The updating of slow-moving landslide inventory maps can be an extremely expensive and time consuming task when carried out with traditional techniques only. As demonstrated on Valfurva area the approach using remote sensing data represents a valuable tool and a sustainable method, in term of time and costs (in relation to the observed area), to a periodic update of the state of activity of slow moving landslides at regional scale in relation to net of monitoring systems. However the main limitations of the PSI techniques, such as not enough benchmarks or satellite images available for certain period, the LOS direction and the resolution could affect the reliability of results; improvements will come from new satellite missions with higher spatial and spectral resolution and different spectral bands and from enhancement of radar data processing that will make a significant advance in obtaining more and widespread PS.

The results of this work confirm the capabilities of multi-interferometric InSAR data to support landslide investigation at regional scale and the contribution of such approach to definition of a sustainable urban planning and infrastructure development where risk conditions are higher. In fact, considering the high cost derived from landslide damages and the difficulties in the assessment of the state of activity, the use of the proposed methodology can give an added value to stake holders for risk mitigation.

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