Università degli Studi di Pavia
Dipartimento di Scienze della Terra e dell'Ambiente

MARTINA CAROLINA AGNESE CIGNETTI

Adaptive strategies for a safe landscape: new approaches for the mitigation of slope instabilities impact on anthropic activities

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Coordinatore:

Prof. Roberto Sacchi

Tutor:

Dr. Francesco Zucca

Co-tutor:

Dr. Daniele Giordan

ADAPTIVE STRATEGIES FOR A SAFE LANDSCAPE: NEW APPROACHES FOR THE MITIGATION OF SLOPE INSTABILITIES IMPACT ON ANTHROPIC ACTIVITIES

A thesis submitted to attain the degree of

PHILOSOPHIÆ DOCTOR IN EARTH SCIENCES

presented by

MARTINA CAROLINA AGNESE CIGNETTI

Accepted on the recommendation of:

Dr. Francesco Zucca, academic supervisor

University of Pavia, Department of Earth and Environmental Sciences

Dr. Daniele Giordan, co-tutor

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Abbreviations

AHP	Analytic Hierarchy Process
DEM	Digital Elevation Model
DsGSD	Deep-seated Gravitational Slope Deformation
DTM	Digital Terrain Model
DInSAR	Differential Synthetic Aperture Radar Interferometry
ESA	European Space Agency
GB-SAR	Ground-Based Synthetic Aperture Radar
GIS	Geographic Information System
GNSS	Global Navigation Satellite System
GPOD	Grid Processing On-Demand
IFFI	Inventario Fenomeni Franosi Italiano – National landslides inventory of Italy
MTI	Multi-Temporal Interferometry
LiDAR	Light Detection and Ranging
LOS	Line of Sight
PSInSAR	Permanent Scatterer Interferometric Synthetic Aperture Radar
RTS	Robotized Total Station
SAR	Synthetic Aperture Radar
SBAS	Small Baseline Subset
SfM	Structure from Motion
UAV	Unmanned Aerial Vehicle
WMS	Web Map Service

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Part I

Synopsis

1

Introduction

Slope instabilities occur in most countries of the World, threatening human life and causing damage, generating large socio-economic impacts both in term of casualties and economic losses (Guzzetti, 2000; Haque et al., 2016; Nadim et al., 2006; Salvati et al., 2010; Spizzichino et al., 2013).

A number of causal factors commonly triggers landslides, as rainfalls, rapid snowmelt, freeze and thaw cycles, earthquakes, water level changes, but also, increasingly, by human activities (*e.g.* deforestation, road cut, wildfires) and climate components (Jaboyedoff et al., 2016; Zalasiewicz et al., 2011). In the last decades, the continuous population growth, associated with the increasing of settlements, led to an expansion of urbanization also in areas at high risk (Glade, 2003). Specifically, in high mountain and hilly regions, highly prone to landsliding, the modifications of natural slopes, due to human impacts should increase the landslide risk (Di Martire et al., 2012). Likewise, changes in climate conditions should have a relevant influence on slope instabilities, affecting landslide frequency and intensity (Crozier, 2010; Gariano and Guzzetti, 2016; Huggel et al., 2012). This leads to investigating their role in landslide occurrence and the assessment of the consequent increase in facilities exposure (Schlögl and Matulla, 2018; Seneviratne et al., 2017).

A straightforward definition of landslide impacts is becoming increasingly important in the context of urban planning and identifying areas potentially subjected to severe damage (Fell et al., 2008; Haque et al., 2016; Kirschbaum et al., 2010; Petley, 2012; Turner, 2018). Several noteworthy studies have been done at European scale, focusing on landslide inventories (Herrera et al., 2018; Kirschbaum et al., 2010; Van Den Eeckhaut et al., 2012) and landslide hazard definition into urban planning (Mateos et al., 2020; Spizzichino et al., 2013). However, many open questions remain as to how to implement and define adaptive urban governance and strategic planning, integrating multi-sources and multi-sensors data, measurements and information, specifically in highly landsliding prone areas as the hilly and mountainous ones.

The long-standing recognition of slope instabilities impacts on human structures and infrastructures promoted the implementation of risk reduction strategies and policies, representing key-elements for environmental sustainability at national and global scales. Considering the landslide risk assessment and management cycle, widely described in the literature (Corominas et al., 2014b; Crozier and Glade, 2006; Fell, 1994; Fell et al., 2005; Hungr, 2018; Hungr et al., 2005; Lacasse et al., 2009), mitigation strategies constitute a central component.

Landslide risk mitigation employs various actions range from scientific, planning and policy tools, aimed at minimizing hazard, reduce exposure and losses and improve adaptive capacities. The choice of the proper activities represents a compound process, variably case by case basis and addicted to slope instability characteristics and its related impacts on human life and anthropic elements. Furthermore, the observation scale that can vary from single slope to regional scale, by analysing from a single landslide case study to several slope instabilities, must be considered. Conventionally, these actions include (i) engineering solutions, (ii) monitoring network and warning system, (iii) land utilization regulations.

Engineering solutions are primarily designed to hazard reduction, taking structural actions, mainly through the slope stabilization (*e.g.* drainage and retaining structures, anchoring systems, barriers), to constrain or limit landslide evolution (Bromhead et al., 2012; Popescu and Sasahara, 2009). This type of measure, usually applied for site-specific slope instability, requires detailed engineering design and represents the most direct and expensive strategy among the mitigation strategies.

Widely used, monitoring networks ensure slope instability inspection, also with early warning purposes. Currently, diverse monitoring system help to collect data on ground deformation, ranging from on-site instruments (*e.g.*, global navigation satellite system GNSS, robotized total station RTS, inclinometer, just to cite a few), to more advanced remote sensing methods (*e.g.*, Differential Synthetic Aperture Radar Interferometry DInSAR, Ground-Based GB-SAR, Light Detection and Ranging LiDAR, Unmanned Aerial Vehicles UAV). On-site monitoring networks allow obtaining ground deformation measures with a high temporal resolution, useful for a better analysis of local phenomena, while in general remote sensing techniques are more suitable for the assessment of deformation trends at a regional scale.

Among the remote sensing techniques, the Multi-Temporal Interferometry (MTI) and LiDAR techniques are the most employed in landslides investigation (Herrera et al., 2013; Jaboyedoff et al., 2012; Wasowski and Bovenga, 2014). The MTI techniques (*i.e.*, Small Baseline Subset SBAS (Berardino et al., 2002), Permanent Scatterers PSInSAR™ technique (Ferretti et al., 2001)) constitute a consolidated method to obtain data with extensive spatial coverage, including those hindered by limited or difficult access. Moreover, the increasing availability of multi-temporal satellite acquisition (*e.g.*, ERS-1/2, Enivsat ASAR, RADARSAT-1/2, just to cite few) allows for long-time slope instabilities observations. Besides, new satellite constellations, providing SAR images acquired with a significantly reduced revisit time (*e.g.*, Sentinel-1/2, 6-12 days), represent an essential improvement for detection and monitor with MTI techniques (Mantovani et al., 2019; Solari et al., 2020; Wasowski et al., 2017). LiDAR techniques, as well as UAV exploitation, provide very high-resolution three-dimensional digital representation of the topographic surface. These techniques may be used to map (Ardizzone et al., 2007;

Jaboyedoff et al., 2012), acquire qualitative and quantitative data (Baldo et al., 2009; Colomina and Molina, 2014; Mayr et al., 2018), and evaluate variations in terrain models obtained through different surveys by change analysis approaches. GB-SAR devices represent a suitable solution for change detection and ground displacement assessment of small-scale areas of interest, able to acquire data operating in continuous, and ensuring data with high spatial-temporal resolution (Luzi et al., 2010; Noferini et al., 2007).
Finally, land utilization regulation is mainly devoted to hazard avoidance by employing land use planning measures, primarily consisting of numerous national and regional laws and policies (Leventhal and Kotze, 2008; Mateos et al., 2020; Scolobig et al., 2014). These actions occurred in response to issues relating to (i) the definition of building restrictions and structural defences, (ii) the definition of floods and landslides risks, and (iii) the zoning in distinct areas of various landslide risk. In this context, slope instabilities identification and mapping at diverse scales (*e.g.*, municipal, regional, national scale) represent important tools, constituting the cornerstones for the generation of landslides hazard and susceptibility maps (Corominas et al., 2014b; Reichenbach et al., 2018).
However, in this wide range of mitigation strategies, the need for new approaches to reduce risk and novel adaptation measures becomes increasingly essential for a safe landscape and environmental sustainability. Nowadays, usage of non-structural measures designed in the light of available knowledge, specific practices and guidelines, are becoming increasingly common in landslide risk and impact reduction (Bründl et al., 2009; Flentje et al., 2007; Porter and Morgenstern, 2013; Powell and others, 2002), mainly demanded by the diverse geological survey and local and or national authorities all over the World. Against this background requirements for a more adaptive and strategic planning approach are researched by considering some still open issues, specifically in terms of: (i) establishment of the potential impacts of diverse typologies of the landslide on anthropic elements; (ii) definition of correct management of a large amount of data in the field of monitoring, and (iii) development of dedicated methodologies and codified procedures for the diverse phases of an emergency, specifically for that period between the phenomena occurrence and mitigations activities implementation.

1.1 Aim and scope

The main goal of this thesis is to implement and define new adaptive strategies for slope instabilities management and regulations, and assess their impact on anthropic activities, to develop decision-making tools for landslide risk management and mitigation. Focusing on diverse typologies of slope instabilities, distribute in the Italian territory, and taking advantage of various on-site and remote sensing techniques, substantial exploitation of the still open issues before mentioned and the challenges of dedicated approaches and methodologies implementation are addressed.
The first open question refers to the establishment of the potential impacts of slope instabilities on anthropic structures and infrastructures. Landslides impacts on human life and public and private facilities, *e.g.* lifeline, buildings, strategic infrastructures, is well-known in the literature

(Hervás and Bobrowsky, 2009; Spizzichino et al., 2013; Trezzini et al., 2013). Rapid and very-rapid slope instabilities are, usually, the most investigated, also with early warning purposes (Allasia et al., 2019; Manconi et al., 2013; Pratesi et al., 2015; Thiebes et al., 2013), due to the primary hazard and risk associated. Instead, very slow or extremely slow phenomena, considered less hazardous, are commonly not monitored with traditional on-site instruments, as classical occur for other landslides. Thanks to the Remote Sensing techniques as the space-borne Differential Synthetic Aperture Radar Interferometry (DInSAR) techniques (Berardino et al., 2002; Ferretti et al., 2001; Hooper et al., 2004), the measurement of the continuous slope deformation of slow and very-slow moving phenomena has been computed and analyzed, over a long-span period (Béjar-Pizarro et al., 2017; Cascini et al., 2010; Crippa et al., 2019; García-Davalillo et al., 2014; Meisina et al., 2013). However, an aspect poorly investigated in literature is the impact of these huge slow-moving phenomena on anthropic activities over time, especially for linear anthropic structures and infrastructures as roads, penstocks, or dams. On that basis, the PhD research intend to fill this gap through the investigation of slow-moving landslide behavior over time and their interaction with anthropic elements, an aspect that represents a fundamental issue, still open. A characterization of the relationships of these slow-moving slope instabilities and anthropic infrastructures, indeed represents a core element in term of land use planning revision and policies update, specifically for mountainous regions.

The second open question concerns the definition of proper management of landslide analysis and monitoring data results. A large amount of data and information, derived from multi-source and multi-sensors acquisitions, are important support for a better comprehension of the studied area. Still, they should represent a problem in term of fruitful data collection and organization over time, both referring to a single phenomenon or group of landslides. In literature, some efforts have been made to emphasize the importance of the correct management of available data, associated to a clear representation and dissemination in the field of landslide monitoring, specifically for single landslide case study (Frigerio et al., 2014; Giordan et al., 2019; Lan et al., 2009; Li et al., 2010; Napolitano et al., 2018).

On the one hand, for the investigation at the scale of a single phenomenon, particularly in the case of active landslides cases, an ongoing monitoring data collection over time can lead to consistent information about each single analyzed phenomenon. This should represent a challenge in term of landslide risk analysis and management, specifically for policy-makers. For this reason, this research is aimed at providing a practical response, consisting on the implementation of a specific tool, named "Operative Monography", to collect and manage all the available information about any single studied phenomenon over time. This tool has been designed to guarantee a useful instrument for policy-makers, specifically in term of future interventions and actions planning. Through a more effective combination of the available information together with ground deformation measurements obtained by the monitoring networks, this dedicated tool represents a key element in slope instability risk management and mitigation for a more effective non-structural management strategy implementation.

On the other hand, considering the occurrence of several slope instabilities on a larger scale, *e.g.* national or regional, the amount of available data significantly grows. Thanks to the diverse typology of monitoring technologies and sensors, the scientific community is going through a data-rich period concerning slope instabilities analysis and observations (Allasia et al., 2019; Bonì et al., 2018; Herrera et al., 2013). Consequently, the increasing demand to collect, manage and in particular to share a vast archive of multi-source and multi-sensor data, supporting slope instabilities investigation, specifically at the regional or national scale, become evident in the scientific community. In this context, web service technologies, as spatial data infrastructures aid to manage large and heterogeneous data infrastructures about diverse slope instability. These solutions may represent a useful instrument for display, collect and share data and information, in agree with well-known standard protocols (*e.g.*, Open Geospatial Consortium). For this reason, this research focus on the analysis of useful, usable and adaptable open-source web-platform. These tools should represent a key element for both scientific community and local/regional authorities, as well as to other stakeholders, for analyzing, manage and share heterogeneous databases, with landslide risk management and land use planning purposes.

Finally, the last open issue concerns the development of dedicated methodologies and codified procedures for landslide risk management, with a focus on the organization of the diverse phases of an emergency. In recent years, the need for policy-makers to define non-structural measures in the framework of landslide mitigation strategies and land use planning becomes increasingly evident (Giordan et al., 2019; Raetzo et al., 2002; Wrzesniak and Giordan, 2017). Along with the classical mitigation strategies, the definition of specific codified actions, operations and responsibilities of the involved stakeholders is crucial for a proper assessment of slope instabilities hazards and the potential impacts associated. Going to this direction, the implementation of a standard procedure aimed at both manage previous data derived from landslide analysis and regulate the interoperability of geoscientists, practitioners and landscape management represents an open issue. For this reason, the core issue of this research is devoted to the development of codified procedures, implemented taking advantage of well-established methodologies for slope instabilities characterization, and landslides risk or susceptibility definition, key elements in terms of slope instability impact assessment and management. In many fields, as clinical or industrial risks, the adoption of standard protocols is mandatory to establish the specific actions that competent institution and stakeholders should carry out. Therefore, in landslide risk management, particularly in cases in which slope instabilities threatening strategic infrastructures (*e.g.*, road network, railways, penstock) or landscapes with renowned cultural and geological heritage, the definition of diverse scenarios, establishing "*who does what and when*", should represent a key element. Specifically, with a focus on pre-emergency, emergency and post-emergency phases. Considering diverse typology of slope instabilities, the definition of an operating methodology, specifically for all those actions taking place between event collapse and the realization of regulation infrastructures work to reduce the residual risk, becomes increasingly important.

1.2 **Conceptual framework of the PhD Thesis**

In order to develop novel and useful decision-making tools for landslide risk management and mitigation, this research is designed to implement diverse methodologies and primarily non-structural measures, through concrete exploitation of various type of slope instabilities, mainly located in the Italian territory.

Among the others countries in Europe, Italy shows a prevalently hilly and mountainous landscape, revealing a notable exposure to landslide hazard, causing significant casualties and damage to anthropic elements (Guzzetti et al., 2005; Salvati et al., 2010). The National Landslide Inventory, named IFFI (Trigila et al., 2008), collects more than 620.000 phenomena, affecting about 8% on the entire national territory. Landslides vary for type and size, ranging from small phenomena, with high velocity and impact forces as rockfalls, shallow landslides (*e.g.* debris flow, rotational slide), to large slow-moving landslides, which may remain active for hundreds of years, as the Deep-seated Gravitational Slope Deformations (DsGSDs).

In order to obtain a framework most comprehensive as possible, in term of landslide type and size, several typologies of the landslide (Table 1) have been considered in this thesis, specifically: (i) Deep-seated Gravitational Slope Deformations; (ii) complex landslides; (iii) shallow landslides; (iv) rockfalls.

Table 1 – Summary of the considered landslide types.

Considered typologies	Brief definition	Main literature
Deep-seated Gravitational Slope Deformation	*Large-slope gravitational deformation of steep, high mountain slopes, manifested by scarps, benches, cracks, trenches and bulges, but lacking a fully defined rupture surface. Extremely slow movement rates, characterized by continuous deformation over time, also for hundreds of years* (Hungr et al., 2014)	(Crosta et al., 2013; Zischinsky, 1969, 1966)
Complex landslide	*Composite slope instabilities without a separate class in landslide classification, usually defined by diverse types of landslide. Usually large slope instabilities, sometimes evolving in rapid and catastrophic events.*	(Cruden and Varnes, 1996; Hungr et al., 2014)
Shallow landslide	*Phenomena triggered by rainfalls with high-intensity and short duration, or precipitation of medium-intensity and high duration, which mainly occur on*	(Caine, 1980; Guzzetti et al., 2008; Hungr, 2005)

	slopes with impermeable bedrock and a shallow permeable layer, affecting small thickness (less than 2-3 meters deep)	
Rockfall	*Detachment, fall, rolling and bouncing of rock or ice fragments. May occur singly or in cluster […]. Usually of limited volume* (Hungr et al., 2014)	(Dorren, 2003; Hungr et al., 2014; Volkwein et al., 2011)

Due to the high variability of considered slope instabilities, in term of kinematic, state of activity and velocity, behaviour and evolution over time, different approaches, methodologies and adaptive solutions have been designed. Also, in term of the scale of investigation, *i.e.* from the slope-scale for the site-specific analysis of a single phenomenon, to the regional scale slope instabilities observation, multidimensional design investigation has been necessary.
Starting with each type of landslide, a reiterated structured, divided into three main phases, is proposed. Figure 1 shows the schematic framework of the reiterate stages applied.

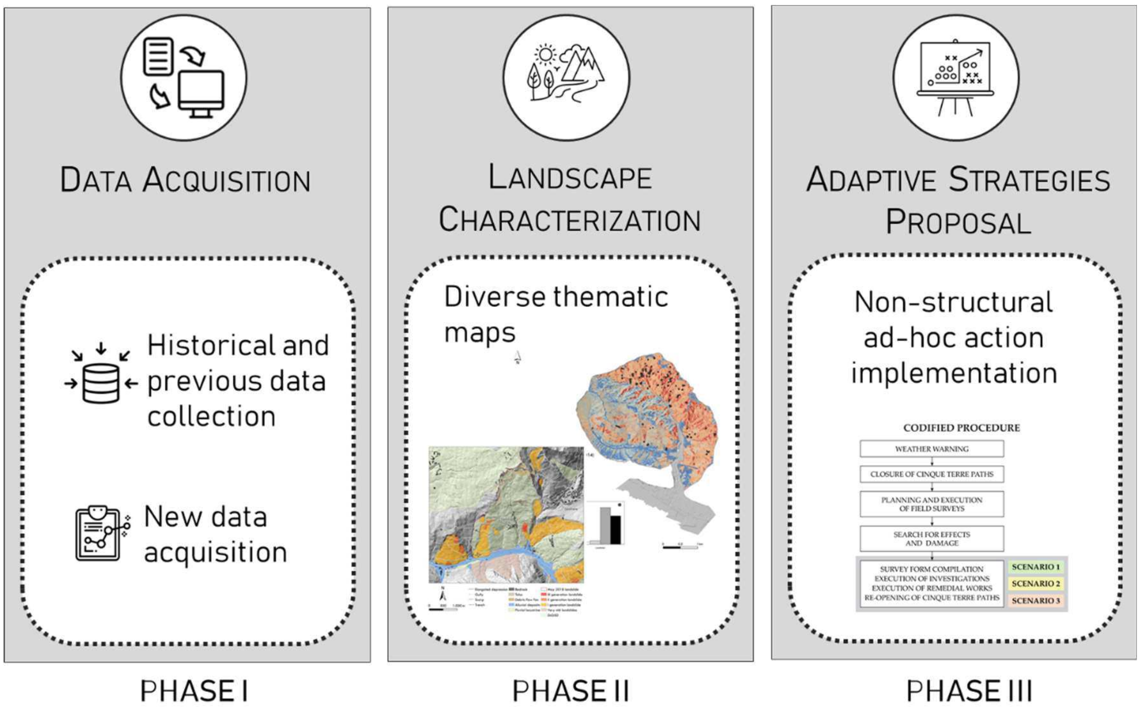

Figure 1 – Schematic framework of the reiterated structured divided into three stages, applied for each considered type of slope instability.

Specifically, the stages of the proposed reiterated structures for the diverse type of slope instabilities considered in this research, *i.e.* DsGSDs, complex landslides, shallow landslides, and rockfalls, are summarized in Figure 2.

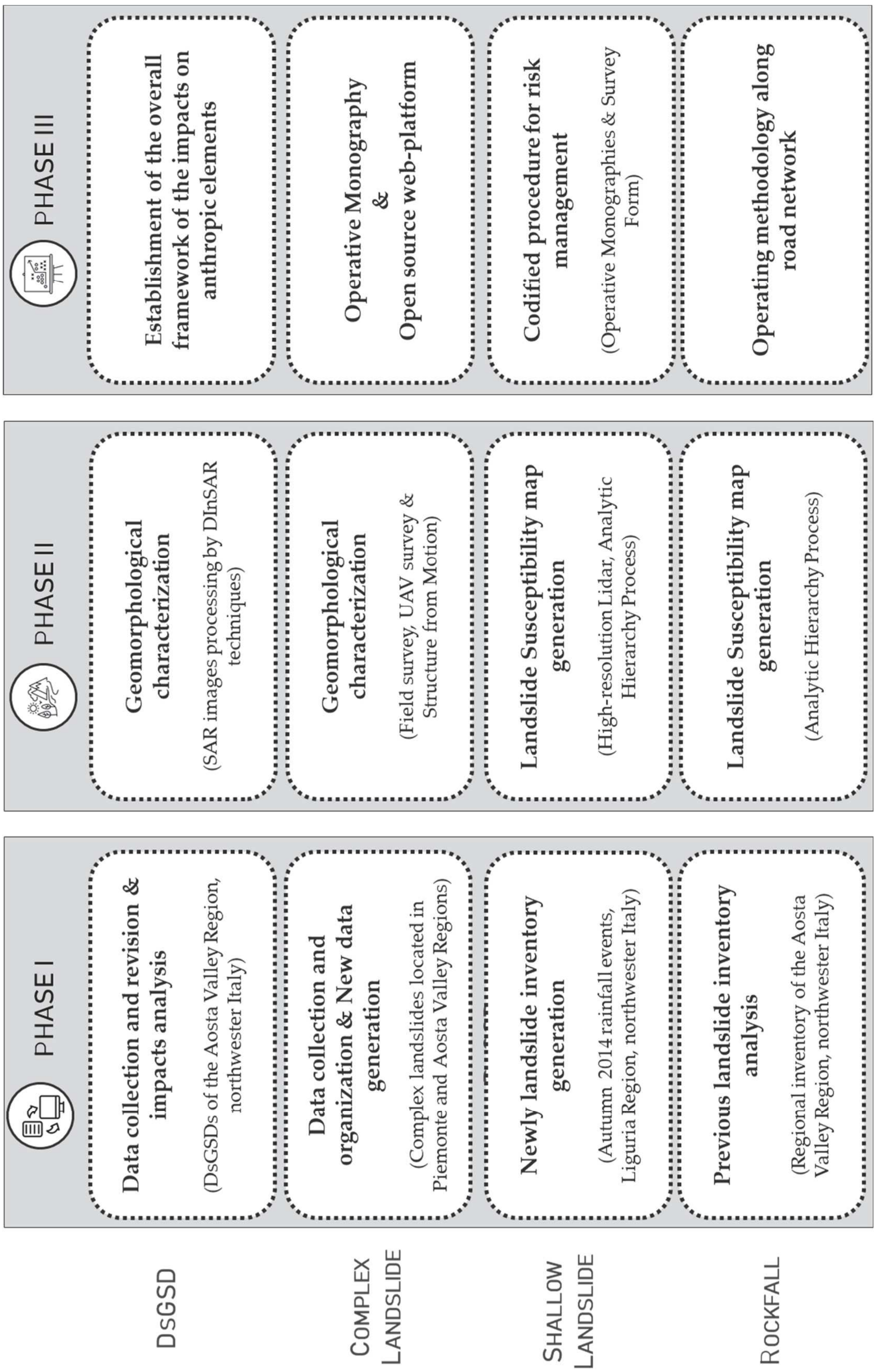

Figure 2 – Schematic framework of the reiterated structure proposed for the diverse type of slope instabilities considered in this research.

Phase I is dedicated to data acquisition and collection, functional to the investigation of the diverse typologies of slope instability considered, to optimize the integrated use of available knowledge.

Landslide phenomena analysis commonly requires a wide variety of data and information. Slope instabilities investigation, usually, concerns geomorphological, geological and structural settings definition, state of activity and evolution characterization and slope deformation measurements. The acquisition of systematic information on landslide type, distribution, behaviour characterization, or deformation range quantification, usually entails time-consuming and resource-intensive. The applicable methodologies are diverse, functional to the type of slope instability investigated and of the observation scale, varying from the most conventional methods as field survey (Corsini et al., 2005; Frodella et al., 2014), functional to slope instability identification and characterization, as well as the traditional on-site monitoring techniques application (*e.g.* GNSS, RTS, inclinometer), providing ground deformation computation highly suitable at the scale of the single case study investigation (Corominas et al., 2005; Heunecke et al., 2011; Manconi et al., 2013). Instead, to carry out a large-scale analysis (*e.g.* national, regional) on several slope instabilities, the relatively recent remote sensing techniques constitute a useful tool highly effective to investigate vast areas, often inaccessible. These techniques exploit data from various sources like satellite, airborne and terrestrial acquisitions (Bonì et al., 2018; Jaboyedoff et al., 2012; Mantovani et al., 2019; Razak et al., 2011; Wasowski and Bovenga, 2014). In particular, multi-temporal SAR data processing provide an effective instrument to characterize the state of activities of large slow-moving phenomena, like the DsGSDs. Moreover, SAR data may be exploited to recognize the most active sectors (Giordan et al., 2017a)(Appendix B) and the potential domains with diverse level of activity of these large phenomena.

A noteworthy instrument is represented by unmanned aerial vehicle (UAV), increasingly widespread in recent years, less expensive compared to remote sensing techniques, and able to conducting repeat surveys in a short time, representing a suitable solution for small landslide and site-specific investigation (Fernández et al., 2016; D. Giordan et al., 2017c; Rossi et al., 2018; Turner et al., 2015).

The availability of multi-source and multi-sensor data and information allows to a slope instability phenomenon characterization as comprehensive as possible. This is functional to the optimization of the existing data, their re-organization and integration for non-structural measures implementation in the framework of the landslide risk management and mitigation. The data acquisition stage, referring to diverse phenomena, varying from site-specific landslides to group of slope instabilities mainly distribute in hilly and mountainous regions, primarily consisted of available data retrieval and newly data acquisition.

For each category of slope instability considered (Table 1) an in-depth data retrieval has been done, referring to both site-specific case studies or regional contexts scale. The primary information sought is: (i) the extent and spatial distribution of slope instabilities; (ii) link with morphological and geological settings; (iii) ground deformation measurements information.

In the last years in Italy, a wide range of data and information concerning slope instability phenomena have been published on-line in dedicated web-GeoPortals. By exploiting primarily national and or regional landslide inventories, variable information on the extent, typology, temporal occurrence of landslides, and in some cases other ancillary data (*e.g.* recorded damage, the volume of the event) have been collected. Moreover, some regional inventories also provide a different level of depth of information which depends on the knowledge available, passing through the regional scale to specific case studies investigation. It is important to note that drawing on the web-GeoPortals, validated sources and documents, in accordance with the principles of the Open Data and of the Open Government (Vetrò et al., 2016), are guaranteed, ensuring essential access points to environmental and territorial information at diverse observation scale. By this way a wide range of data and information freely usable and downloadable in various formats (*e.g.* .shp, .csv, GeoTiff, WMS, raster) are retrievable.

The available data retrieval and collection become fundamental in the PhD research to define the current knowledge about both a single phenomenon at the slope scale and group of landslides distributed at the national or regional scale. A proper collection and re-organization of this information and data are designed to ensure the enhancement and the optimization of the existing data for a functional and more effective landslide risk management and mitigation through their integration in the implementation of non-structural measures.

Jointly, new data acquisitions have been carried out, focusing both on site-specific case studies and slope instabilities investigation over vast areas. Due to the high variability of the landslide typology and the survey scale, diverse approaches and methodologies have been applied. On the one hand, in the case of site-specific analysis mainly related to newly and or reactivated landslides events, dedicated field campaigns and investigations have been carried out, also exploiting UAV high-resolution images acquisitions. On the other hand, for slope instabilities analysis over vast areas, as in the case of numerous landslides occurred during relevant rainfall events, LiDAR acquisition and orthophotos associated have been used.

The Phase I becomes fundamental, representing a preliminary step toward landslides morphological and behaviour assessment, their relationships with anthropic structures and infrastructures valuation, and also landslide risk and susceptibility definition. Established a clear basis of knowledge about one or more slope instabilities and a fruitful re-organization and interrelation of the available information and data through the stage one, Phase II mainly consists in landscape characterization referring to each type of considered slope instability. Specific thematic maps have been generated, focusing on diverse physiographic and geographic areas, with varied and combined purposes:

i. geomorphological and geological settings characterization
ii. assessment of slope instability evolution over time
iii. phenomena interactions with anthropic elements and related impact definition
iv. identification of those areas more susceptible to a specific type of landslide

As mentioned before, most of the areas of interests are located in Italian territory, mainly in hilly and mountainous regions. Furthermore, the diverse typology of slope instabilities considered (Table 1) exhibits a highly variable observation scale, ranging from single case studies to slope instabilities investigation over wide areas. At this stage, the combined use of diverse methodologies and techniques ensured a highly detailed description of the various investigated slope instabilities at the diverse scale, also considering the specific characteristics of the landscape, its potential geological and cultural heritage, and its peculiarities in term of human impact.

For geomorphological and geological settings characterization and the assessment of the slope instability evolution, diverse methodologies have been applied and or implemented for specific case studies investigation (*e.g.* DsGSDs, complex landslides). In particular, beyond data collected by traditional field surveys and orthophotos interpretation, the Structure from Motion (SfM) technique (Westoby et al., 2012) has been exploited, as in the case of the complex landslide typology. This photogrammetric technique is a relatively new image processing based on computer vision algorithms, able to generate Digital Elevation Models and orthoimages with high-resolution. Through the acquisition of very-high and high-resolution images by UAV surveys, and by exploiting both aerial and terrestrial photos, these techniques are highly suitable for small areas investigation.

For wide areas investigation, a specific mention shall be made for satellite data acquisition and processing with dedicated software and script (*e.g.* SqueeSAR™, SBAS, script developed by the Centre Tecnològic Telecomunicacions Catalunya (CTTC) of Barcelona), highly suitable to measure ground deformation variability over highly extended and inaccessible areas. In order to define the state of activities of slope instabilities at a regional scale, Multi-temporal Interferometric (MTI) techniques are exploited (Herrera et al., 2013; Wasowski et al., 2017), specifically for DsGSDs characterization and their morpho-structural domains identification (Giordan WLF). Moreover, thanks to the employment of new and innovative free-services like the European Space Agency (ESA) Grid Processing On-Demand, *i.e.* G-POD tools, a SAR images processing in an unsupervised fashion, based on the validated Parallel-SBAS (P-SBAS) algorithm (Casu et al., 2014), to measure ground deformation of specific case study an area of interest, could be carried out (Cignetti et al., 2016). Generally, these remote sensing techniques are suitable to observe and monitor ground displacements over extended areas, specifically for slow-moving landslides, as the DsGSDs. However, some intrinsic limitations of DInSAR techniques (*e.g.* phase decorrelation on vegetated areas, coherence loss due to large revisit time, phase decorrelation due to large or rapid displacement, line-of-sight LOS measurements only), must be considered. Recent satellite constellations, providing SAR images with significantly reduce the revisit time (*e.g.* Sentinel-1 6-12 days), represent an important improvement for detection and monitor slope instabilities. A testing work by exploiting Sentinel-1 images has been done in the framework of the internship at the CTTC of Barcelona for several site-specific DsGSDs phenomena investigation.

Concerning the investigation of the relationships between landslides and anthropic elements, Geographic Information System GIS-environment has been exploited, combining previous data and information collected and acquired in Phase I (*e.g.* shallow landslides, DsGSDs). For anthropic elements identification and collection, the principal regional cartographic elements derived from regional technical maps of the areas of interest, have been used. Among the slope instability considered, a focus has been dedicated to DsGSDs, slowly phenomena but with continuous deformation over time, poorly investigated in term of landslide risk assessment and management. This aspect is fundamental to define a more comprehensive as possible framework of the landslide impacts on human life and anthropic structures and

infrastructures, specifically for those slow-moving phenomena, usually considered with a low or almost totally absent hazard, as the DsGSDs.
In term of identification of areas more susceptible to landslides, the Analytic Hierarchy Process (AHP) (Saaty, 1977) has been applied to generate landslide susceptibility maps for both shallow landslides and rockfalls typologies. Among the numerous methodologies available for landslide susceptibility assessment (Reichenbach et al., 2018), mainly grouped on knowledge-driven, the data-driven and physically-based methods, the AHP is a semi-quantitative index-based method. This method can organize and analyze a multi-criteria decision, useful in landslide susceptibility analysis that depends on a multiple-knowledge of causative factors in landslide occurrence. Landslide susceptibility express the proneness to landsliding of an area, based on such environmental characteristics (Corominas et al., 2014a), constituting an initial step towards the landslide risk assessment.
Based on the effective management of the available information and the knowledge and characterization of the landscape, Phase III is totally devoted to implement and define dedicated and specific adaptive strategies, with the concrete exploration of the various slope instabilities considered. The development of dedicated methodologies for landslide risk management, is increasingly important, specifically for those areas highly urbanized, in some cases including cultural and geological heritage, or presenting strategic anthropic structures and infrastructures.
The main intent of this research is to develop a contextualized response to environmental characteristics for each type of slope instabilities, able to provide a real tool for policy-makers in the framework of landslide risk management and land use planning. Besides the classical structural mitigation strategies and remedial works applied to reduce landslide risk, the definition of specific actions, operations and responsibilities of the involved governments, technician and the other stakeholders, is fundamental. Specifically, in the organization of the diverse phases of an emergency, these aspects become essential. The actions may be diverse and with different purposes, mainly summarized in:

i. implementation of methodologies and tools to improve the definition of the overall framework of slope instabilities impacts on anthropic structures and infrastructures;
ii. delineation of guidelines and regulations for more effective interoperability of geoscientist, practitioners and governments in the diverse phase of an emergency;
iii. proper management of a large amount of data and information about slope instabilities and their administration overtime definition;
iv. exploitation of suitable open-source services for multi-source and multi-sensor slope instabilities data and information collection, management and sharing.

Considering slope instabilities interfering with highly anthropized landscape or with anthropic structures and infrastructures, together with the usual characterization and analysis of slope instabilities and the eventual remedial work structuration, the non-structural measures able to integrate available knowledge, become essential for practices and agreements definition. These non-structural measures will have to include diverse aspects, from landslide analysis, legislative framework, to policies able to regulate the interoperability of geoscientists, practitioners and other stakeholders. In this research, codified procedure for diverse type of landslides risk management and mitigation in different contexts are developed. These procedures, leveraging on the well-established methodologies for slope instabilities investigation, and landscape characterization presented before, propose a standard protocol to follow in the diverse potential scenarios. By this way, it is possible to establish those specific actions that competent institution and the other stakeholders should undertake, focusing on the various phases of an emergency, specifically for impulsive phenomena like shallow landslides and rockfall events. A diverse issue altogether concerns the DsGSDs phenomena. A dedicated action is carried out to the definition of relationships between these slow-moving slope instabilities and anthropic structures and infrastructures. In general, landslide impact is an aspect widely investigated in the literature, particularly for those landslides with high velocity and high impact (Crosta et al., 2012; Giordan et al., 2013; Mantovani F. et al., 2000). However, for slow to very-slow-moving phenomena (*i.e.* DsGSDs) this aspect is partially overlooked or less investigated than other kinds of landslides. Through the investigation of the long-term impact of DsGSDs on anthropic elements, this research wants to try to establish the basis for a more suitable and effective land-use planning that, actually, consider only partially these phenomena in urban planning legislation.

Another critical challenge in the framework of landslides characterization and related risk management and mitigation is represented by a proper collection and management of a large amount of data and information about slope instabilities and their administration over time. At the slope-scale, active phenomena threatening human life and or anthropic elements are usually investigated by a series of field survey analysis, ground deformation measurements, evolution models. In order to improve knowledge about landslide behaviour, commonly multiple investigations are often repeated several times by diverse practitioners and technicians on behalf of the competent authority. This should generate a large amount of data and information, which time to time have a different structure and data organization and presentation, sometimes creating possible misunderstanding. In this research, the answer to this issue is represented by the implementation of the so-called “Operative Monographies”, a standard document with the ambivalent function of providing a reasoned guidance for the effective management of the available data and information, and to propose future interventions and actions. The suggestion of a standard document that integrates multi-source information and data (*e.g.* monitoring network acquisitions, geological, geomorphological, structural data), easily readable and updatable over time, aims at providing a useful tool applicable in diverse context and for diverse type of slope instabilities, useful for landslide risk handling and land use planning purposes.

Jointly, for slope instabilities analysis over wide areas, information and data can significantly increase. In that case, web-GIS services constitute a valuable instrument representing a repository to store, manage and share landslide multi-source and multi-sensors data and information. This research leverages on open-source services, *i.e.* GeoNetwork, with a framework based on institutional arrangements and technologies, and with specific policies on metadata and data sharing and management. Standard formats and protocols guarantee prompt and user-friendly accessibility of data and information to different stakeholders, allowing their reusing in landslide risk management and in urban planning practices in a secure way.

1.3 **PhD research structure**

The PhD research was mainly carried out at the Research Institute for Geo-Hydrological Protection of the National Research Council (CNR-IRPI) of Turin, in which I am Research Fellow from 2014. Specifically, the research was developed and took place with the Geo-monitoring Group (GMG) of the CNR IRPI, mainly operating in the field of geo-hydrological processes investigation and monitoring, also as Centre of Competence of the Italian National Civil Protection Department, and with the University of Pavia. This allowed to the availability of diverse facilities (*e.g.* LiDAR acquisitions, UAVs surveys, on-site monitoring networks) and know-how, extremely useful and functional in the field of this PhD research.
Following the introduction section (Chapter I), devoted to defining aim and scope and the conceptual framework of the thesis, four other chapters, one for each type of slope instability considered in this research, are structured: Chapter 2, DsGSDs; Chapter 3, complex landslides; Chapter 4, shallow landslides; Chapter 5, rockfalls. In each chapter, a brief introduction to present the stages of the reiterated structure proposed is made, followed by the results performed and presented in the form of published or in preparation scientific publications.

Chapter 2 – Deep-seated Gravitational Slope Deformations

Paper I: Giordan D., Cignetti M., Godone D., (in preparation) *Geomorphological map of the main Deep-seated Gravitational Slope Deformations of the Aosta Valley Region (NW Italy)*. To be submitted to Journal of Maps.

Paper II: Cignetti, M., Godone, D., Giordan, D., Zucca, F. (2020) *Impact of Deep-seated Gravitational Slope Deformation on urban areas and large infrastructure in the Italian Western Alps*. Science of the Total Environment, **740**, 140360.
DOI: 10.1016/j.scitotenv.2020.140360

Chapter 3 – Complex landslides

Paper III: Giordan, D., Cignetti, M., Wrzesniak, A., Allasia, P. Bertolo, D. (2018) *Operative Monographies: Development of a new tool for the effective management of landslide risk*. Geosciences, **8(12)**, 485.
DOI: 10.3390/geosciences8120485

Paper IV: Cignetti, M., Godone, D., Wrzesniak, A., Giordan, D. (2019) *Structure from motion multisource application for landslide characterization and monitoring: The Champlas du Col case study, Sestriere, north-western Italy.* Sensors, **19(10)**, 2364.
DOI: 10.3390/s19102364

Paper V: Cignetti, M., Guenzi, D., Ardizzone, F., Allasia, P., Giordan, D. (2019) *An open-source web platform to share multisource, multisensor geospatial data and measurements of ground deformation in mountain areas*. ISPRS International Journal of Geo-Information, **9(1)**, 4.
DOI: 10.3390/ijgi9010004

Chapter 4 – Shallow landslides

Paper VI: Cignetti, M., Godone, D., Giordan, D. (2019) *Shallow landslide susceptibility, Rupinaro catchment, Liguria (Northwestern Italy)*. Journal of Maps, **15(2)**, 333-345.
DOI: 10.1080/17445647.2019.1593252

Paper VII: Giordan, D., Cignetti, M., Godone, D., Peruccacci, S., Raso, E., Pepe, G., Calcaterra, D., Cevasco, A., Firpo, M., Scarpellini, P., Gnone, M. (2020) *A new procedure for an effective management of geo-hydrological risks across the "Sentiero Verde-Azzurro" trail, Cinque Terre National Park, Liguria (north-western Italy)*. Sustainability, **12(2)**, 561.
DOI: 10.3390/su12020561

Chapter 5 – Rockfalls

Paper VIII: Cignetti M., Godone D., Giordan D., Bertolo D., Thuegaz P., Paganone M. (Accepted 9 November 2020) *Rockfall susceptibility along the regional road network of Aosta Valley Region (northwestern Italy)*. Journal of maps.
DOI: 10.1080/17445647.2020.1850534

In the last section, Chapter 6, the main consideration and conclusions of this research are presented.
In Part II are reported the appendix, divided into two sections. Appendix A includes all the annexes (*e.g.* thematic maps, supplementary materials) of the papers published during the PhD research.
The Appendix B, instead, includes two paper published immediately before the beginning of the PhD thesis, which constitutes key elements in the PhD research line, respectively for shallow landslides and DsGSDs typologies, and, for this reason, reported in full:

Giordan D., Cignetti M., Bertolo D. (2017a) *The use of morpho-structural domains for the characterization of Deep-seated Gravitational Slope Deformation in Valle d'Aosta*. In Workshop Landslide Forum, Springer, Cham, pp.59-68.

Giordan D., Cignetti M., Baldo M., Godone D. (2017b) *Relationship between man-made environment and slope instability: the case of 2014 rainfall events in the terraced landscape of the Liguria Region (northwestern Italy).* Geomatics, Natural Hazards and Risk, 8(2), 1833-1852.

2

Deep-seated Gravitational Slope Deformations

Deep-seated Gravitational Slope Deformations (DsGSDs) are large-slope gravitational deformation, affecting entire valley flanks and extended for hundreds of meters in depth. Featured by extremely slow movement rate (*i.e.* mm/year up to few cm/year) and huge dimensions, these phenomena are generally well distinguished from all other types of landslides. DsGSDs are widespread in high mountain slopes, manifested by diverse linear morphological features as scarps, benches, cracks, trenches and bulges, but lacking a well-defined rupture surface. Due to the slow-moving rate, the effect of these phenomena on anthropic elements is poorly or even not considered both in the scientific community and by policy-makers in land use planning management. Despite the extremely slow movement, the long-term impact of these phenomena, characterized by continuous deformation rate over time, may constitute a relevant natural hazard, variably affecting settlement and anthropic structures and infrastructures.

By exploiting a territory highly affected by DsGSDs as the Italian Western Alps, in the Phase I of the reiterated structure proposed in the thesis (Figure 2.1), an in-depth analysis of historical and previous data collected in the national and regional landslide inventories and web-GeoPortal (Centro Funzionale Regione Autonoma Valle d'Aosta, 2019) have been carried out. Moreover, diverse results obtained from previous scientific research carried out within the GMG group for some DsGSDs located in the Aosta Valley Region (Giordan et al., 2017a) (Appendix B), allowed to an in-depth characterization of these huge phenomena. In Giordan et al. 2017a, operating through the interpolation of SAR data in a GIS-environment, based on a combined analysis of SAR data velocity measurements, geomorphological and structural elements within a specific DsGSD, the definition of the main morpho-structural domains that characterize these phenomena have been obtained. The results of this research have been published in a scientific paper immediately before the start of PhD research. For this reason, the article is not included in the thesis papers. However, the paper is annexed in Appendix B. In general, this first stage allowed to define the general framework of the current knowledge, in term of distribution, extension, state of activity of these huge phenomena and their relation with anthropic elements widespread in an alpine territory, currently missing.

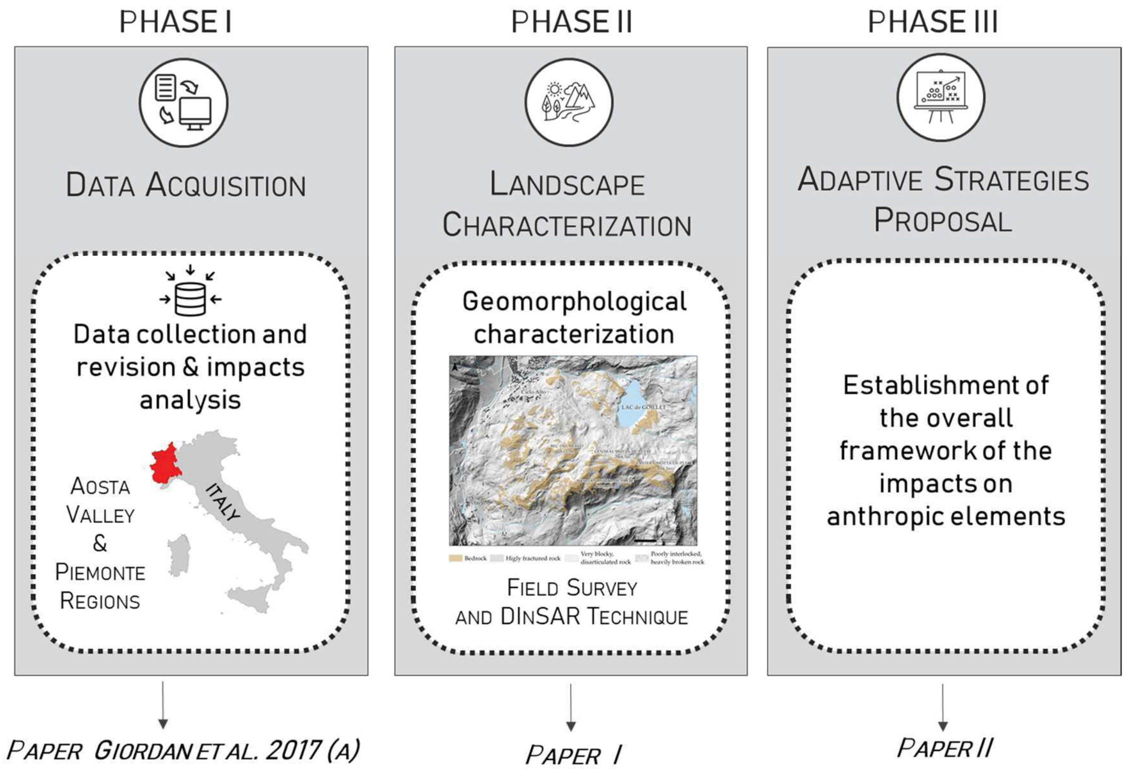

Figure 2.1 – Reiterated structure proposed for the DsGSDs typology.

Though previous field data analysis and revision, a geomorphological characterization of some of the alpine DsGSDs are generated in the Phase II, focusing on the identification of the main morpho-structural features that characterize these phenomena and their interaction with strategic anthropic structure and infrastructures. The geomorphological map of four of the main active DsGSDs interacting with anthropic elements of strategic importance, located in the Aosta Valley Region (northwestern Italy) have been designed and presented in the *Paper I*.

Leveraging on the data and information analysis, geomorphological characterization and also taking in advantage SAR data analysis for DsGSDs state of activity definition, an overview of the DsGSDs impacts on anthropic structures and infrastructures at the Italian Western Alps scale has been carried out in the Phase III. The overall framework of the impacts of DsGSDs on anthropic elements and their handling in land use planning regulation is a still open issue, poorly considered or totally missing both in the scientific community and in the legislative framework. The assessment of DsGSDs impact of both settlements and structures and infrastructures represents a key element, fundamental for a functional review of the current legislative framework and DsGSDs consideration concerning strategic infrastructures planification, has discussed and presented in the *Paper II*.

The full version of the published or in preparation scientific papers is available below.

Paper I: Giordan D., Cignetti M., Godone D., (in preparation) *Geomorphological map of the main Deep-seated Gravitational Slope Deformations of the Aosta Valley Region (NW Italy)*. To be submitted to Journal of Maps.

Paper II: Cignetti, M., Godone, D., Giordan, D., Zucca, F. (2020) *Impact of Deep-seated Gravitational Slope Deformation on urban areas and large infrastructure in the Italian Western Alps*. Science of the Total Environment, **740**, 140360. DOI: 10.1016/j.scitotenv.2020.140360

Note

Geomorphological map of the main Deep-seated Gravitational Slope Deformation of the Aosta Valley Region (NW Italy)

D. Giordan[1], M. Cignetti[1,2,*]

[1] National Research Council, Research Institute for Geo-Hydrological Protection, Strada delle Cacce 73, Turin, Italy.

[2] Department of Earth Sciences, University of Pavia, Italy.

[*] Corresponding author: martina.cignetti@irpi.cnr.it

Abstract: The Aosta Valley region is a small mountainous region (north-western Italy), revealing a remarkable exposure to landslide hazards. Deep-seated Gravitational Slope Deformations (DsGSDs) are a widespread phenomenon, affecting about 13% of the regional territory. In this study, a detailed geomorphological mapping of some notable DsGSDs of the Aosta Valley that interfere with penstocks, hydroelectric tunnel and other strategic infrastructures has been performed. The procedure has been prevalently based on field survey, associated with orthophotos interpretation. Great emphasis has been given to the distinct morphological features typical of the DsGSDs. Through a slope-scale map of each considered phenomenon, all the specific landforms and morphological features, the rock mass fracturing, as well as the second landslides frequently associated to these huge phenomena have been defined, showing their distribution and spatial relationship. A comprehensive definition of the morphological setting of the four considered DsGSDs, constitutes a key point for the assessment of their long-term evolution useful to define their potential impact on anthropic elements and a proper land use planning management.

Keywords: Slow-moving landslides; Glacial morphodynamic; Landforms mapping; Hydroelectric tunnel investigation; Rock fracturing.

1. Introduction

Deep-seated Gravitational Slope Deformation (DsGSDs) are rather characteristic phenomena of the alpine regions (Ambrosi & Crosta, 2006; Crosta, Frattini, & Agliardi, 2013; Mortara & Sorzana, 1987). In literature, these phenomena have been defined in different ways, depending on the study approach and the hypothesized evolutionary mechanisms (e.g. sacking, rock mass creep, lateral spread (F. Agliardi, Crosta, & Zanchi, 2001; Zischinsky, 1966). The DsGSDs are long-lasting gravity-induced large slope instability, involving entire valley flanks, ranging from several kilometers in length and hundreds of meters in depth, and characterized by very slow deformation rate (mm/year, up few cm/ year). Due to their dimension, multiple controlling factors influence the long-term evolution of these phenomena (F. Agliardi, Crosta, & Frattini, 2012), among the main: i) glaciation and deglaciation; ii) seismicity; iii) tectonic and topographic stresses; iv) rock dissolution. All these controlling factors, together with significant geomorphological changes (e.g. valley erosion, valley deepening, drainage network action), influence spatially and temporally the long-term evolution of these huge phenomena (Crosta et al., 2013). Distinct morphological and structural features characterize the DsGSDs, comprehending extended scarps, counter scarps, trenches and double ridges, and downthrown blocks, typical of the upper and middle portion, while toe building, enhanced rock fracturing, characterize the lower portion.

The lengthy long-lasting evolution with continuous deformation rate, can deeply influence mountain region morphology evolution (Crosta et al., 2013; Pánek & Klimeš, 2016). Even the slowly movement, the DsGSDs may have an impact on anthropic elements over time. This effect is particularly evident on those more extended linear elements as road network, pipelines, hydroelectric tunnels or penstocks. Moreover, the DsGSDs are often associated to secondary fast mass movements (e.g. rockslide, rock falls, debris flows), which may constitute an added natural hazard.

The definition of the morphological setting, together with the assessment of the state of activities of these phenomena, represents a key element for the risk evaluation and the definition of the impact of DsGSDs on anthropic elements for a more efficient risk mitigation and land use planning.

Among the alpine regions, due to the variability in geological, lithological, geomorphological and structural settings, the Aosta Valley Region (north-western Italy) represents a peculiarity in term of number of $DsGSD_s$ that affect about 13% of the entire regional territory (Trigila, Iadanza, & Spizzichino, 2008).

In this paper, we focus on four representative DsGSDs, all involving urbanized areas and/or road network and penstocks, located across the Aosta Valley Region (NW Italy), all interfering with linear anthropic infrastructures: i. Croix-de-Fana DsGSD, ii. Motta de Pleté DsGSD, iii. Villeneuve DsGSD, iv. Hône DsGSD. Mapping the DsGSDs linked with such strategic infrastructures from a morphological point of view, is a crucial task for identify the most critical areas in term of risk assessment, evaluate the potential interactions and related damages, and consequently realize proper urban planning. Through a detailed geomorphological characterization, based on field survey and aerial photointerpretation, we try to characterize the study areas from a geomorphological point of view, functional for delineate the diverse kinematic domains recognizable for each considered phenomenon. In order to define the DsGSD behavior and its dynamic evolution, the geological, lithological, geomorphological and structural context of each considered study areas have been analyzed. In accordance with Giordan, Cignetti, & Bertolo, 2017, much attention was paid to map all the surficial morpho-structural evidences, the level of rock mass fracturing, and the analysis of the minor landslides associated to these large deep-seated phenomena and their long-term evolution, in order to outline the diverse mechanisms that characterize the evolution of each considered phenomenon.

2. Methods and Materials

Focusing on the four DsGSDs, i.e. Croix-de-Fana, Motta de Pleté, Villeneuve, and Hône (Figure 1), four geo-thematic maps based on geomorphological criteria have been drafted.

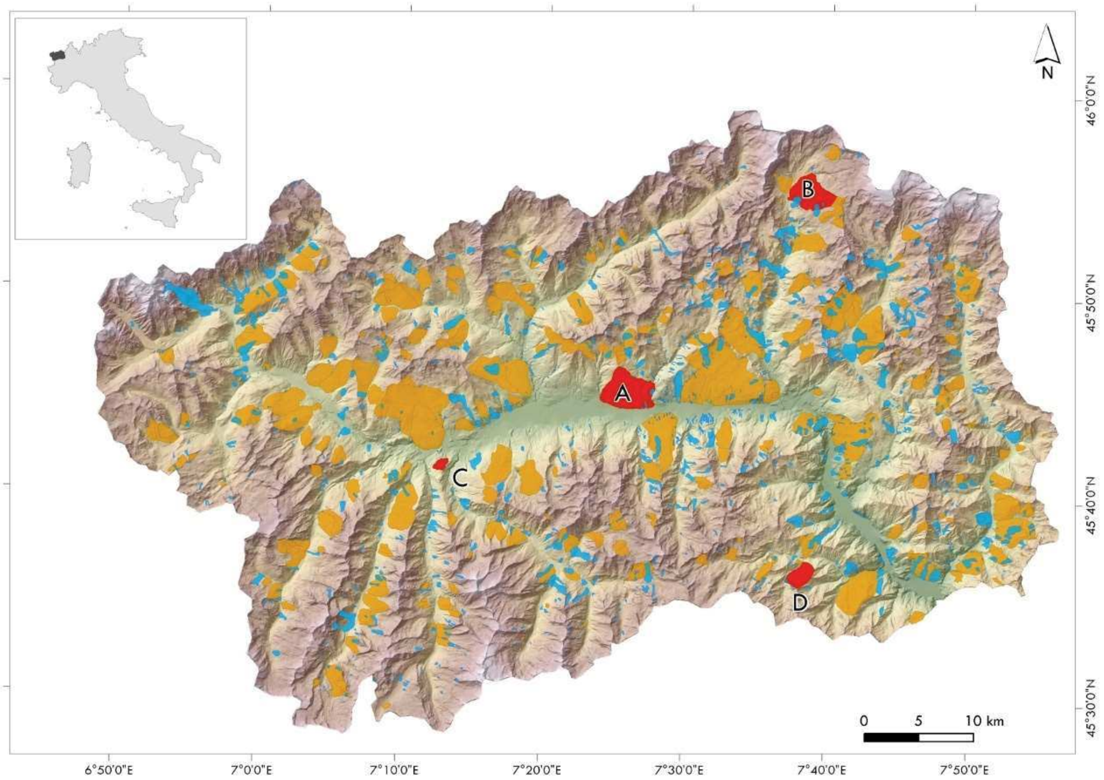

Figure 1 – Relief terrain of the Aosta Valley Region (NW Italy). The map shows the landslides distribution across the regional territory; the blue polygons correspond to the IFFI ((ISPRA Ambiente, 2007) inventoried landslides, the orange polygons to the DsGSD$_s$ and the red ones to the four case studies: A) Croix-de-Fana; B) Motta-de-Pleté; C) Villeneuve; D) Hône DsGSDs.

We operate evaluating and distinguishing the evidences of the surface deformation that are clearly linked to the DsGSD development. In fact, DsGSDs display peculiar geomorphic evidences. We point out our attention to three main elements:

a) Gravitational landforms features;
b) Level of rock mass fracturing;
c) Secondary landslides associated.

By a Geographic Information System (GIS), we perform an inclusive geomorphological map of the four considered DsGSDs. All the collected data are stored in a spatial database.

Geological and geomorphological data are collected by an accurate and extensive unedited field work presented in Giordan, 2006. Further, we employed a combined analysis of orthoimages and digital terrain models (DTMs) derivative products (e.g. slope, aspect), in order to integrate survey data by e remote interpretation. This method supplies a suitable representation of the topographic surface, able to highlight possible surface morphology signatures (Ardizzone, Cardinali, Galli, Guzzetti, & Reichenbach, 2007; Břežný & Pánek, 2017; Colombo, Paro, Godone, & Fratianni, 2016). Moreover, previous unedited survey works of the study areas are available (Martinotti, 1995, 1996; Martinotti & Carraro, 1989; Paolina et al., 1986), supplying relevant source data: i) thematic mapping, ii) technical report relative to linear infrastructures project (hydroelectric plants and tunnels), and iii) geognostic survey (e.g. drill data).

Geo-thematic maps of the four case studies aim to portray at their best the deep-seated mechanism and evolution of the DsGSDs. Therefore, the distinctive morphological features and landforms of these phenomena, constitute the primary topic of these maps. A focus is made on those classical geomorphic evidences clearly linked to the DsGSD dynamic. Such gravitational landforms included, for example, main scarps and counter scarps, trenches, e.g. linear cut structures with variable aperture and depth, ridge depression or double ridges, all morphological expression of extensive domains, typical of the upper portion of the slope. Instead, in the lower portion of the slope, distinctive features related to compressive domains, are represented by toe building and highly rock mass fracturing.

A shaded relief, computed from a 2 m cell size Digital Terrain Model (DTM), distributed by the Aosta Valley Region, constitute the topographic base of these maps. This base layer is able to highlight the relief landforms and constitutes a valuable support in geomorphological mapping. Relative to the lithological aspect, as in the case for geomorphological mapping, distinction is made between bedrock and deposits. During the field work, an outcrop map has been performed, distinguishing the single lithologies, following the main geological units of the Western Alpine chain. In addition to the data retrieved from the field survey, extra themes are added for bedrock structure characterization. A differentiation about blockiness and the rock mass conditions was done. The bedrock is subdivided in three main groups: i. highly fractured, ii. very blocky disarticulated and, iii.

poorly interlocked, heavily broken rock masses. The rock masses characterization added another item, useful to define the DsGSD behavior and its state of activity.

Finally, an assessment of the type and state of activity of the minor landslides related with the $DsGSD_s$ was carried out, mainly on the basis of field observations and the data available in the Italian Landslide Inventory (IFFI) (ISPRA Ambiente, 2007).

3. Results

Four detailed maps, based on geomorphological criteria, of the selected case studies, accompanied by a geological-structural sketch map and a map of the regional DsGSDs distribution included in the Main Map, have been drafted. The geomorphological and geo-structural peculiarities derived from the analysis of the four case studies based on the methods previously exposed, are described below.

3.1 Croix-de-Fana DsGSD

The Croix-de-Fana DsGSD covers an area of about 13 km^2, located in the middle portion of the main valley (north side), close to the Quart municipality. The DsGSD extends from the namesake peak (2211.3 m a.s.l.) up to the Dora Baltea river (525 m a.s.l.) on the main valley floor (Figure 2), with average slope of about 19°. Diverse localities are scattered along the slope, mainly distributed on the medium-low sectors, in correspondence of the less steep portion of the valley flank. Among the main strategic structures and infrastructures of the area of interest, the hydroelectric plant of Quart, constituted by a penstock associated with two galleries, crosses the medium-low portion of the DsGSD.

The bedrock belongs to two main alpine domains: i) Piedmont Domain, here represented by prasinites, calcschists with intercalation of mica marbles and metabasites; ii) Austroalpine System represented by orthogneiss, fine-grained gneisses and subordinate amphibolite lenses. The Austroalpine System rocks prevalently outcrop in the north-west portion of the DsGSD, thrusting onto the Piedmont Domain rocks distributed along the south-east sector. A multiphase ductile deformation affects the bedrock, presenting low-angle shear planes, locally reactivated involving Quaternary deposits (Giardino, 1995) (Figure 2d). A Plio-Quaternary brittle deformation induced a series of high-angles fault that acted as head scarps for gravitational sliding along low-angle shear planes. A regional E-W oriented fault system, the Aosta-Ranzola fault (Bistacchi et al. 2001), interested the lower part of the slope, in correspondence of the main bottom valley. Martinotti et al., 2011 proposed a schematic representation of the complex kinematic system of the Croix-de-Fana, strictly related to the Aosta-Ranzola shear zone, actively deformed by a conjugate extensional system (modified in Figure 2b).

The whole slope has a glacial footprint testified by ancient valley floors at different elevation, showing the typical step-like profile. From the elevation of 1300 m a.s.l., in correspondence of the main flat areas, a series of wide ancient glacial valleys floor, associated to widespread erratic boulders and sheep-backs, interest the central portion of the DsGSD. These less steep portions are separated by highly steep scarps, often corresponding to the source areas of active landslides (ISPRA Ambiente, 2007). The main landslide, actually monitored in the Regional Monitoring Network (Giordan et al., 2018), is the Vollein landslide, a rotational slide engraved by the Marmore River on the toe located in the eastern portion of the DsGSD. Other gravitational evidences are testified by highly fractured rock, in correspondence of some sheep-back in the south-east portion of the DsGSD, close to the penstock of hydroelectric plant of Quart.

In the lower portion, different order of glacial and fluvio-glacial terraces locally presents a tilting produced by pushing of the deep failure. Starting from the Quaternary, watercourses activities superimposed the glacial landforms. A structural control over the drainage pattern results evident. This is particular visible in the lower-middle portion of the DsGSD, where the length-ways streams are heavily dependent to high angle fractures.

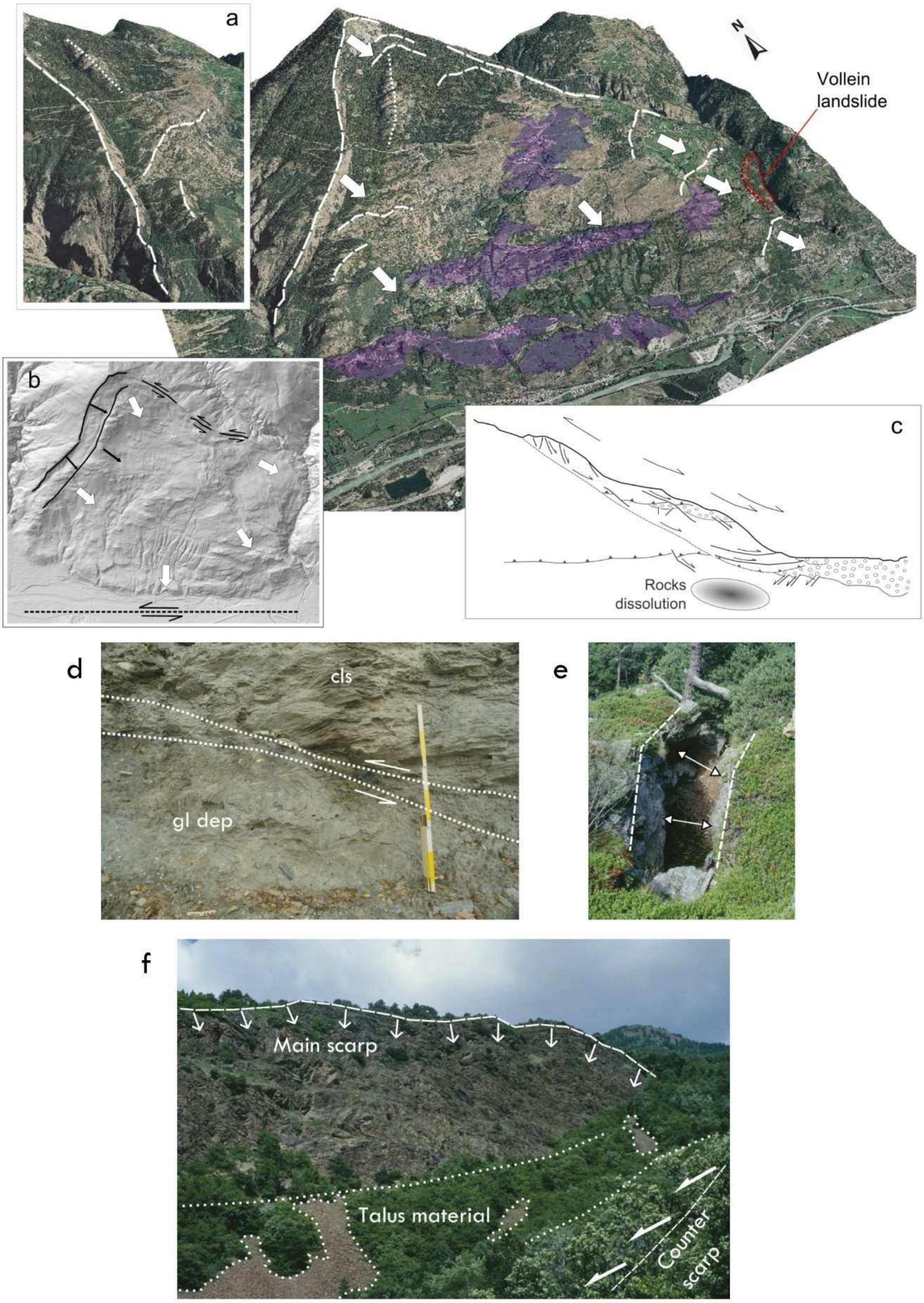

Figure 2 – Three-dimensional scheme of the Croix-de-Fana DsGSD; main scarps (in white), glacial deposits (violet). The white arrows show the displacement direction. On the eastern side of the DsGSD is located the Vollein landslide (red lines): a) Zoom on the main scarp and counter scarp associated; b) sketch map of the

kinematics relation between the Aosta-Ranzola fault and the DsGSD (modified from (Martinotti et al., 2011)); c) sketch profile of the DsGSD showing the relationship between the upper extensional zone evolution and the lower compressive one (modified from (Giardino, 1995); d) low-angle shear plain connecting the calcschists of the Piedmont Domain (cls) and the glacial deposits (gl dep), visible in the lower sector of the DsGSD; e) Trench highly evolved; f) main scarp visible along the western portion of the DsGSD, associated to extended talus material and a counter scarp forming a graben structure (Photos by Giordan D.).

In this context, the gravitative dynamic relative to the DsGSD of Croix-de-Fana displays an upper extensional zone (Figure 2c), limited along the upper slope sector by an extended scarp (3.2 km), variable oriented N40°-N10°, in the western portion of the DsGSD (Figure 2f). This main scarp is associated to a counter scarp to form a graben structure (Figure 2a). Other minor scarps, which are mostly parallel to the main one, appear in the sector of this phenomena, between Croix-de-Fana peak and Avisod and Fonteil hamlets. A series of gravity-induced features, such as trenches (Figure 2e), gravity scarp and elongated depression, are identifiable along the slope.

The lower sector, instead, is characterized by a compressional zone witnessed by fractured rock masses, with local evidences of rock dissolution, collapse zones like sinkholes and open fractures. The deep dissolution is testified by the water samples, collected during the Quart hydroelectric tunnel survey (Alberto, Giardino, Martinotti, & Tiranti, 2008).

In general, the DsGSD of Croix-de-Fana can be divided in two distinct cinematic domains, corresponding to a highest portion, characterized by large extensional structures, and a lower compressive portion, characterized by a massive presence of low-angle plane, associated to collapse zones, which testify the most recent phases of the slope evolution, adversely interacting with the hydroelectric plant of Quart that crosses the lower portion of the DsGSD with a WNW-ESE gallery, and the middle-low portion with a NNW-SSE gallery associated to a penstock. In the central and eastern portions, minor domains are distinguishable in correspondence of the secondary gravitational phenomena (e.g. Vollein landslide) associated to the DsGSD.

In summary, the Croix-de-Fana DsGSD evolution resulted from a combination of a number of factors combined with diverse level of interaction over time. Among them, the slope decompression related to the glacier withdrawal, during and after deglaciation, induced a deep gravitational collapse, exploiting the pre-existing low-angle shear plane, related to the Aosta-Ranzola fault system. Rocks permeability for fracturing promoted the gypsum and anhydrite dissolution, activating local collapse zones.

3.2 Motta-de-Pleté DsGSD

The Motta-de-Pleté DsGSD covers about 8 km^2, located in the right side of the upper part of the Valtourenenche, close to the Breuil-Cervinia municipality, one of the most famous ski-resort of the region. This phenomenon extends from the E-W oriented ridge between the Motta-de-Pleté Oriental peak (3061 m a.s.l.) and the namesake Central peak (2868 m a.s.l.), with average slope of about 25°. It involves the Cielo-Alto ski-resort on the northwestern limit, and is crossed in the middle by a penstock extended from the Goillet Lake up to the Perrère hydroelectric plant (Figure 3).

The bedrock comprises rocks of the Piedmont Nappe System, here represented by the Zermatt-Saas Unit (i.e. serpentinites, serpentinoschists and metabasites) and the Combine Unit or Tsaté Unit (i.e. calcschists and prasinites), separated by the Pancherot-Cime Bianche Unit (i.e. quartzites, dolomitic marbles, calcareous marbles, pseudocarnioles and evaporites) (Dal Piaz, G., Bistacchi, A., Gianotti, F., Monopoli, B., Passeri, L., Schiavo, A., Bertolo, D., Bonetto, F., Ciarapica, G., Gouffon, Y., Massironi, M., Ratto, S., Toffolon, 2015).

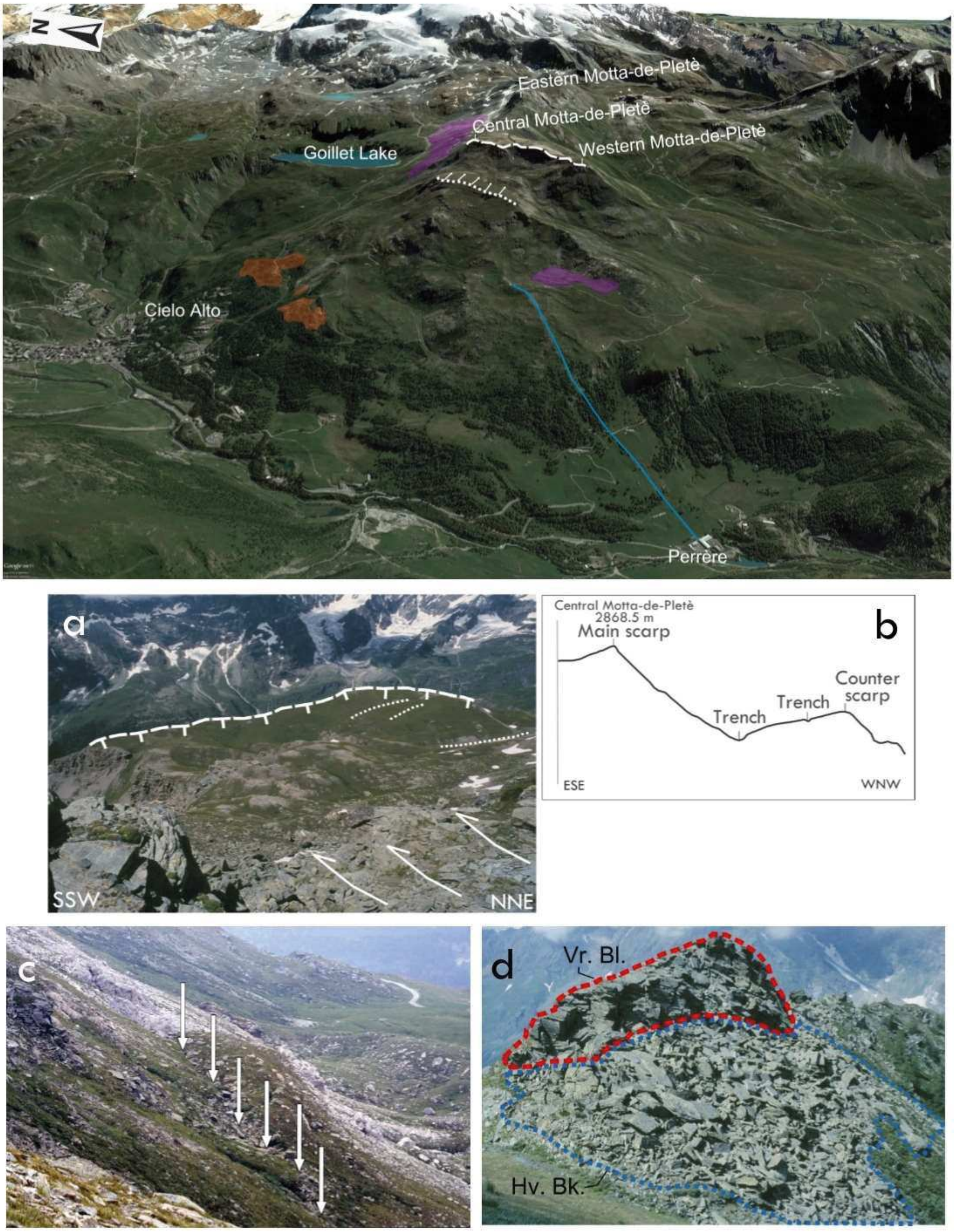

Figure 3 – here-dimensional view of the Mott-de-Pleté DsGSD (from Google Earth): main scarp (white dashed line), counter scarp (white dotted line), rock glaciers (violet), poorly interlocked, heavily broken rock masses (orange), hydroelectric plant (light blue). a) Zoom on the rotated block of calcschists delimited by a counter scarp (dashed line), and its b) sketch profile from the main scarp (Central Motta de Pleté) to the counter scarp; c) elongated depression located below the Western Motta de Pleté peak; d) rock masses outcrops close to the

Cielo-Alto hamlet, very blocky rocks poorly interlocked (Vr. Bl.), and heavily broken rocks collapsed onto themselves (Hv. Bk.).

Hummocky topography, extended rock glaciers and moraine ridges are evidences of a periglacial environment, presenting extensive rocks outcrops. The main scarp between Central and Western Motta de Pleté peaks, corresponds to a listric fault that cause the rotation of a calcschist block that actually presents a counter slope (Figure 3a, 3b). This area is characterized by trenches, elongated depression, deep fractures and carsick caves, which testify the tensile stresses in place (Figure 3c). A series of large blocky slide widely affects the slope, e.g. Perrere sector, as reported also in the IFFI catalogue (ISPRA Ambiente, 2007).

Moving downstream, the rocks involved in this gravitational phenomenon display a progressive increase of the fracturing. From the Bec Pio Merlo peak (2617 m a.s.l.), a slope profile with jagged steps shows up, with fractured to very blocky rocks outcrops. Proceeding to Cielo-Alto locality, the rocky extended outcrops diminished, becoming a poorly interlocked, heavily broken rock masses collapsed onto themselves (Figure 3d). In particular, geological analysis reveal that only the Tsaté Units are affected by the deep-seated deformation. Instead, the Pancherot-Cime Bianche Unit rocks potentially constitute a weak layer that acted as basal plane of the DsGSD. This is confirmed by the Perrère hydroelectric plant surveys and drilling, which allows to observe a slightly fractured Zermatt-Saas unit topped by highly fractured Combin Unit. The main remedial work into the tunnel concerned the water seepage concentrated at the tectonic contact between those units (Martinotti et al., 2011).

The Motta-de-Pleté DsGSD derivative setting shows a more active deformation in the lower and marginal sectors than in the higher ones. In particular, the deformation is concentrated in the marginal portion of the DsGSD, corresponding to the Cielo-Alto locality, where damages to numerous hotels and buildings have been observed.

3.3 Villeneuve DsGSD

The Villeneuve DsGSD covers a surface of about 4 km^2, sited in the middle portion of the main valley (south side), a few kilometers to Aosta municipality. This deep-seated gravitational slope is located on a gentle slope, laterally delimited by the Valsavaranche and Cogne valleys, respectively on the west and the east side, characterized by high steep slope. The DsGSD is crossed on the east and north-side by a hydroelectric plant, variably oriented from NS to ENE-WSW, extended from Mt. Poignon down to the Dora Baltea River.

The DsGSD is located in a north-south ridge, constituted by Piedmont Nappe System (calcschists, prasinites, marbles and carnioles) and Gran San Bernardo Unit (crystalline basement represented by micaschists and gneisses) rocks. A complex folded, with two isoclinal phases and an open folding event, affects the bedrock. A younger shear plane crossed the folds.

An important glacial action operated on the entire ridge, by depositing glacial material on a series of terraces, starting from Mt. Poignon (1567.6 m a.s.l.), associated to meaningful sheep backs. Watercourses superimposed the glacial landforms, forming very steep rocky slopes, curved out by the principal tributary valleys streams (Figure 4). In the central portion of the DsGSD, an evident depression of about 200.000 m^2 can be observed (Figure 4a, Figure 4b). The gentle morphology shows a glacial deposits subsidence, bordered by a sector with disjointed and poorly interlocked rocks, associated to trenches, counter scarps and widespread rockfalls and debris coverages. The absence of streams and springs, suggests a deeper circulation of the water. The surrounding area characterized by a steeper slope, resulted stable revealing rocky outcrops without joints. The collapse has been attributed to a deep dissolution of soluble rocks (Dal Piaz, 1992) (Figure 4c), as confirmed by the drilling performed to investigate the DsGSD and the Mt. Poignon hydroelectric plant interactions (Martinotti et al., 2011). In correspondence of the Grand Eyvia Torrent, rock cliff shows karstic caves outcrops (Figure 4c). The sequence (500 m hole), undertaken in correspondence of the collapsed portion, developed the presence of anhydrite and gypsum topped with a disarticulated rock mass, covered by landslide deposits on the surface. The soluble rocks separate highly fractured sequence of calcschists and marble to the Gran San Bernardo crystalline basement, here represented by joint-free micaschists.

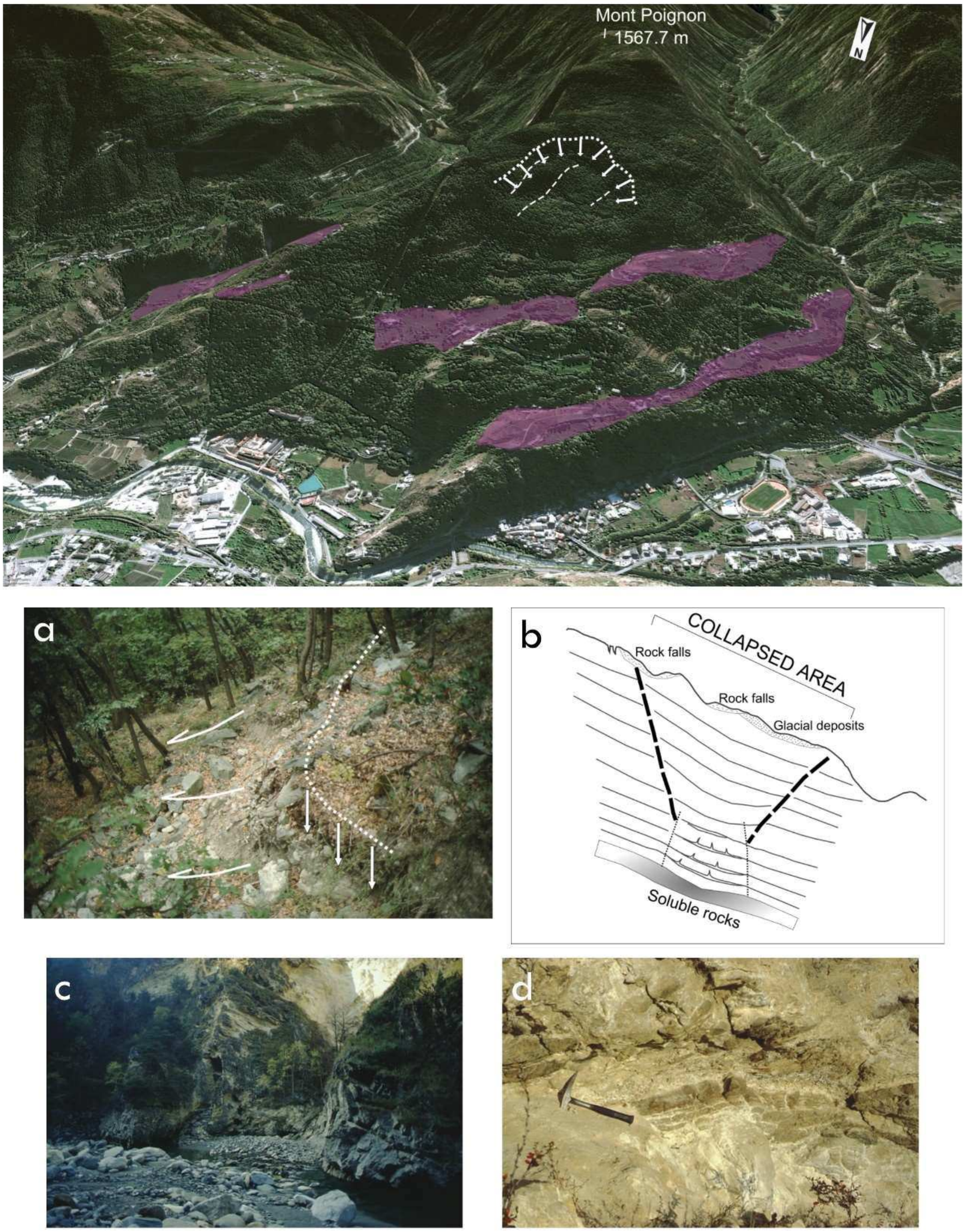

Figure 4 – Three-dimensional view of the Villeneuve DsGSD (from Google Earth). In the central portion sets a wide collapsed area (dotted line), totally hidden by forest. Extended glacial terraces interest the whole slope (violet); a) zoom on the collapsed zone; b) sketch profile of the collapsed area (modified from (Martinotti et

al., 2011)); c) karstic caves outcropping along the Grand Eyvia Torrent (right side of the DsGSD); d) carnioles level outcropping along the Grand Eyvia Torrent.

The collapsed area is a closely bounded area, as testified by the geological data provided by the highway tunnel in the lower portion of the slope.

The Villeneuve DsGSD is primarily caused by the deep-dissolution of anhydrites and gypsum lenses. The geomorphological setting is the result of in-depth infiltration of meteoric and glacial water, capable to undermine soluble rocks (Alberto et al., 2008). Actually, this process is still active, as testified by recent surface deformation and by the high sulphate content in water deep sampled during the highway tunnel surveys.

3.4 Hône DsGSD

The Hône DsGSD covers an area of about 10 km^2, and is located at the entrance of the Aosta Valley, in the lower Champorcher Valley (right slope). The elevation of the Hône DsGSD varies widely, ranging from 500 m, close to Pontboset village, to 2142 m a.s.l. at the Cime Cocore peak, with average slope of about 37°. This deep-seated gravitational slide is the largest phenomenon and the lesser known of the other analyzed cases (Figure 5), and is crossed by a penstock in its lower portion from Pontbose to Hône.

From a geological point of view, the basement rocks entirely belong to the Sesia-Lanzo Zone, prevalently constituted by albitic-cloritic-epitotitic micaschists and gneisses (Compagnoni, 1977). At the scale of the entire slope, bedrock is observable in correspondence of extended outcrops fairly competent. A lengthy ductile shear zone, prevalently constituted by cataclastic rocks, associated to local level of pseudotachilites (mm to cm thickness), highly conditioned the instability of the entire slope (Figure 5c). This shear zone acted as a moderate dipping plane (25° NW), along which the DsGSD movement took place. The basal plane is named Graisettes shear zone and mostly outcrops in the marginal portions of the slope, along the tributary valleys of the Ayasse Torrent (e.g. Graisettes hamlet) (Figure 5b). In the upper portion of the slope, this shear appears over the watershed, along the east south-east face of the Cime Cocore mountain relief, strictly conditioned the nearby rock masses fracturing. In fact, along the watershed formed from Cime Cocore peak towards South West, the bedrock displays a poorly interlocked heavily broken rock masses, collapsed into themselves (Figure 5a). In deep analyses conducted during the hydroelectric station planning confirmed the shear plane presence along the slope. The shear zone shows a variable thickness, ranging from few meters to tens of meters that divides a lower unit constitutes by gneiss and micaschists poorly fractured from a heavily fractured gneiss and micaschists upper portion.

Morphologically, the entire slope displays glacial and fluvial features. Glacial features are indicated by moraine ridges, widespread glacial deposits, and rock glaciers, while the fluvial ones principally by the Ayasse Torrent that deeply incised the lower portion of this gravitational phenomenon. Instead, the typical morphological and structural features that characterize the DsGSD are not so widespread. Only on the upper part of the slope are distinguishable a number of features, e.g. elongated depression (Figure 5d), closed depression and double ridge, associated to the highly fractured rock masses evolving in shallow-slope instabilities.

The Hône DsGSD dynamic strictly depends on the constant dip shear zone plane that involve the whole slope. This shear zone displayed an active role in the control of the DsGSD evolution, primarily on the fracturing of the rock masses. An initial slope instability implicated surficial rock masses in a down-slope movement along this extended shear plane. Then, the upper part of the deep-seated gravitational slope evolved as a collapse, showing poorly interlocked heavily broken rock masses, collapsed into themselves, strictly related to landforms resulting from shallow-slide instabilities. A superimposition of valley glacial modeling and a subsequent deep slope incision by the main and tributary valleys rivers has been recognized.

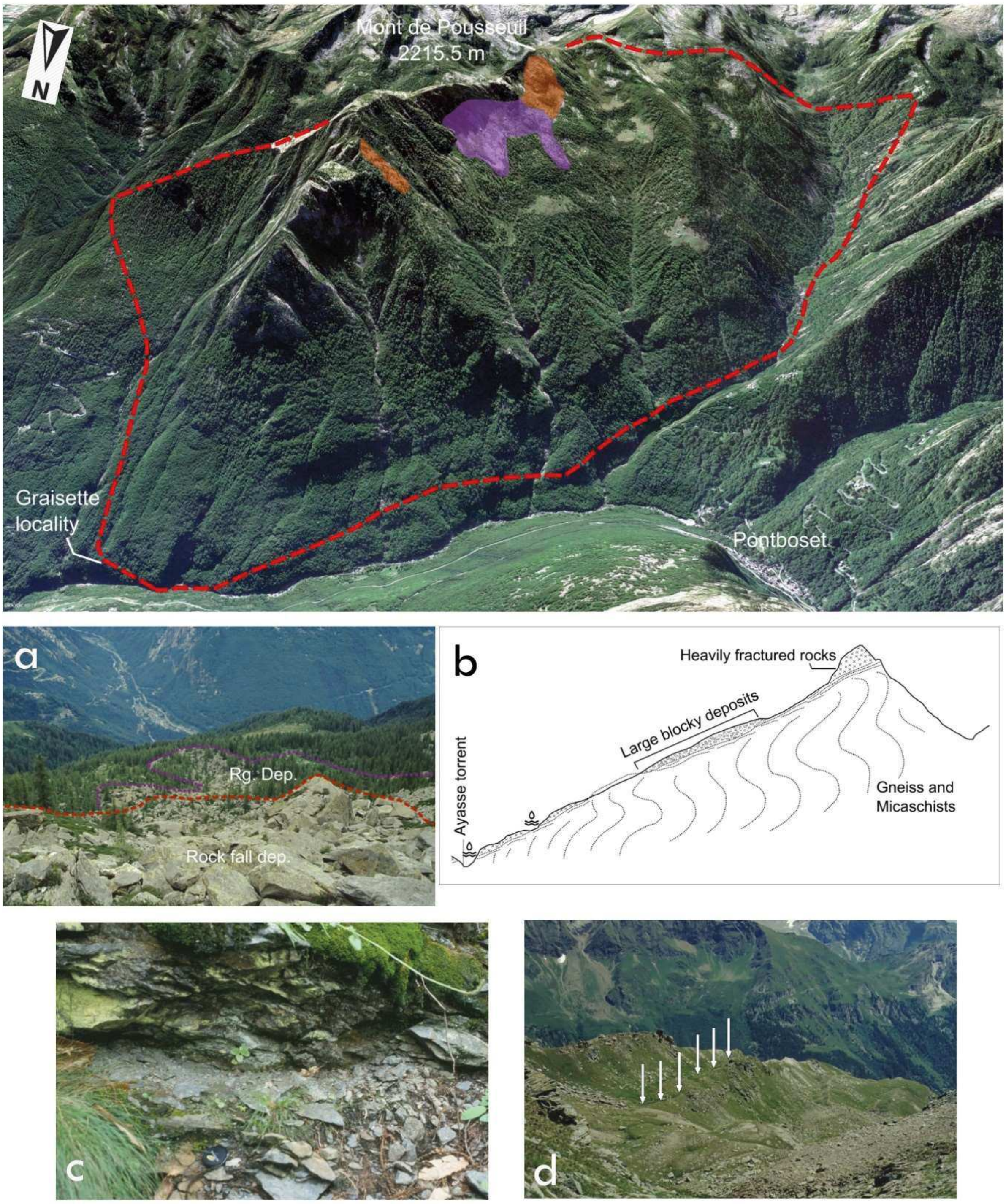

Figure 5 – Three-dimension view of the Hône DsGSD (from Google Earth): shear zone plane (red, rock glaciers (violet), large blocky deposits (orange). a) landslide deposits (red) constitute by large blocky without matrix interacting with rock glacier deposits (violet); b) sketch profile of the shear zone plane of the Hône DsGSD (modified by (Martinotti et al., 2011)); c) shear zone plain detail outcropping in Graisette locality; d) elongated depression located in the upper portion of the DsGSD.

4. Discussion and Conclusions

In mountain region, as the Aosta Valley one, numerous DsGSDs widely affect the landscape (Federico Agliardi, Crosta, Zanchi, & Ravazzi, 2009; Crosta et al., 2013; Pánek & Klimeš, 2016). They normally involved entire high-relief valley flanks by a long-term and complex evolution with a typical slow motion (F. Agliardi et al., 2012). These huge phenomena are the result of a composite geological, geomorphological and structural settings, also presenting an interconnection to the occurrence of other slope deformations (e.g. rock avalanches, debris flow, slumps).

In this paper, we have considered four DsGSDs case study, corresponding to four representative phenomena in Aosta Valley environment: Croix-de-Fana, Motta de Pleté, Villeneuve and Hône DsGSDs. These case studies well represented the most common controlling factors that condition and discriminate the DsGSDs behavior and evolution in this region (Martinotti et al., 2011). The DsGSDs geomorphological map including each case study has been generated.

A detailed mapping of these four deep-seated gravitational phenomena has been performed. Great attention was paid to the field survey observations, in order to highlight the distinct morphological and structural features that characterize these kinds of phenomena. The field data have been integrated with a remote investigation, based on the combined analysis of orthoimages and DTM derivative products. Information deriving from geognostic survey, prevalently operated for remedial works in the hydroelectric plants and tunnels, constituted a fundamental dataset, normally rare or absent, to confirm the surficial findings.

Medium and large-scale surveys have been able to delineate and characterize the specific landforms of these huge phenomena, showing the distribution and properties of all distinct features and their correlation spatially, useful for the assessment of the long-term and complex evolution of these large slope instabilities.

All the mapped DsGSDs correspond to long-history phenomena subject to a composite evolution over time, following the last Pleistocene glacial retreat (Cossart, Braucher, Fort, Bourlès, & Carcaillet, 2008; Lebrouc, Schwartz, Baillet, Jongmans, & Gamond, 2013). They are the result of the combination of several controlling factors, as lithology, tectonics, gravity as delineated by Martinotti et al. 2011. The glacial action played a key role forming the typical alpine valley profiles with valley floors at different elevation, relative to the progressive deepening of the Balteo Glacier. During the glacial retreat, the disappearance of ice masses pressure, induced the glacial debuttressing of the valley. In the four considered cases, an evidence of early post-glacial activity was found, as a factor of instability triggering. Jointly, the neo-tectonic history played an important role on large slope instability (F. Agliardi et al., 2001). For instance, in the case of Croix-de-Fana DsGSD the Aosta-Ranzola system actively deformed and control the geometrical pattern and the kinematics of this phenomenon, inducing relevant down-slope scarps, involving the entire slope. Also lithological and tectonic aspects drove the DsGSDs dynamics, as in the case of the shear plane that drove the Hône DsGSD, testified by a progressive fracturing state of the rock masses. In addition, deep-seated dissolution of soluble rocks, here represented by sulphate rocks, can cause underground and superficial effects (e.g. collapse zones, sinkholes, collapsed slopes, closed depressions).

The described DsGSDs geomorphological mapping provides the basis to define the state of activity of each study areas, allowing to define the long-term evolution of these huge phenomena and estimate the potential related hazardous conditions and impact on strategic anthropic structures and infrastructures, for a more convenient land use planning.

Software

The geomorphological map has been performed with ESRITM ArcGis (10.3 version) software, edited in ArcMap^{TM}.

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Impact of Deep-seated Gravitational Slope Deformation on urban areas and large infrastructures in the Italian Western Alps

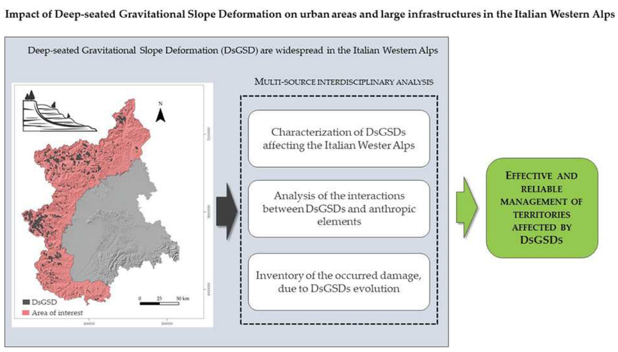
M. Cignetti [a,b], D. Godone [a,*], F. Zucca [b], D. Bertolo [c], D. Giordan [a]

[a] National Research Council of Italy, Research Institute for Geo-Hydrological Protection (CNR IRPI), Torino 10135, Italy
[b] Department of Earth and Environmental Sciences, University of Pavia, Pavia 27100, Italy
[c] Strutture Attività Geologiche, Regione Autonoma Valle d'Aosta, Quart 11020, Italy

HIGHLIGHTS

- DsGSDs remarkably impact on anthropic settlements and infrastructures.
- Current legal framework lacks on DsGSDs handling in land use planning.
- Multisource spatial analysis approach can improve knowledge state.
- The upgraded knowledge is the basis for correct land management coping with DsGSDs.

GRAPHICAL ABSTRACT



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ABSTRACT

Deep-seated Gravitational Slope Deformations (DsGSDs) are huge ground-deformation slow evolving phenomena, highly widespread in alpine territory. Their long-lasting evolution, with continuous deformation rate, may represents a natural hazard, able to endanger various anthropic structures and infrastructures. Until today, the development of technical and regulatory tools, aimed to effectively manage the interactions between DsGSDs and anthropic elements, has been generally lightly considered in risk management and land use planning. The definition of the type and severity of impacts on the anthropic elements, becomes increasingly important in terms of urban planning and risk management, and deserve an update in the current adopted procedures.
Focusing on the Western Italian Alps, we implemented an interdisciplinary analysis, based on multi-source data, by means of geoinformatics, remote sensing and archive consultation approaches. Intersecting DsGSDs available information with the urbanized territory in a Geographic Information System environment, we obtained, despite the high data heterogeneity, an overall framework of the existing interactions. Specifically, we defined the interactions between these large phenomena and buildings, roads and rail networks, and linear infrastructures, as penstocks, waterworks or dams, also highlighing the state of activity of the inventoried phenomena. Moreover, we analysed the degree of the DsGSD impacts on the anthropic elements, detecting and classifying all the documented damages within the Italian Western Alps territory. The obtained results highlight the need for an innovative approach in DsGSDs risk assessment, both in terms of the definition of their behavior over time and of their impacts on the anthropic elements, for a more effective land use planning and a proper handling of these phenomena in the legislation framework.

* Corresponding author.
E-mail addresses: martina.cignetti@irpi.cnr.it (M. Cignetti), danilo.godone@irpi.cnr.it (D. Godone), francesco.zucca@unipv.it (F. Zucca), d.bertolo@regione.vda.it (D. Bertolo), daniele.giordan@irpi.cnr.it (D. Giordan).

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1. Introduction

A clear definition of landslide hazard is of paramount importance in the context of urban planning, by outlining the areas more susceptible to be seriously damaged (Fell et al., 2005, 2008).

Deep-seated Gravitational Slope Deformations (DsGSDs) are extended slow-moving slope instabilities that represent a still open issue, in term of geological risk assessment and impact definition. DsGSDs are considered as specific phenomena hardly attributable to the conventional classification system of landslides. Compared to the other landslides, which are characterized by faster displacement rates and high intensity, these phenomena show a very slow displacement rates, not impulsive, causing potential damage associated to a continuous deformation over time. Commonly, DsGSDs movement may last for long periods through a progressive failure comparable to a slow creep, with a corresponding large cumulative displacement, that could evolve until catastrophic collapse (Pánek and Klimeš, 2016). In literature, the occurrence of these huge phenomena is referred to Late-glacial period, and continuous through the Holocene until present day (Agliardi et al., 2012). Considering the long-term evolution of these slow-moving gravity-induced phenomena, DsGSDs can be recognized as hazardous phenomena with regard to their effects on structures and infrastructures (Cignetti et al., 2019a; Crippa et al., 2019; Frattini et al., 2013; Pánek and Klimeš, 2016). Even the very slow movements, the lengthy long-lasting evolution, characterized by continuous deformation rate, may constitute a relevant natural hazard, affecting anthropic elements. It should also be considered the risk connected to secondary rapidly evolving landslides, often associated to these huge phenomena, mainly triggered by structural and mechanic deterioration of the rock slopes, due to DsGSDs evolution (Hradecký and Pánek, 2008).

Despite the long-term impact of these phenomena on strategic structures and infrastructures, and the smaller fast-evolving secondary landslides associates, a clear hazard assessment methodology and a dedicated urban planning regulatory framework are still lacking in Italy. In addition, due to their limited displacement rates and their areal extension, these phenomena are not usually monitored by on-site instruments, as it is being done for smaller and faster landslides. This may cause an underestimation of the movement rate and, consequently, of the potential effects of the DsGSDs on human activities and other anthropic elements at risk.

Relatively recent Remote Sensing technologies, specifically the space-borne Advanced Differential Synthetic Aperture Radar Interferometry (A-DInSAR) techniques (Berardino et al., 2002; Ferretti et al., 2001; Hooper et al., 2004), are widely exploited for the measurement of ground displacements over a quite long time span, providing data with extensive spatial coverage and, monitoring areas hindered by limited accessibility. This feature succesfully allows to detect these slow moving phenomena in high mountain regions, obtaining time series describing the ground deformation behavior over periods of several decades (Cignetti et al., 2016, 2019b; Herrera et al., 2013; Mantovani et al., 2019; Notti et al., 2013; Solari et al., 2019; Strozzi et al., 2005).

In the Italian Western Alps, DsGSDs are widely diffused (Ambrosi and Crosta, 2006; Crosta et al., 2013; Mortara and Sorzana, 1987), affecting entire valley flanks and extended in depth for hundreds of meters, with very slow deformation (*i.e.* mm/year up to a few cm/year) (Agliardi et al., 2009). Multiple factors control their evolution, including lithology and structural setting, tectonics and topographic conditions, glaciation-deglaciation, postglacial debutressing, seismicity, rock dissolution (Alberto et al., 2008; Crosta et al., 2013; Martinotti et al., 2011). Different linear morpho-structural features characterize these phenomena, showing different deformation styles (Crosta et al., 2013; Giordan et al., 2017; Martinotti et al., 2011). Commonly, the upper slope sector shows trenches, scarps, double ridge, counter scarps, ridge top depression, highlighting an overall extensional regime. Conversely a compressive regime characterises the lower portions, evidenced by toe bulging and variably fractured rock masses (Crosta et al., 2013). Secondary landslides, including a broad range of instabilities (*e.g.* rock falls, rockslides, rotational and translational slides), usually occur in the middle and lower portion, as a consequence of the progressive and continuous evolution of these large phenomena.

In this work, focusing on the Italian Western Alps area, we developed a multi-source investigation on a large-scale mountain region, to evaluate the impacts of DsGSDs on the anthropic activities. As a matter of fact, it is important to note that the Alpine territory, despite its high relief, is one of the most anthropized mountain chain in the World, with diffuse environmental and cultural heritage. The Alpine landscape has been shaped by centuries of human presence and, through its social, cultural and economic footprint, represents a territory highly susceptible to landslide hazard. It also represents a strategic and economic hinge between North and South Europe, extensively urbanized and populated.

The analysed DsGSDs are extracted by the current regional landslides inventory of the Piemonte and Aosta Valley regions (ARPA Piemonte, 2011; Centro Funzionale Regione Autonoma Valle d'Aosta, 2019; ISPRA Ambiente, 2007). The principal aim of this study is to: (i) examine the overall state-of-art of the knowledges relative to these huge phenomena, obtainable from the available data; (ii) identify all the potential interactions existing between the main anthropic elements and the widespread linear infrastructures in the area of interest; (iii) define the degree of the DsGSDs impacts on the anthropic elements by investigating the type of historically documented damage.

The paper is organized as follows: first of all, a brief description of the area of interest has been done in section two, followed by an exposition of the multi-source interdisciplinary analysis of the DsGSDs phenomena in Section 3, which led to multiple results on (i) state of activity and characterization of DsGSDs of the investigated area, (ii) their potential interaction with the numerous anthropic elements in the alpine area, and (iii) the effective impacts generated by the investigated phenomena documented over the years, presented in section four.

Through the definition of the current knowledge of the impacts of DsGSDs evolution on the diverse anthropic elements widespread in a mountainous territory, as the Italian Western Alps one, actually underestimated both from a methodological and regulatory point of view, a useful tool for the evaluation and management of the territories affected by DsGSDs may be implemented for a more effective geohazard assessment and land use planning regulation.

2. Study area

The area of interest is included in the Western Alps, defined on geographic and toponyomic criteria in agreement with the SOIUSA Classification (*Suddivisione Orografica Unificata del Sistema Alpino*), the International Standardized Mountain Subdivision of the Alps-ISMSA (Marazzi, 2005). More in detail, we focused on the Italian Western Alps (Fig. 1), in north-western Italy, involving the entire territory of the Aosta Valley Region, from here AVR, and part of the Piemonte Region (about 45% of the regional territory), from here PR.

Compared to others mountainous areas in the World, the Italian Western Alps, despite the impervious territory with steep slope ranging from about 300 m a.s.l. to peaks higher than 4.000 m (*e.g.* Mt. Bianco, 4810 m; Mt. Rosa, 4.635 m; Mt. Cervino, 4.478 m), are densely urbanized and relatively populated (1.202.755 of people (ISTAT, 2019)). According to the data from the Regional Technical Map of PR (Piemonte GeoPortal, 2019) and AVR (SCT GeoPortal, 2019), the road network is extended in all the main valleys and lateral ones, with a total length of thousands of km. Several hundreds of km of the road network corresponds to highways that connect the Italian alpine side with the neighbouring countries, *i.e.* Switzerland and France. A dense rail network, hundreds of km long, connects the main towns and the neighbouring countries. Finally, the number of buildings corresponds to hundreds of thousand units, mainly distributed in the middle-lower

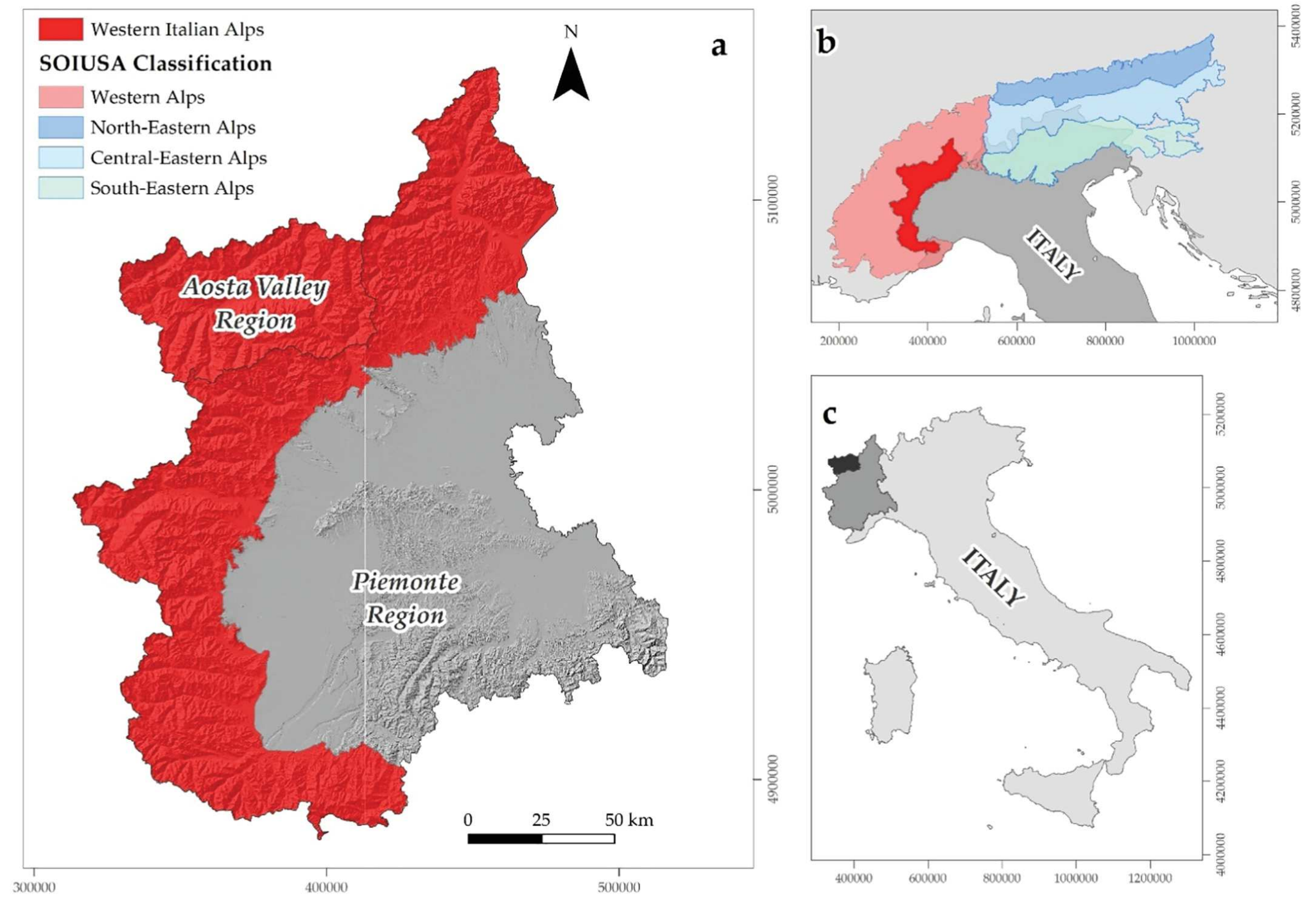

Fig. 1. Location of the study area: a) Italian Western Alps, in light red the area of interest (AOI) involving the Aosta Valley and part of the Piemonte Regions territories; b. Alpine area subdivision according to the SOIUSA classification (Marazzi, 2005), in dark red the Italian Western Alps; c. location of the Aosta Valley Region, in dark grey, and Piemonte Region, in grey.

portions of the numerous main and tributary alpine valleys. Among these buildings, apart from the residential and industrial and the main urbanized areas as squares, parking and so on, there are many sites with great historical and artistic value, such as castles or fortifications.

Due to the high relief energy, combined with complex lithological and structural settings of the Italian Western Alps, landslides are highly widespread, making this territory heavily exposed to this type of natural hazards. As a matter of fact, in the Italian Western Alps, as to the Italian Landslide Inventory (Trigila et al., 2008), named IFFI project (*Inventario dei Fenomeni Franosi Italiani*), a total of 799 Deep-seated Gravitational Slope Deformations are listed. For the AVR, this regional catalogue converges in the "*Catasto Dissesti*"(Centro Funzionale Regione Autonoma Valle d'Aosta, 2019), a regional landslide catalogue available on a web-portal, collecting 263 DsGSDs. Instead, with regard to the PR, the regional IFFI inventory converge in the "*Sistema Informativo Frane Piemonte*" (SiFraP) (ARPA Piemonte, 2011), a geographic system available online, collecting 536 DsGSDs.

3. Material and methods

In order to define the potential interactions of DsGSDs and their impacts with the anthropic elements, we operated through a multi-source interdisciplinary analysis. Firstly, we exploited the existing institutional sources, available online (*e.g.* regional landslide inventory, regional technical maps), with the purpose to gather and define the existing information on these phenomena. In particular, we focused on the available data to establish an overview of the location, the geomorphological characteristics and the state of activity of the inventoried phenomena. Subsequently, operating in a Geographic Information System (GIS) environment, we analysed the interactions between the DsGSDs and the main anthropic elements in the AOI. Finally, we operated an in-depth research of the relevant and known damage due to DsGSDs evolution, reported both in scientific papers and in internal technical reports, to define the effective damage due to these huge phenomena and to characterize them. The following sections describe in detail the implemented methodology.

3.1. Analysis of the existing landslide inventories and associated data

We investigated the state of knowledge about the Italian Western Alps DsGSDs, by referring to the IFFI Project (ISPRA Ambiente, 2007), analysing the two available regional landslides inventories of the PR and AVR, respectively named SiFraP (ARPA Piemonte, 2011) and AVR IFFI (SCT GeoPortal, 2019), associated to the "*Catasto Dissesti*", available online. We mainly focus on the analysis of several datasets concerning:

i. Geographical distribution;
ii. State of activity;
iii. The occurrence of secondary associated landslides;
iv. Presence of on-site ground monitoring networks.

With regard to the state of activity of the DsGSDs of the area of interest, it is important to note that for the PR, the SiFraP catalogue contains this type of information, since its first implementation. Based on previous studies (ARPA Piemonte et al., 2010), in the cases where there was not a sufficient amount of information for defining the actual state of activity, DsGSDs were set as not classified. The state of activity of the PR DsGSDs, since then, has been restated, mainly on the basis of A-DInSAR time series, starting with ESA ERS-1/2 and ENVISAT ASA (1992–2003) data, and progressively updated, or revised, by taking advantage of newest derived datasets (*i.e.* RADARSAT-1/2, CosmoSkyMed, Sentinel-1). In fewer cases, the review and the updating have been carried out exploiting the data provided by ground-based monitoring tools. In the case of the use of A-DInSAR, the classification of a DsGSD as "active" or "dormant" state of activity was given only for proven cases, in which there was an adequate persistent scatterers (PSs) coverage within DsGSD under study (Meisina et al., 2013).

With regards to the AVR, the regional IFFI catalogue reports only the type of slope instability. In order to obtain a consistent classification, following the criteria used by other authors in PR, we carried out an assessment of the DsGSDs state of activity of the AVR, based on the available Synthetic Aperture Radar data (*i.e.* RADARSAT-1/2 satellites), processed with SqueeSAR™ technique developed by Telerilevamento Europa, and PS-Mapping data (Sentinel-1) and applied by the AVR Geological Survey during the EU Risknat project (Broccolato and Paganone, 2012; Solari et al., 2020).

3.2. Analysis of the potential interaction between DsGSDs and the main anthropic elements

For each DsGSD, an analysis of the potential interactions with the main anthropic elements within the Italian Western Alps have been performed. We considered both surficial and sub-surficial features, with a particular attention to those linearly extended, more susceptible to highlight the deformation produced by the DsGSDs. Besides these long-lasting gravity-induced large slope instabilities, we also considered the associated secondary landslides, which potentially could dangerously interact with road and rail networks.

Four main categories of anthropic elements are considered:

i. buildings;
ii. road network;
iii. rail networks;
iv. others linear infrastructures, *e.g.* waterworks, penstocks, hydroelectric plants, dams.

We operated in an open source geographic information system (GIS) environment (QGIS Development Team, 2009). Through selection and intersection tools, we analysed the interaction between DsGSD polygons and the considered groups of anthropic elements, organizing data in a spatial database.

We extracted all the current anthropic elements, analysing the diverse available institutional sources in the framework of land use planning. For sake of clarity, we investigated separately the existing interactions regarding the DsGSDs of the PR and those of the AVR, due to some differences in the data structure and information typology. More specifically, we used the available data from the Regional Technical Map (CTR) of both PR and AVR areas. Table 1 shows the number of the four main categories of anthropic elements considered, in term of length of roads, railways or linear infrastructures and number of buildings, distinct for each region.

The CTR, acquired by the Cartographic Service of the PR in the year 1991–2005, besides road and rail network, and buildings, contains also the data about waterworks, pipelines and dams. Moreover, the buildings category includes both residential and industrial buildings, urban elements like squares and parking are included as well. Regarding to roads and railways, the PR CTR provides a high degree of information, by differentiating, for example, the tunnelled sections. All the data are available at the scale 1:10.000 with reference system WGS84/UTM 32 N EPSG 32632, and they are freely downloadable in shapefile format (Piemonte GeoPortal, 2019).

Table 1
List of the number of buildings, and length of road network, railway and linear infrastructures divided in the AVR and PR.

Category	AVR	PR
Buildings	74,030	309,482
Road network	4193 km	28,082 km
Railway	257.5 km	443.5 km
Linear infrastructures	248 km	160 km

Also for the AVR territory, the CTR published in 2005 have been considered to acquire information about the main anthropic elements. In particular, we collected the data about buildings, divided by typology (*e.g.* residential, industrial, buildings with historical and/or artistic value, and urban areas as parking or squares), roads and highways, railways, distinguishing sections in tunnels or on bridges, penstocks and waterworks. Dams have been derived by the authors from the lake shapefile and orthophotos. All the data are available at scale 1:10.000 with reference system ED50/UTM 32 N EPSG 23032, and freely downloadable in shapefile format (SCT GeoPortal, 2019).

4. Results

On the basis of the implemented multi-source interdisciplinary analysis, multiple results have been obtained. Leveraging on the data stored in the regional inventories in connection with DsGSDs, the state of knowledge of these phenomena have been defined for the AOI. This allowed us to characterize the 799 inventoried DsGSDs (263 of the AVR and 536 of the PR), in term of distribution and state of activity. Then, through the GIS-based analysis implemented, the overall framework of the interactions between DsGSDs and the main anthropic elements have been defined, specifically in term of type of structures or infrastructures that intersect the observed phenomena and the number of intersections for each inventoried DsGSDs. Finally, drawing on the available information stored in the national and regional inventories, as well as those reported in technical documents and scientific publications, the damage due to DsGSDs evolution have been assessed.

4.1. State of knowledge of the Italian Western Alps DsGSDs

The analysis of the two official landslides catalogue of PR and AVR, allows to collect several important characteristics and information about each DsGSDs of the area of interest.

About the 8% of the Italian Western Alps territory is affected by these large slope-instabilities. Considering the territory of the Aosta (AO) for the AVR, and of the diverse Provinces of the PR (*i.e.* Torino (TO), Cuneo (CN), Verbano-Cusio-Ossola (VB), Vercelli (VC) and Biella (BI)) within the Italian Western Alps (Fig. 2a), the highest concentration of DsGSDs is in the AVR, corresponding to the 13% of the entire provincial/regional territory. Follows the TO Province, with the 10.5% of the mountainous territory involved, with a concentration in the main valleys of the region (*i.e.* Susa Valley, Chisone Valley, Pellice Valley) located in the middle-low portion of the TO Province. Similar values are recorded for the CN and VB Provinces, respectively of the 4.7% and 4.5%, lower percentage are observed in the VC and BI Provinces.

As previously mentioned, we detected some differences in the structure and type of information, in the two regional landslides inventories. Indeed, a definition of the state of activity of the DsGSDs is reported only for the SiFraP catalogue of PR, while the AVF IFFI catalogue reports only the type of collected phenomena. Taking advantage of the RADARSAT-1/2 database, observing SAR data at regional scale, based also on the former analysis by the AVR geological survey (Broccolato and Paganone, 2012), we performed a prompt assess of the state of activity of the

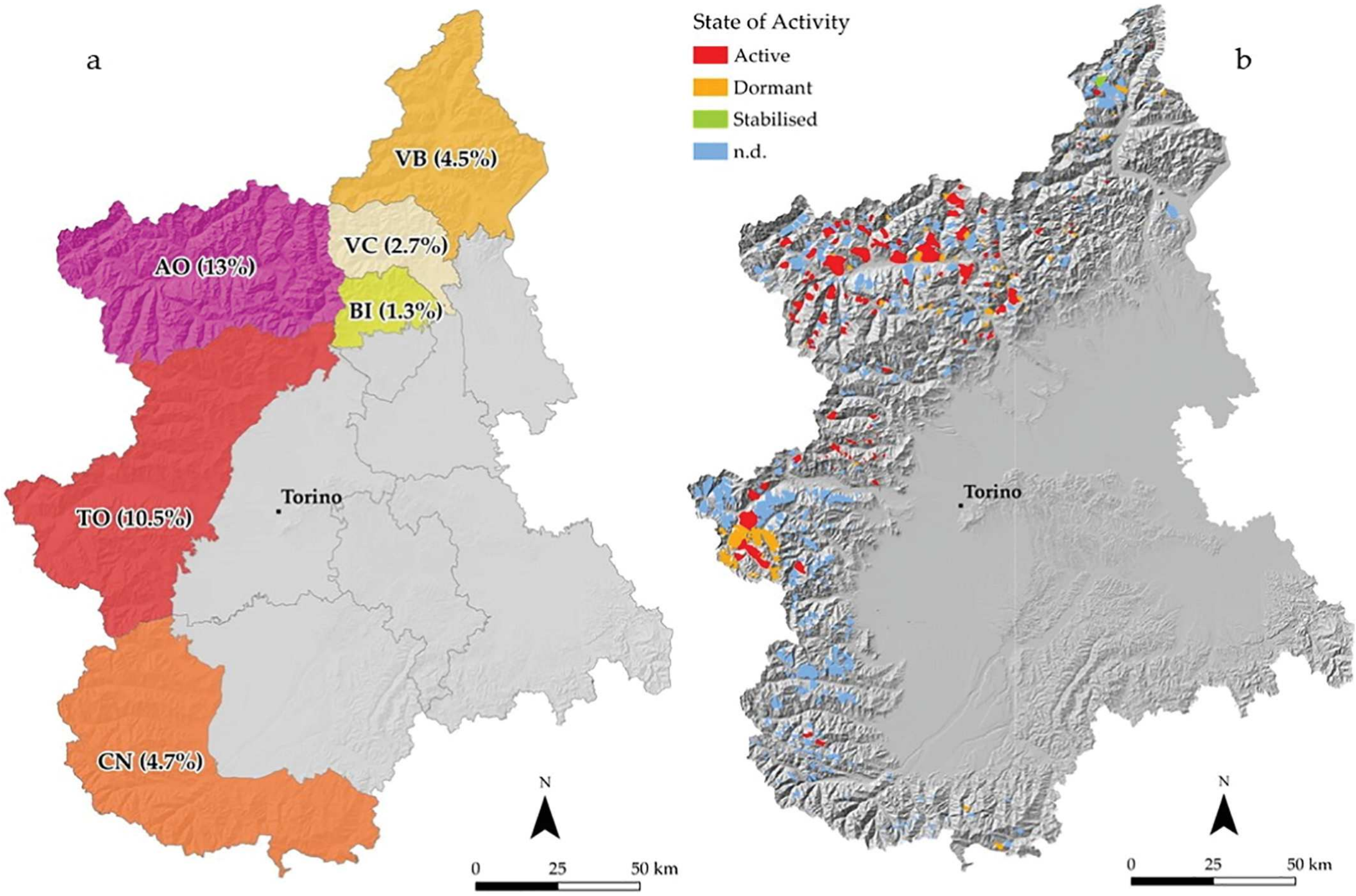

Fig. 2. (a) Percentage distribution of the DsGSDs within the provincial territory of the AVR and PR, relative to the alpine portion; (b) DsGSDs distribution within the Italian Western Alps territory, classified on the basis of the state of activity (Data source: for the DsGSDs of the PR, SiFraP (ARPA Piemonte, 2011); for the DsGSDs of the AVR, IFFI catalogue (ISPRA Ambiente, 2007).

AVR DsGSDs, analysing the Permanent Scatterers/Diffuse Scattered within the DsGSDs areas. By this means, at the Italian Western Alps scale, it can be observed that 17% of the DsGSDs are classified as active, the 14% quiescent, while for the most of them the state of activity is undetermined (69%) (Fig. 2b).

DsGSDs showing active state of activity are mainly distributed in the AVR and locally in the middle portion of the PR, in the Susa and Stura Valleys.

Concerning the secondary induced landslides, commonly associated to DsGSDs, we observe that the 64% of the DsGSDs show the occurrence of associated smaller slope instabilities. The examined landslides derived from the two regional catalogues SiFraP for PR (ARPA Piemonte, 2011), and IFFI for AVR (SCT GeoPortal, 2019), as well as the analysed DsGSDs phenomena. Fig. 3 shows the percentual values of the associated landslides occurred in the DsGSDs areas, calculated in terms of surface, divided per type, and separated between AVR and PR. The landslide classification corresponds to that reported in the regional inventories.

To give an overview of the entire area of interest, most of these secondary landslides associated to DsGSDs are complex landslides, rockfalls and/or topplings, and rotational or translational slides. Often, specifically in the case of complex landslides, the secondary landslides are instrumented with on-site monitoring networks. For sake of clarity, only for PR, the SiFraP catalogue reports, for each landslide and/or DsGSD, the existing instruments (*e.g.* Global Navigation Satellite System (GNSS), inclinometers, piezometers). Based on these data, we assessed that about 8% of the PR DsGSDs present on-site instruments, or directly installed on DsGSDs or on their secondary landslides.

4.2. DsGSDs interaction with anthropic elements

The analysis of the potential interactions between DsGSDs and anthropic elements highlights that the 59% of these long-lasting gravity-induced phenomena interfere with one of more of the considered group of features. Always maintaining the AVR and PR areas separated, we first analysed the interaction with each of the considered elements.

Fig. 4 shows the classification of each DsGSDs of the Italian Western Alps, according to the existing interaction with the four considered categories buildings, road network, railways, and other linear strategic elements (*e.g.*, waterworks, penstocks, dams). By using CTR vector data for both AVR and PR areas, a homogeneous analysis has been possible. The use of these datasets allows a complete overview of all the anthropic elements widespread within the area of interest, adding also specific information about the stretches in tunnels or on bridges, the type of buildings, and the type of such strategic infrastructures as waterworks, penstocks or dams.

Concerning the overall urban areas distribution, nearly 50% of the DsGSDs are occupied by buildings (Fig. 4a), which are in the majority for residential use. Fig. 5 shows the frequency distribution of these buildings, highlighting the degree of their aggregation, *i.e.* if they are clustered or single buildings. It can be noted that the buildings located on the DsGSDs are mainly single houses and small urban agglomerations. Rarely, a limited number of hamlets, villages and towns are interested by DsGSD phenomena. Among them, there are renowned touristic locations such as Sauze d'Oulx, Sestriere (TO Province), and Valtournenche and Courmayeur (AO region).

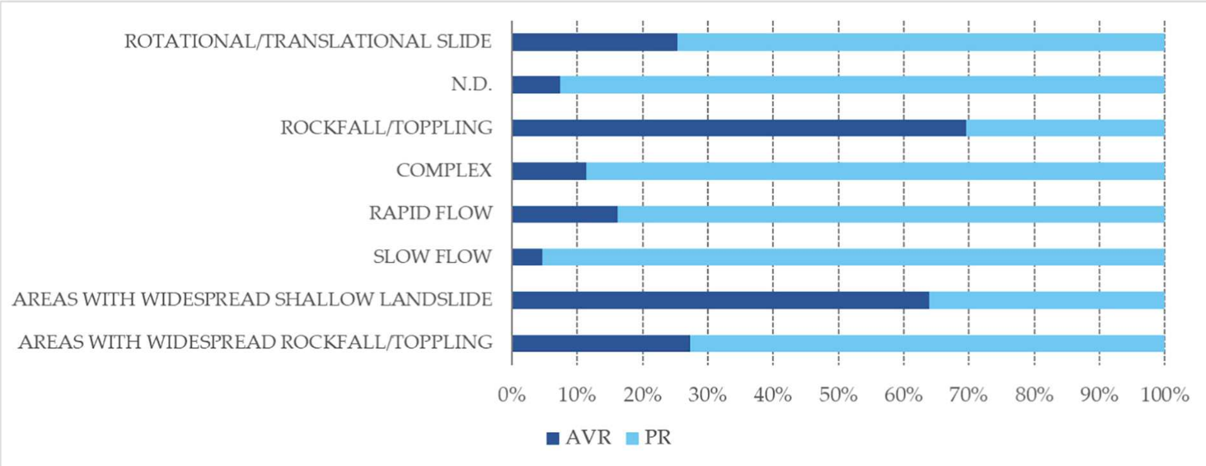

Fig. 3. Bar plot of the secondary landslides associated to DsGSDs of the Italian Western Alps, classified per type, following the same classification reported in the IFFI catalogue (ISPRA Ambiente, 2007).

Observing the state of activity of the DsGSDs that affect urbanized areas, we detected that the 22% are active, mainly distributed in the AVR and in the upper Susa Valley, in the middle portion of the PR. It is worth to note that about the 64% of DsGSDs affecting urbanized areas have an undetermined state of activity.

Regarding to the transportation networks, the 41% and the 37% of DsGSDs, respectively of the PR and AVR, intersect the road network, while the 2%, in both cases, intersect railways (Fig. 4b and c).

By cross-referencing those typologies with the DsGSDs state of activity, we detected that most of the identified intersections occur with main roads (*e.g.* provincial to municipal), not in tunnels, within DsGSD active/reactivated/suspended (about 65%), mainly distribute in the AVR area. Instead, tunnels and highways stretch to cover a small percentage in both regions (about 2–3%), and they are mainly interfering with phenomena with an undefined state of activity.

We also analysed the potential intersection of the DsGSDs with some linear elements (*e.g.* waterworks, dams, hydroelectric plants) derived from various CTR levels, detecting a percentage of about 4% of the PR cases, and 15% of the AVR ones (Fig. 4d). Most of these linear elements are affected by DsGSDs phenomena located in the AVR areas. In fact, several hydroelectric plants, including dams and penstocks, are located in this region (CVA SpA, 2019). These strategic infrastructures, extended linearly for many km (*e.g.* Quart, Breuil-Cervinia, Beauregard), intersect numerous DsGSDs of the AVR territory, both on the surface and in depth. Considering the Italian Western Alps DsGSDs state of activity, 2.5% of DsGSDs affecting these strategic infrastructures are active, while about the 4% are undefined.

Fig. 6a is focused on the whole territory of the Italian Western Alps and shows the DsGSDs distribution, divided in classes based on the number of intersections with the considered anthropic elements, referring to the four main groups “buildings”, “road network”, “railways” and “other linear elements” (§ 3.2), and the relative percentage (Fig. 6b). More than half of DsGSDs show at least one or two interactions with the considered man-made structures and infrastructures groups. The cases with the higher number of large intersections are distributed in the northernmost part of the PR (VB Province), in the middle-low portion of the PR (TO Province), in correspondence of several of the main valleys of this region (*i.e.* Susa Valley, Chisone Valley, Pellice Valley), and variably spread in the AVR territory.

Fig. 7 highlights the observed interactions with DsGSDs divided into thirteen categories, based on the number of intersections and the type of intersected elements. In addition to the cases without intersections, we notice that the greatest number of interactions occur with the category “B”, *i.e.* buildings, and “B + Ro”, *i.e.* building and road network. Follow, to a much lesser extent, the categories “Ro”, *i.e.* road networks, and “LE + B + Ro”, *i.e.* linear element as penstocks, waterworks or pipelines, buildings and road networks.

4.3. Survey of documented damage

Cross-referencing the various information derived from the available databases, together with literature and private technical reports, we detected the damage actually recognized in the Western Italian Alps territory. For the PR area, we mainly referred to the documents associated to some DsGSDs inventoried in the SiFraP catalogue. With regard to part of the collected phenomena, some of them are described by a detailed monography, drafted by the ARPA Piemonte (ARPA Piemonte, 2011). This synthetic document contains a series of geomorphological maps associated to an identifying tab with geographic, morphometric, geological-geomorphological, monitoring systems, and eventual notices of damage description in a brief form.

For which concerns the AVR, we mainly referred to the information reported in the “*Catasto Dissesti*” web-catalogue (Centro Funzionale Regione Autonoma Valle d'Aosta, 2019). This service provides diverse ancillary data about phenomena description, triggering factors (if known), and occurred damage.

Considering the long-lasting evolution of DsGSDs, a total of 28 cases of documented damage related to the continuous deformation trend of these huge phenomena were detected across the Italian Western Alps. Table S1 (see Supplementary material) enumerate each case, by specifying geographical location, type of damage, and sources of information. A brief description of the phenomena is reported, pointing out the kinematic characteristics of DsGSD and the eventual correlation with secondary landslides occurrence.

Observing the listed damage due to DsGSDs activity (Table S1), a highly variable degree of impact of these huge phenomena on anthropic elements is evident. Fig. 8 shows some examples, pointing out the main typologies of impacts. In general, the impacts due to DsGSDs evolution are not impulsive, as it happens for fast landslides with high magnitude, but slow and uninterrupted, often requiring a continuous maintenance of the affected structures and infrastructures. Damage range from a slight effect, as in the case of Champlas du Col, in which urbanized areas reveal no damage or crackings, while secondary landslides occurrence caused important damages to the main road (Fig. 8a), to a gradual increase Variable impacts are observable from evident damage to group of buildings and/or village/town (*e.g.* Grange Sises) (Fig. 8b), or to the road network with its interruption (*e.g.* Torre delle Giavine), up to high impact to strategic elements. Important linear infrastructures, as penstocks, hydroelectric plants, dams, are, in general, more sensitive to the DsGSDs evolution, as recorded in the case of the Beauregard

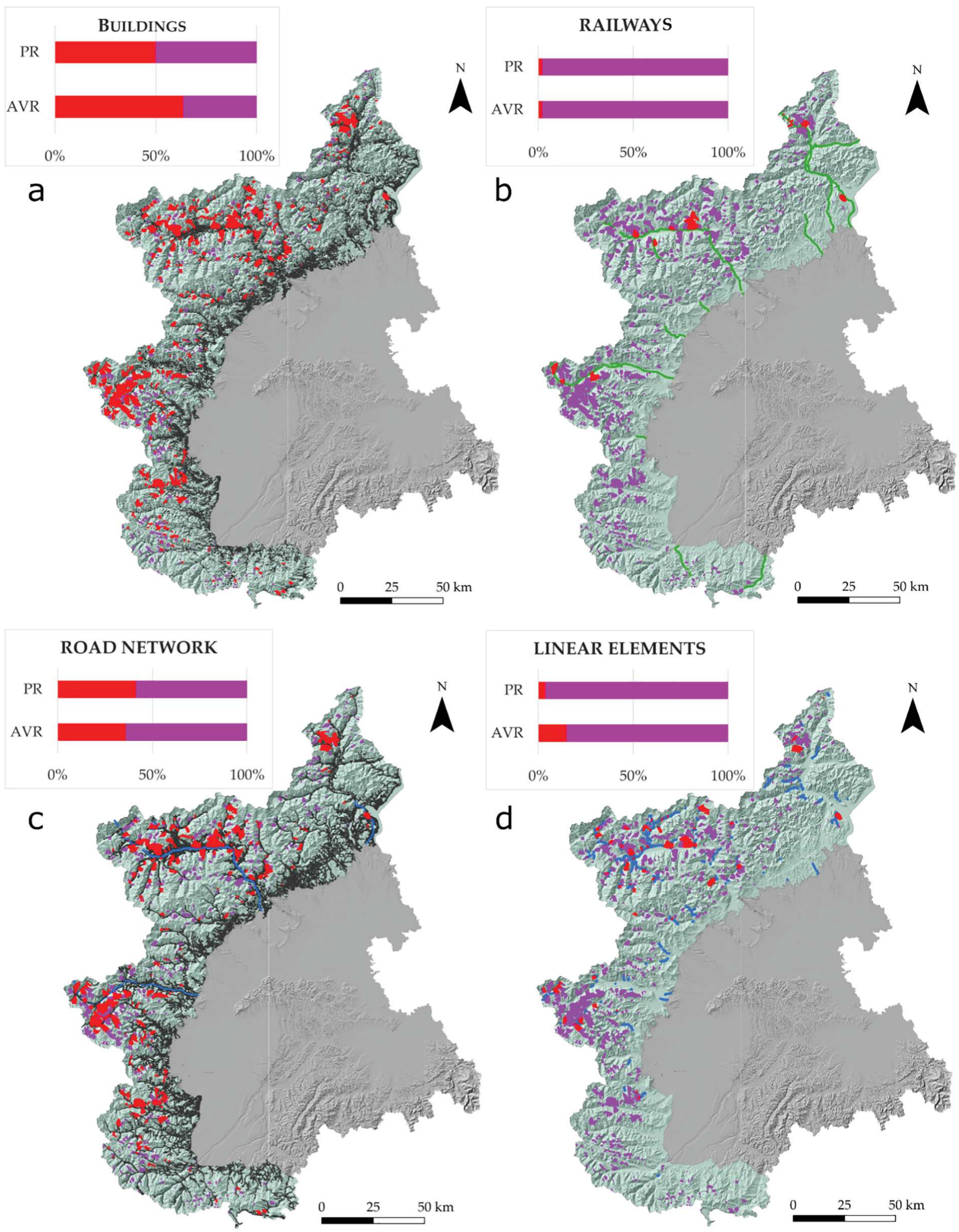

Fig. 4. DsGSDs of the Italian Western Alps classified according to the type of the intersected anthropic element: a) intersection with buildings (dark grey dots); b) with railway (green polylines); c) with road network (road in dark grey polylines, highways in blue); d) with linear elements as waterworks, pipelines, penstocks and dams (blue polylines). Red polygons correspond to such phenomena intersecting the various elements, while the purple polygons represent those without intersection. Each map is associated to the bar plot of the percentage of DsGSD phenomena that intersect (in red) or not intersect (in purple) such features.

Dam (Fig. 8c), in which anomalous stresses and deformation in the dam structure, due to a DsGSD affecting the dam left shoulder, led the owners to the dismantling of this strategic infrastructure. In other cases, as in the Croix-de-Fana DsGSDs (Fig. 8d), the slow but continuous deformation rate led to a periodic maintenance of the concrete lining of a hydroelectric bypass tunnel, primarily in correspondence of those

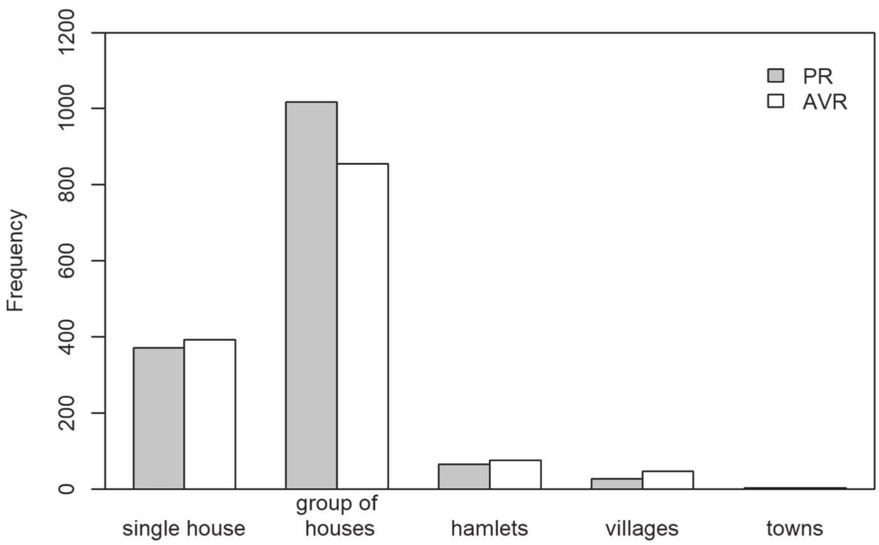

Fig. 5. Bar plot of the frequency of buildings distributed in 5 classes, distinguished between the PR and AVR location.

portion placed at the boundary of the DsGSD, or at the border of domains with distinct kinematic behavior.

5. Discussion

The study of the impacts of DsGSDs on anthropic elements, within the area of interest, highlights the need to drawn the attention of land management experts and regulators to the effects of these huge phenomena evolution on urbanized areas and man-made structures and infrastructures.

In the Italian Western Alps, DsGSDs affect a relevant portion of territory, respectively the 13% of the AVR territory (SCT GeoPortal, 2019) and the about 5% of the PR one (ARPA Piemonte, 2011). Based on A-DInSAR data and/or *in-situ* monitoring network, we were able to distinguish these huge phenomena in (i) active, (ii) dormant, and (iii) undefined, in term of state of activity. It should be recalled that, for PR area this classification is already reported in the SiFraP catalogue (ARPA Piemonte, 2011), reporting 13% of DsGSDs as active. Unfortunately, more than half of catalogued phenomena of Piemonte, about the 73%, have been classified as undefined by the SiFraP, without the possibility to define the state of activity. Instead, for the AVR case, we directly performed a dedicated analysis, taking advantage of Radarsat-1/2 and Sentinel-1 A-DInSAR data, observing that about 26% of DsGSDs are active, while the 59% in an undefined state. At the Italian Western Alps scale, our analysis has shown that, on a total of 799 phenomena, 17% are active, and 14% dormant. It should be noted that the A-DInSAR techniques may generally be suitable to assess the activity status of the DsGSDs. However several intrinsic limitations of this technique (*e.g.* slope geometry, land use/land cover and the line-of-site (LOS) measurements only) must be carefully weighted when performing a large-scale analysis. These limitations could hamper the reliable assessment of the activity of many DsGSDs phenomena, which consequently have to be classified in an undefined activity state (Bonì et al., 2018; Casagli et al., 2016; Colesanti and Wasowski, 2004).

By performing a cross-referencing between DsGSDs and the main anthropic elements potentially at risk, our analysis reveals that more than a half of the inventoried DsGSDs (about 59% of the cases) affect structures and infrastructures, as well as urbanized areas. It is worth to note that in alpine regions, DsGSDs represent wide areas, with relatively gentle slopes, which, together with alluvial fans, are the most urbanized areas of this almost entirely mountainous territory. In general, we observed that the majority of the DsGSDs interactions occur with residential buildings and main roads. In addition, on a total of 140 active DsGSDs, the 11% are variably occupied by small agglomerations of buildings and/or villages and towns, about 8% interact with main road (*e.g.* provicial, municipal), and 2.5% affect strategic infrastructures mainly represented by linear elements, as penstocks, waterworks and dams. Furthermore, in 548 cases with undefined state of activity, about 35% interfere with buildings, 21% with the main roads and 4% with other structures and infrastructures.

The overall framework we obtained shows a clear interaction between these long-lasting gravity-induced phenomena and the main anthropic elements distributed across the area of interest. Moreover, focusing on the effective damage actually recorded in the Italian Western Alps territory, we detected a certain degree of variability in term of impact. We observed that the impact is mainly related to: (i) intrinsic behavior of DsGSDs, (ii) secondary landslides occurrence, (iii) presence of diverse morpho-structural domains, and (iv) boundary effects.

Since the investigated area is a mountainous territory, the degree of dissemination of buildings is not as clustered as expected in other mountain areas. Often, the intrinsic behavior of DsGSDs mainly affects groups of buildings and/or urban areas, as well as the main roads (*e.g.* Punta Lavasse, Valtourenenche). In fact, we observed several cases in which DsGSDs evolution affects local hamlets, as Cielo Alto hamlet (Breuil-Cervinia municipality), as well as renowed urban villages and town (*e.g.* ski resorts like Sauze d'Oulx, Sestriere). In some cases the damage disrupted the building, leading to the precautionary evacuation of the buildings. In many cases, smaller and faster landslides associated to DsGSDs evolution, affect the road network, causing the traffic interruptions, as in the case of Champlas du Col. Moreover, even though the number of intersections with other kinds of infrastructures such as hydroelectric plants, waterworks or dams is less frequent, it is important to note the strategic role of these infrastructures. In particular, considering their linear extent, the susceptibility of these anthropic elements to a slow and continuous displacement over time, can be very high. In particular, DsGSDs are often characterized by different deformation styles, referable to the kinematics of distinct morpho-structural domains (Giordan et al., 2017; Pánek and Klimeš, 2016), showing some sectors with high degree of evolution, more prone to cause injuries to the intersected anthropic elements, as in the case of the Beauregard Dam. Likewise, the boundary effect generates diverse stress conditions on these linear elements, in correspondence of those portion placed at the boundary of the DsGSD, as in the case of Croix-de-Fana DsGSDs that affects the hydroelectric tunnel.

Considering the available regional landslide inventories, we noticed that some dissimilarities occur in the available information reported in the two existing regional landslides catalogues, each with its own

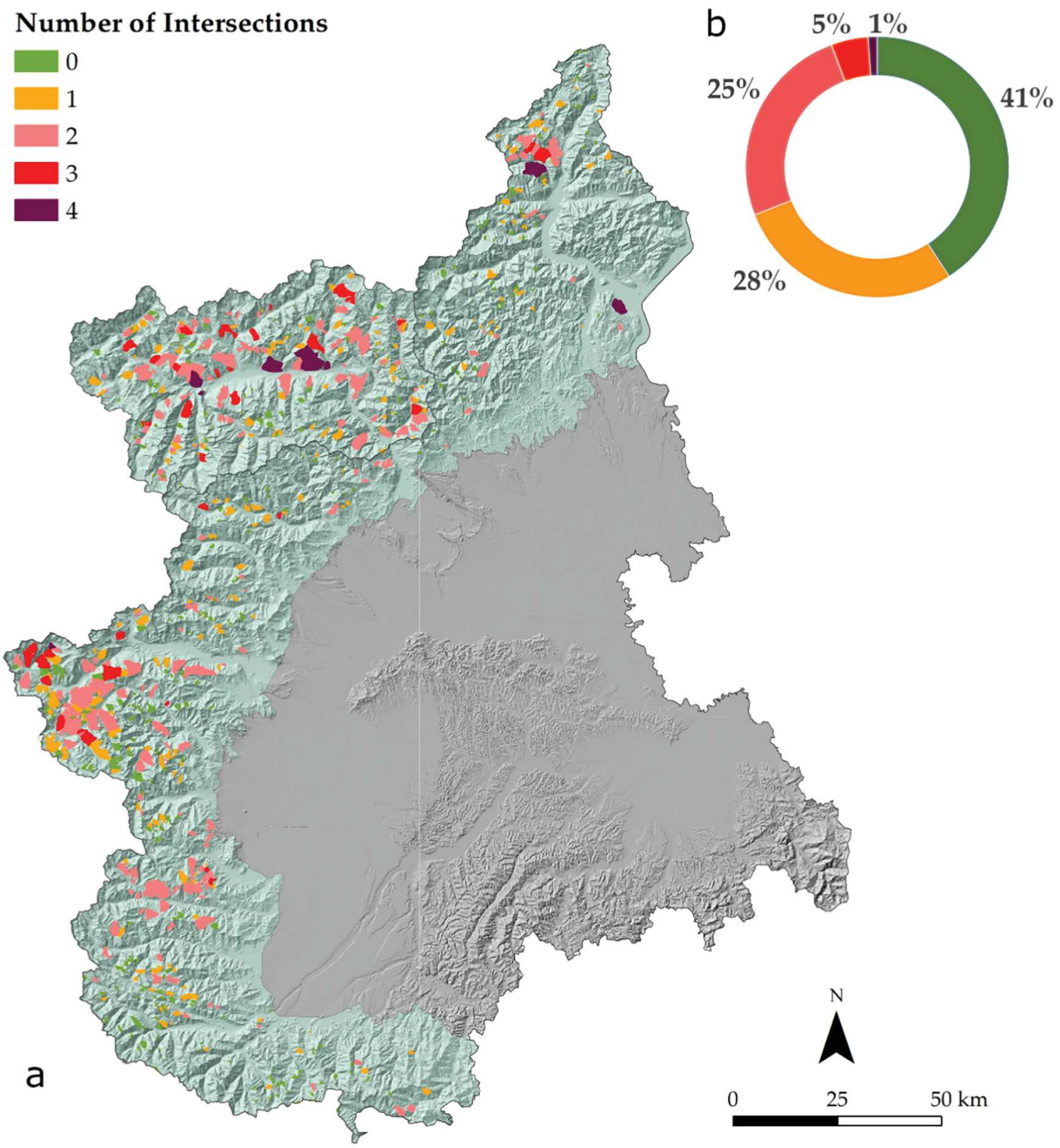

Fig. 6. DsGSDs classified on number of intersections with the main anthropic elements; a) map of the DsGSDs distribution; b) Funnel chart of the corresponding percentage of DsGSD for each class.

structure, making the DsGSDs analysis difficult because of non-homogeneous criteria.

At the same time, considering the regulatory framework, a wide range of laws actually exists. The policies and laws are different between the PR and AVR territory, resulting in a heterogeneous framework within the Italian Western Alps territory. In general, the regional territory of both regions is divided in homogeneous territorial units, by defining their level of geo-hydrological risks and by establishing specific risk classes. However, distinct laws, norms and land use planning regulation (Scolobig et al., 2014), related to a hierarchal link and applicable only at different scales (*e.g.* General Regulatory Plan (PRGC) at municipal scale, Territorial Coordination Plan (PTC), operating at provincial scale, and Regional Territorial Plan (PTR), for PR, or Territorial Landscape Plan (PTP), for AVR, at regional scale) exist for each region, without a general and common guideline. For which regards the DsGSDs, the current legislative framework lacks of a specific regulation in the risk classes definition, as for the other type of slope instabilities. In fact, the current legislation, both at national and regional scale, refers to landslide risk zonation specifically on the basis of the state of activity, without a specific distinction between landslides and DsGSDs. Only the geomorphological and slope instability maps, always provided with PRGC, report both the landslides and DsGSDs locations, without defining specific action to be carried out concerning the potential impact of these large phenomena on anthropic elements. An initial analysis was made at provincial scale (ARPA Piemonte et al., 2010), and then in Drago et al., 2012, by a dedicated investigation of DsGSDs role in land use planning, laying the bases for a preliminary discussion on this issue.

Starting from the last years, some efforts have been done by local and regional authorities (*i.e.* planning instrument named "*Ambiti Inedificabili*", areas where it is prohibited or there are limitations to build, referring to the L.R. 11/1998 of the AVR), approving specific variants of the PRGC of sites featuring DsGSD, and dedicated studies (Delle Piane and Perello, 2012), in term of risk zonation of these phenomena.

These observations underline the need to consider also this type of phenomenon in risk assessment and a starting point for a land use planning policy more suitable and effective. However, the progressive evolution of the scientific methodologies (*i.e.* satellite ground motion monitoring, 3D sub-surface modelling) and regulatory framework,

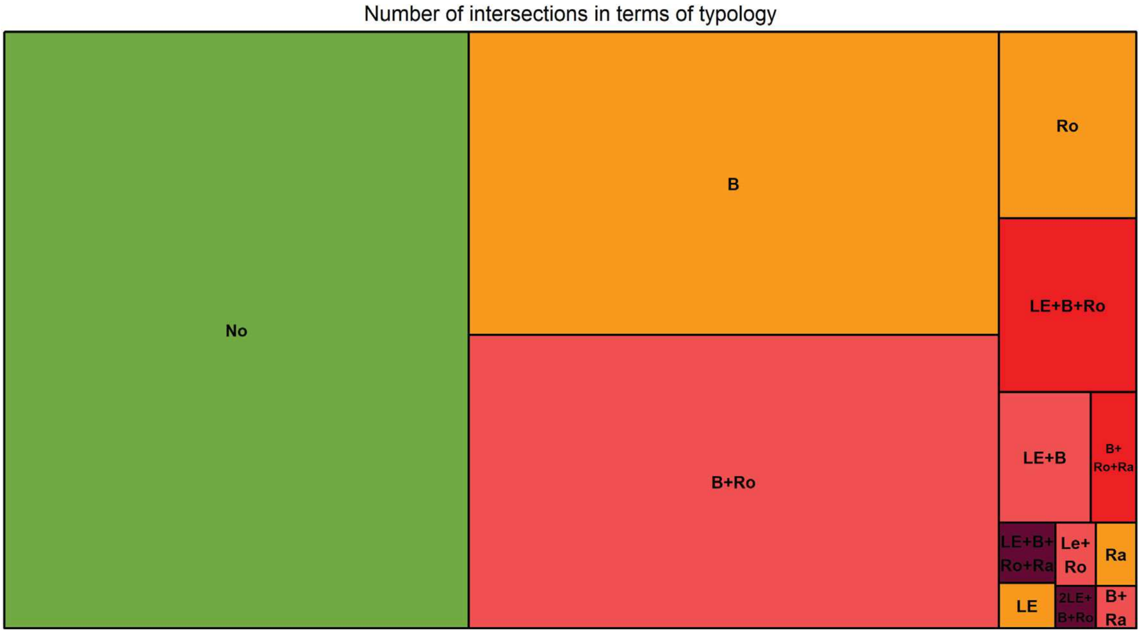

Fig. 7. Tree-map chart showing the proportion of the intersection frequencies between the alpine DsGSDs and the diverse anthropic elements identified (B buildings, Ro roads, Ra railways, LE linear elements *i.e.* waterworks, penstocks, pipelines and dams). Four main classes are distinguished: in green no intersection class; in dark yellow one intersection between DsGSDs and one of the considered anthropic elements; light red, intersection with two of the considered elements; red with three of them; dark purple with four features.

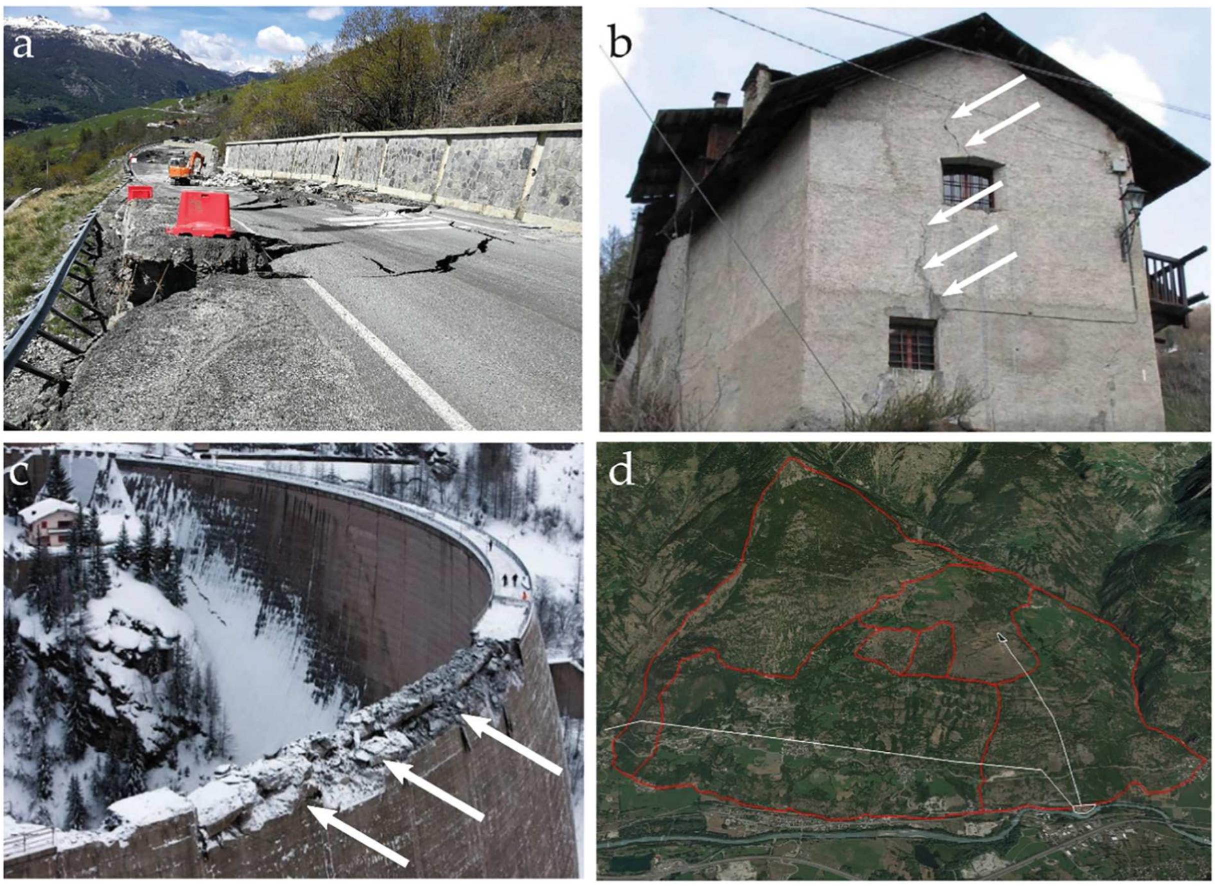

Fig. 8. Main impact of DsGSD evolution on anthropic element recognized in the Italian Western Alps: a) Champlas du Col case, with slight effect on urbanized areas, and relevant road damage (SP23) due to secondary landslides associated to the DsGSD (Photos of Giordan D.); b) Grange Sises case, with evident cracking and injuries to the building (indicated by the white arrow) of the namesake village (Photo ARPA Piemonte, 2011); c) Moriond case, with high impact of DsGSD on the Beauregard Dam on the left side, now almost completely dismantled (initial stage of the dismantling indicated by the white arrow) (Photo available online); d) Croix-de-Fana case, with relevant impact to the linear elements of the hydroelectric plant (white element), mainly along the edge and in correspondence of the diverse domains (in red) of this huge phenomenon (Google Earth view).

improved and refined over time, have led to a certain degree of complexity in their implementation. In this context, there is a growing need to elaborate specific land management and planning regulations also for the territories which are affected by the DsGSDs, having regard to their proven impact on anthropic structures and, particularly on those with relevant extension specifically in designing the strategic infrastructures.

6. Conclusion

The evaluation of DsGSDs impacts, by number and type, on the main anthropic features, is a key element in the urban planning framework, primarily to ensure the public safety and to prevent damage to strategic assets and the related economic losses. We carried out a multi-source analysis of those interactions, the survey of the documented damage, as well as the survey of the current land use planning regulatory framework concerning these large phenomena, aspects that play an important role in the hazard assessment in mountain areas.

Our analysis highlights the effects that DsGSDs behavior have on anthropic elements, pointing out the need for a comprehensive assessment and definition of their effects and of their degrees of impact. These findings are intended to be the scientific background for a functional review of the current regulatory framework, in order to define and include modern tools for an effective and safe management of the territories affected by DsGSDs into the urban planning legislation. The current study could also be an useful benchmark for an extensive analysis on larger study areas, such as the whole Alpine chain or the Apennines, where due to the abundance of information, big data and/or machine learning approaches could be proposed.

CRediT authorship contribution statement

M. Cignetti: Conceptualization, Methodology, Formal analysis, Investigation, Data curation, Visualization, Writing - original draft.**D. Godone:** Methodology, Formal analysis, Investigation, Visualization, Writing - original draft.**F. Zucca:**Supervision, Writing - review & editing.**D. Bertolo:**Supervision, Writing - review & editing.**D. Giordan:**Conceptualization, Supervision, Writing - original draft.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data: list of the documented damage to anthropic elements, caused by DsGSDs long-lasting evolution over time in the Italian Wester Alps area of interest

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2020.140360.

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3

Complex landslides

Complex landslides are composite slope instabilities, usually composed by diverse type of landslides, referring to Cruden and Varnes, (1996) classification. Due to their complexity, in-depth investigations and analysis are requested to landslide risk assessment and mitigation. Usually, leveraging on both on-site monitoring network and remote sensing techniques, the characterization of slope instabilities in term of state of activity, the definition of their behaviour over time can be carried out. An interdisciplinary analysis, combining archive consultation approaches and new data acquisitions with field survey and aerial or satellite images acquisitions, should represent a useful approach for landslide hazard definition in a comprehensive way. By exploiting a territory variably affected by active complex landslides as the Aosta Valley and the Piemonte regions (northwestern Italy), the Phase I of the reiterated structure proposed in the thesis (Figure 3.1), mainly consisted in available data and information analysis and collection, primarily with reference of regional monitoring networks measurements, technical reports, institutional regional GeoPortals and national or regional inventories. Usually, considering active complex landslides affecting important settlements and or strategic anthropic structures and infrastructures, an in-depth analysis is required. This generally may lead to a series of field survey analysis, ground deformation measurements, evolution model implementation, repeated several times to improve the knowledge about slope instability evolution. However, a large amount of data and information may also require dedicated management and organization of the data and information, to avoid possible misunderstanding. Trying to solve this issue a dedicated document, *i.e.* Operative

Monography (OM), able to provide standard guidance for effective management of the available data and information, and to propose future interventions and actions, has been implemented and tested for the active landslides included in the regional monitoring network of the Aosta Valley Region (northwestern Italy), and presented in the *Paper III*.

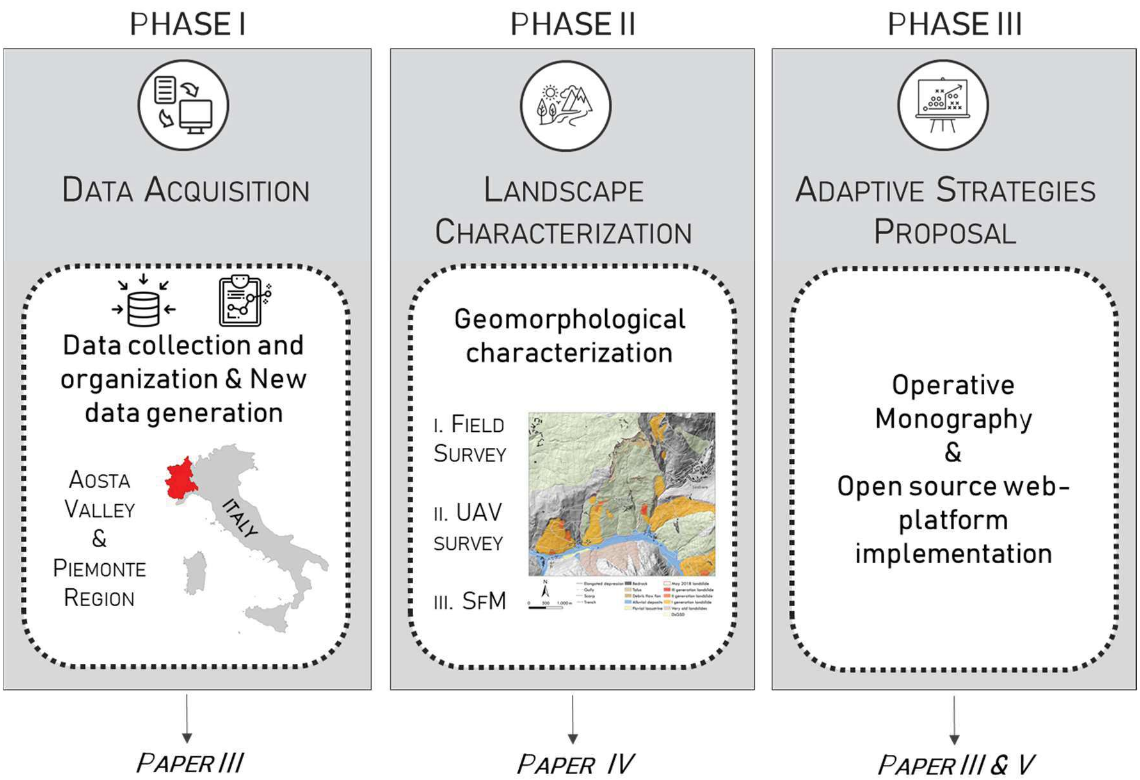

Figure 3.1 - Reiterated structured proposed for the complex landslide typology.

Phase II was mainly devoted to the geomorphological characterization of new or re-activated landslides, leveraging on both traditional field surveys and the UAV surveys, by exploiting the Structure from Motion (SfM) technique, but also through the SAR data analysis and interpretation. The multi-source and multi-sensor data and information acquisition allowed to a more comprehensive slope instability interpretation and characterization, as tested for the Champlas du Col landslide (Piemonte, northwestern Italy) case, and presented in the *Paper IV*. In alpine regions, often threatened by active complex landslides, a properly data collection, organization, management and also sharing, represent a key element to a properly landslide risk assessment and management and land use planning purposes. Specifically, for the collection of a large amount of data and information over time, web-GIS services based on software based on institutional arrangements and technologies, and with specific policies on metadata and data sharing and management, should be a reasonable solution. In parallel with the implementation of the OMs, Phase III consisted of an open-source web-platform implementation. The employed platform, *i.e.* GeoNetwork software, guarantees the usage of a tool with standard formats and protocols. This web-platform was tested in the framework of a national project devoted to process, collect and organize both on-site and remote sensing ground deformation measurements of various slope instabilities located in hilly and

mountainous regions over wide areas. This guarantees prompt and user-friendly accessibility of multi-source and multi-sensor data and metadata, allowing a proper use and reuse for policy-makers and other interested stakeholders, mainly for landslide characterization and risk assessment purposes, as presented in the *Paper V*.
The full version of the published scientific papers is available below.

Paper III: Giordan, D., Cignetti, M., Wrzesniak, A., Allasia, P. Bertolo, D. (2018) *Operative Monographies: Development of a new tool for the effective management of landslide risk*. Geosciences, **8(12)**, 485. DOI: 10.3390/geosciences8120485

Paper IV: Cignetti, M., Godone, D., Wrzesniak, A., Giordan, D. (2019) *Structure from motion multisource application for landslide characterization and monitoring: The Champlas du Col case study, Sestriere, north-western Italy*. Sensors, **19(10)**, 2364. DOI: 10.3390/s19102364

Paper V: Cignetti, M., Guenzi, D., Ardizzone, F., Allasia, P., Giordan, D. (2019) *An open-source web platform to share multisource, multisensor geospatial data and measurements of ground deformation in mountain areas*. ISPRS International Journal of Geo-Information, **9(1)**, 4. DOI: 10.3390/ijgi9010004

geosciences

Article

Operative Monographies: Development of a New Tool for the Effective Management of Landslide Risks

Daniele Giordan [1], Martina Cignetti [1,*], Aleksandra Wrzesniak [1], Paolo Allasia [1] and Davide Bertolo [2]

1 National Research Council of Italy, Research Institute for Geo-Hydrological Protection (CNR IRPI), Torino 10135, Italy; daniele.giordan@irpi.cnr.it (D.G.); aleksandra.wrzesniak@irpi.cnr.it (A.W.); paolo.allasia@irpi.cnr.it (P.A.)

2 Strutture Attività Geologiche, Regione Autonoma Valle d'Aosta 2, Quart 11020, Italy; davide.bertolo@regione.vda.it

* Correspondence: martina.cignetti@irpi.cnr.it; Tel.: +39-011-3977-831

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Abstract: Active landslide risk assessment and management are primarily based on the availability of dedicated studies and monitoring activities. The establishment of decision support for the efficient management of active landslides threatening urban areas is a worthwhile contribution. Nowadays, consistent information about major landslide hazards is obtained through an interdisciplinary approach, consisting of field survey data and long-time monitoring, with the creation of a high populated dataset. Nevertheless, the large number and variety of acquired data can generate some criticalities in their management. Data fragmentation and a missing standard format of the data should represent a serious hitch in landslide hazard management. A good organization in a standard format can be a good operative solution. Based on standardized approaches such as the ICAO (International Civil Aviation Organization), we developed a standard document called operative monography. This document summarizes all available information by organizing monitoring data and identifying possible lacks. We tested this approach in the Aosta Valley Region (NW Italy) on five different slow moving landslides monitored for twenty years. The critical analysis of the available dataset modifies a simple sequence of information in a more complex document, adoptable by local and national authorities for a more effective management of active landslides.

Keywords: landslide monitoring; dataset management; decision-maker support; Aosta Valley Region

1. Introduction

Landslides are one of the most common natural disaster throughout the world [1,2]. Different authors have studied their impact on population and infrastructure [3–5], which also pointed out the costs and effects on society.

The definition of the impact of landslides is usually performed through dedicated risk management procedures [6–9]. These operations are multi-component decision-making processes aimed at reducing the impact of landslides on territories and infrastructure, and creating mitigation strategies. This entails a compound framework of various actions such as (i) land use planning, (ii) engineering intervention, (iii) monitoring and warning system [10].

In Italy, landslides constitute a big issue, affecting about 6.9% of the regional territory [11], often causing causalities and economic losses [12]. Landslide risk management requires participation at various levels by national, regional, and municipal authorities, often with the support to decision makers of the scientific community. It is notable that, in the case of large active phenomena involving urban areas, infrastructure, and population, the National Civil Protection intervention is required.

A broad overview of those phenomena becomes an essential guidance for any decision and evaluation in landslide risk management [13], and land use planning establishment [14,15].

The underlying element in landslide risk management consists of landslide inventory and associated dataset. In Italy, the Italian Landslide Inventory, named IFFI [11], involves national, regional, and local institutions. This inventory has a homogeneous and integrated collection mode of landslide data over the entire national territory. Specifically, for each inventoried phenomenon, IFFI produced a "Landslide Data Sheet" [16], which collects the qualitative and quantitative parameters of the considered phenomenon. The structure of this project is a GIS group of layers and an associated database. From that project, regions and local authorities derived similar products like: (i) "Piedmont Landslides Information System" (SiFraP) [17], (ii) "Catasto Dissesti" a landslide registry of the Aosta Valley Region [18], (iii) "Carta Inventario delle Frane" a map inventory of the Emilia-Romagna Region [19], (iv) the Tuscany inventory [20], (v) the "AVI project" tested on the Umbria and Marche Regions [21].

Inventories and datasets are cornerstones in support investigations, by providing updated information on where and when landslides occurred. In recent years, innovative approaches have provided an important step forward by integrating the existing inventory with other resources derived from technical community [22], or benefit from application of semantic engine to scan news available on internet [23]. Alongside, the scientific community emphasized the importance of correct management of data, their clear representation and dissemination in the field of landslide monitoring [24–26].

Taking into account active landslides, consistent information about each single unstable area may occur. Indeed, the high vulnerability of those cases required an in-depth characterization of the hazardous landslides. For more complex and hazardous situations, simple identification and mapping of phenomena is not enough. In these cases, regional and local authorities commonly carry out or order landslide investigation studies, concerning the exploitation of the internal structure of the landslide, its type of movement, state of activity, history, triggers, etc. These studies aimed to evaluate the current hazard level can be supported also by monitoring systems that are fundamental for the definition of the evolution of the slope instability. Due to the kinematic evolution of active landslides, these analyses can go on for many years, also by repeating, in order to provide advancements in the interpretation of landslide behavior. It should be noted that the repetition and the progressive update of the studies from the past generates a flux of additional information that is hard to handle.

In fact, this sequence of information, based on a dataset that can evolve during the time, can produce differences in the geological model, in landslide geometry definition, or in the evaluation of the level of danger, and/or the identification of elements at risk according to landslide activity. The accumulation of new information and the possible definition of models that can differ from precedents should be carefully considered and managed in order to avoid the presence of documents or studies with conflicting conclusions.

As mentioned before, the study of active landslides frequently requires the use of several monitoring systems, able to support the development of the geological model, control landslide evolution, and if necessary, to be exploited as an early warning system in case of collapse of the landslide. Monitoring can be performed using traditional in situ system as: (i) Global Navigation Satellite System (GNSS) [27,28]; (ii) Robotized Total Station (RTS) [29]; (iii) inclinometer and piezometer boreholes [30]. In addition, can be used remote sensing techniques, like: (i) Ground Based SAR [31]; (ii) satellite SAR interferometry [32–34]; (iii) Light Detection and Ranging LiDAR [35,36].

By considering active landslides, on one hand, the scientific community proposed effective methodologies and integrated services for design, evaluate and manage landslide risk [20,24,26]. Moreover, many researches discussed landslide monitoring networks [36], landslide risk assessment [7], and early warning system application [37,38]. On the other hand, policy-makers entrusted private agency to investigate and collect information on landslide behavior and their evolution over time. If we consider the amount of data that could be generated on a single landslide by: (i) Data collected in landslide inventories; (ii) thematic studies (e.g., technical reports, maps and technical annexes) of the unstable area; and (iii) the associated monitoring activities, we can realize that one of the future critical issue will be the correct management of available information. A "Risk management guidelines" document has been proposed by AGS [9] in Australia, a "Code for practices for landslide hazard and land use planning" [6] is described by [8] in Switzerland, highlighting the need of the regional authorities for a standardized approach for the risk mitigation. However, a tool for handling those multi-source and varied data, specifically for active landslides involving urban and/or elements at risk, focused on the organization and standardization of consistent information derived from the assessment of an unstable area, is actually missing. After many years in which the scientific community has dedicated their efforts to the acquisition of information about landslides, nowadays one of the most important challenges is the correct use and management of available data and studies. Often, the exclusive use of web-GIS solutions is not enough, because several web-GIS are simple repositories where thematic studies and monitoring data are stored and available. The difference between the availability of information and their "usable" version has been called usable science and its importance has been pointed out in many fields like, for example, climate change [39–41]. The main aspect of this approach is that scientific information have to be useful and usable [41] and that decision makers must perceive information "not only credible, but also salient and legitimate" [42]. In landslide study, the correct organization of data requires a document where data are analyzed and commented, and the state of the art of what we know and what do not yet know of the studied phenomena is outlined.

This work presents a methodology developed to provide a guidance for an effective management of large and complex data regarding active landslide risk management. In particular, we considered landslides that have a long monitoring and studying history due to the possibility that a critical evolution could cause a partial or total collapse. To collect and organize all available information, we developed a document named Operative Monography (OM) that provides an overview of the available data about a certain unstable slope. OM have a standard organization of sections and contents that has been defined considering other similar documents developed for others purposes. In particular, we considered the organization model defined by the International Civil Aviation Organization's (ICAO) Operative Manual structure. In the civil aviation field, the ICAO sustained strong efforts to achieve a clear and detailed definition of how the manual of operation of a private company that manage aircraft should be organized and managed. Starting from this example, we tried to follow the same approach for the definition of a document model that can be adopted as a standard model in the field of landslide study and monitoring.

The OM could be a useful tool for public safety authorities, which supplies always updated brief overview of each hazardous phenomenon located in the areas of high vulnerability. The document has been designed to collect available data to support decision makers combining a rigorous scientific method with a usable science approach.

We developed and tested OMs in the Aosta Valley Region (NW Italy). This mountainous region is affected by more than 5218 slope instabilities, and six of them are highly hazardous. The Regional Geological Survey has studied these six large complex landslides since many years, collecting various thematic studies (e.g., geological, geomorphological, hydrological, risk scenario). Moreover, a regional near real time monitoring network has been implemented in order to control the evolution of the most critical landslides. The development of OMs starts with analysis of the large amount of data of the regional archive, in order to assess all the information acquired on the unstable area and outline eventual data fragmentation, missing data, or other relevant data that should represent a strong problem in effective landslide hazard management. In this paper, we discuss the organization of data archive, focusing on the five landslides of Bosmatto, Becca di Nona, Chervaz, Citrin, and Vollein, all located across the regional territory. All these landslides are characterized by a long and slow evolution, emphasized by a large amount of data and information, associated with long-time ground deformation time series derived from a near real-time monitoring network data acquisition, acquired in the last twenty years. We analyzed both the data of the existing monitoring systems, and all the data collected over time (e.g., technical reports, thematic maps, technical annexes).

In this work, we operated as follows: (i) We analyzed the private regional archive; (ii) we implemented the OM standard structure; and (iii) we redacted the OMs. An example of OM is presented and discussed. The OM structure is divided into four main sections relative to: (1) General information about the unstable phenomenon, (2) previous data analysis and organization, (3) ground deformation time series analysis, and (4) synthesis of the actual knowledge of the slope instability and eventual proposal of integration with new studies or monitoring activities.

Proposed OMs can be considered a possible standard in the management of studied landslides and they also represent a pilot test suitable for further investigations in other geographic and physiographic contexts and can be considered a useful instrument to support the reduction of effects of natural hazards on human activities.

2. Landslides of Aosta Valley Region

The Aosta Valley is a small region (3200 km^2), located in an alpine mountainous territory in northwestern Italy. The elevation ranges from 312 m (Pont Saint Martin) to 4810 m a.s.l. (Monte Bianco peak), and more than half of its territory has an elevation above 2000 m a.s.l.. This territory reveals a notable exposure to landslide hazards (Figure 1), in which geo-structural setting and geomorphological history strictly influence landslides occurrence.

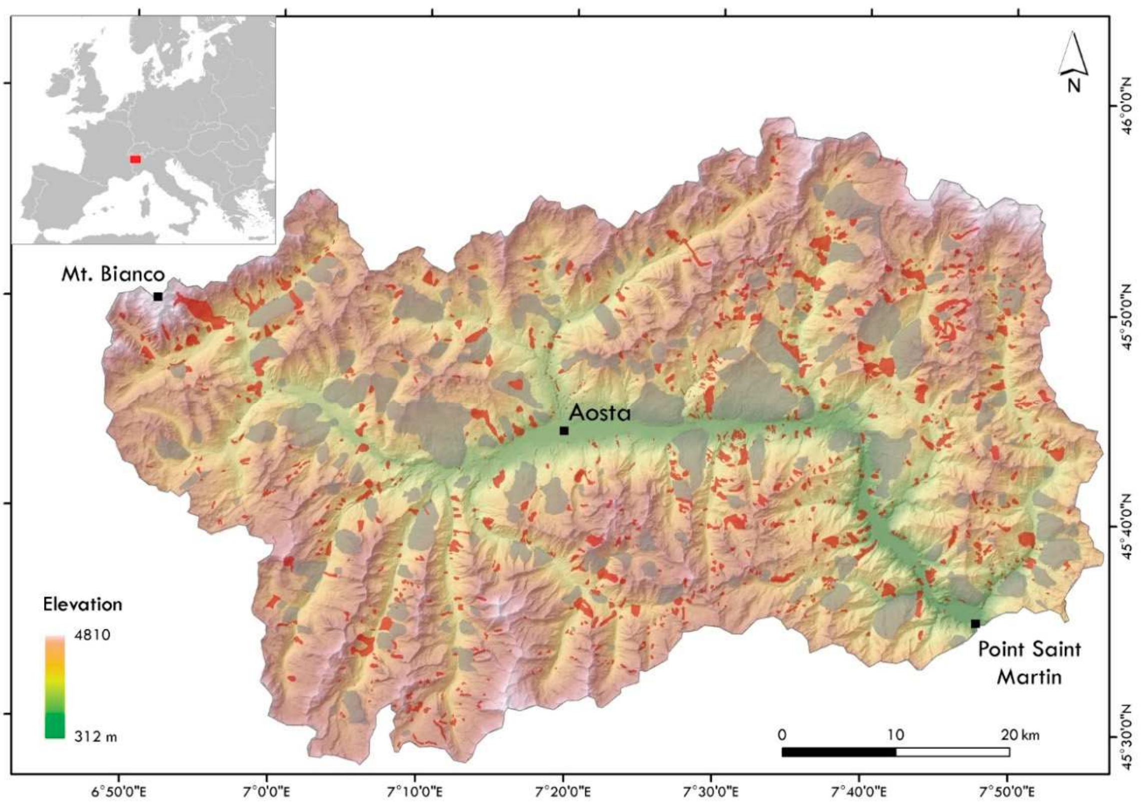

Figure 1. Landslides map distribution of the Aosta Valley Region (northwestern Italy): Grey polygons correspond to the Deep-seated Gravitational Slope Deformations, red ones to the landslides inventoried in the IFFI project (IFFI - Italian Landslide Inventory) Catalogue [11].

The geological setting of the Aosta Valley region is the outcome of the African and European plates collision. This region passes through the Europe-vergent Austroalpine-Penninic structural domains of the Western Alps [43,44]. A complete section of the orogenic prisms outcrops, crossing the complex pile of nappes constitute by the tectonic-metamorphic units represented by: (i) The Austroalpine domain, (ii) the ophiolitic Piedmont zone, and (iii) the Pennidic domain. The alpine relief in this section is characterized by a long-term tectonic activity and by a neo-tectonic dislocation system represented by the Aosta-Ranzola fault [45]. This structural-geological context deeply influenced the relief evolution and the slope dynamics [46].

Morphologically, glacial morphodynamic prevails and influences the ancient and the actual slope setting, principally due to the debuttressing caused by glacier retreat. Watercourses dynamic superimposes the glacial landforms, generating fluvial deposits and forming alluvial and detrital fans set by debris-flow phenomena [47].

Based on a regional landslide inventory, more than 17% of this region is affected by gravitational phenomena [48]. Regional landslide inventory includes large amount of phenomena of various types and sizes. It is periodically updated by regional authorities [18] and it currently comprises 12,589 phenomena. Such phenomena include shallow landslides (e.g., debris flow, planar and rotational slide), rock fall, and large slope instabilities. Complex landslides and Deep-seated Gravitational Slope Deformations (DsGSDs) are respectively the 9% and the 5.4% of the total amount of regional landslides [49].

Considering the large number of inventoried phenomena in Aosta Valley Region, only some of them are active and directly threaten urbanized areas and infrastructure. It is worth to note that the level of risk can increase according to the magnitude of the landslide and the vulnerability and exposition of elements at risk. Therefore, regional authorities operate by a discernment of active landslides based on their impact on infrastructure and population. They have managed the risk related to these phenomena by specific measures to define prevention strategies and useful land use planning. These measures include the acquisition of all the basic information and knowledge for each unstable phenomena, based on an interdisciplinary approach, concerning a multi-scale and temporal investigation.

In Aosta Valley, there are about thirty active landslides monitored in the past or currently measured by different monitoring networks that in some cases can also involve urbanized areas and/or infrastructure. Among those cases, in the paper we present the application of OM on five phenomena studied for many years and are currently monitored by near real time monitoring systems. They correspond to the landslides of: (1) Bosmatto, (2) Chervaz, (3) Vollein, (4) Becca di Nona, and (5) Citrin (Figure 2). This reduced group of phenomena consists of active large complex landslides that could seriously threaten urban areas. Therefore, they are studied and investigated by in-depth analysis (e.g., geological-geomorphological and structural surveys, hydrological and hydrogeological survey, risk scenario) Table 1 reports location, type of phenomenon, and volume for each considered landslides.

All considered landslides are monitored by remote near-real time systems (with continuous measurements) and by temporary systems (with periodical measurements) because of the possibility that the displacement rate can increase and a total or partial collapse can occur. Near real-time monitoring systems automatically measures the superficial displacement by means of Robotized Total Station - RTS (Vollein, Chervaz), Global Positioning System receivers - GPS (Bosmatto, Chervaz, Becca di Nona), and extensometers (Bosmatto, Becca di Nona, Citrin). Additionally, in the case of Chervaz, inclinometric columns [50] were installed to measure deep-seated displacement. For all these sites, the superficial displacement is also manually measured by means of GPS receivers, with periodical campaigns.

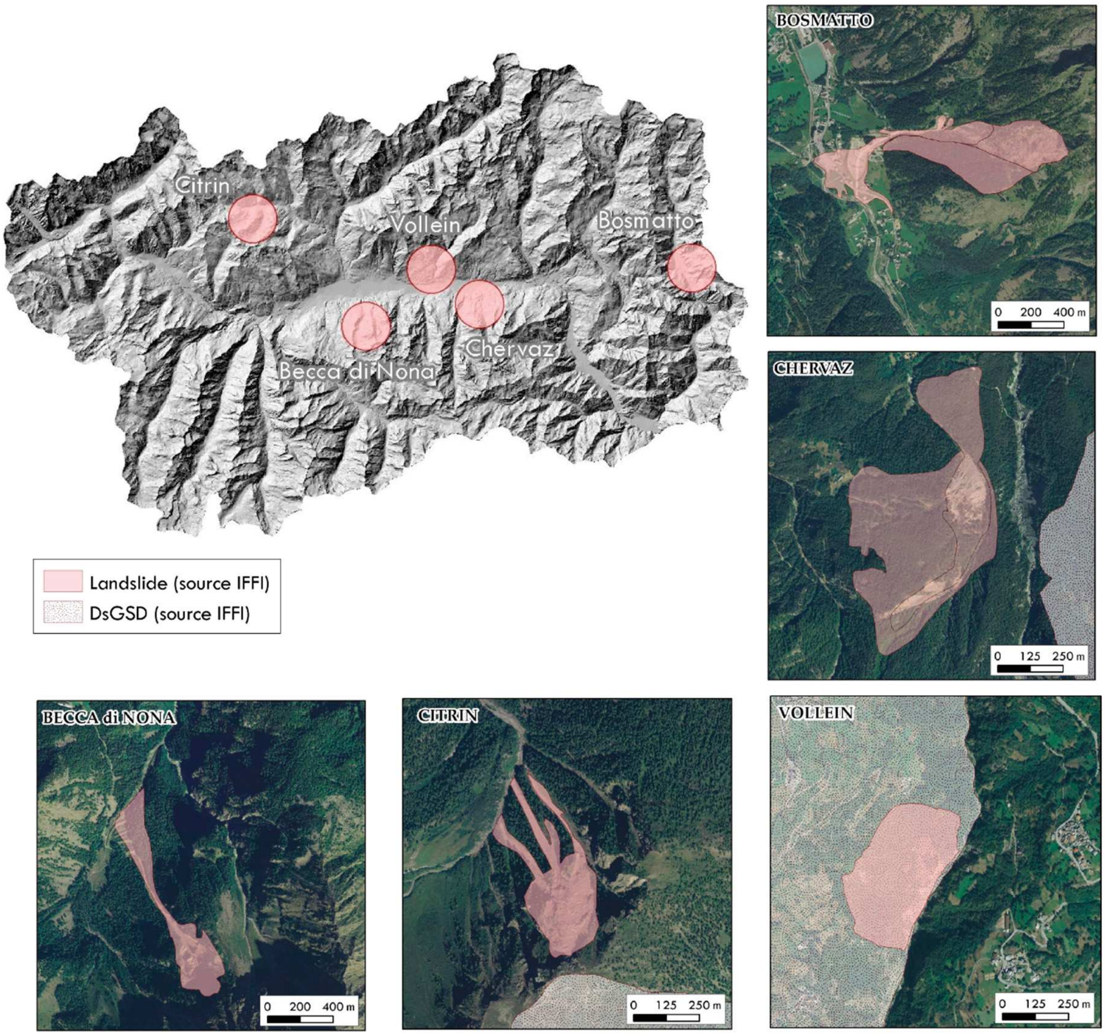

Figure 2. Location of the five complex active landslides of the Aosta Valley Region. Presented polygons came from IFFI Project [11]

Table 1. Summary of the landslide monitoring network system of the Aosta Valley Region.

Landslide	Location	Type	Volume (10^6 m^3)
Bosmatto	Gressoney Saint-Jean, Lys Valley	Complex landslide evolving in debris flow	2
Chervaz	Chambave-Fenis municipalities	Complex landslide	1.2
Vollein	Quart municipality	Complex landslide evolving in roto-translational slide	1.5
Becca di Nona	Chervansod-Pollein municipalities	Complex landslide prevalently slide	1.9
Citrin	Saint-Rhêmy-en-Bosses municipality	Complex landslide	1.5

3. Methods

The development of the OM, based on the Aosta Valley Region case study, is structured in two principal steps: (i) Previous data and available material acquisition, and (ii) OM structure description. The OM structure is divided in sections about: (i) General information about unstable area; (ii) previous data analysis and organization; (iii) ground deformation time series analysis; and (iv) synthesis and eventual improvement proposals.

3.1. Back Data and Available Material Acquisition

Geological Survey of the Aosta Valley Region collected a large amount of various kind of data in the last decades, for the six most critical gravitational phenomena of Bosmatto, Becca di Nona, Chervaz, Citrin, Vollein, and Mont de la Saxe. In the case of a partial or total collapse of the instable mass, the vulnerability of elements at risk can be very high because inhabited areas are involved. The first five phenomena have a long-time slow evolution often linked to activation (or reactivation) occurring during a rainfall event, described extensively by a large number of technical studies and especially by long-time ground deformation series acquired by a near real-time monitoring network. In some cases, the monitoring even acquired for twenty years. Instead, for the Mont the la Saxe case study, the near real-time monitoring network started from 2009 [24].

Focusing on these slow evolution landslides, we examined the regional archive that constitutes the main source of information necessary to create and compile the OM. This archive mainly consists of scientific and technical reports, thematic maps, technical annexes, and internal reports, acquired in the last twenty years. Based on the analysis of available data, we extracted eight common principal categories:

- Geological-Geomorphological survey (GeoGeomS);
- Geological map (GeoM);
- Geomorphological map (GeomM);
- Structural Survey (StrM);
- Geological Profile (GeoP);
- Hydrological/Hydrogeological (Hyd/Hydg);
- Risk scenarios and Spatial prediction model (Rsk/Sc);
- Monitoring Network report (MonNet).

Those categories correspond to the main topics widely investigated in the field of landslide risk assessment and management. In some cases, ancillary data are reported, including e.g., geophysical surveys, electric tomography surveys, technical reports for monitoring network installation, and engineering interventions.

The Geological Survey of Aosta Valley often entrusted landslide analysis and data elaboration to private and public agencies, which use different ways to represent the same typology of data or that could reach different conclusions according to the dataset available at the moment of the study. Those activities generated a multiplicity of technical reports prepared in different ways about the same topic (e.g., structural-geology, profiles and maps, risk scenarios). During the analysis of the available data, we found a great amount of available information that have been collected by the regional authority. In some cases, the usual approach, which is the redaction of thematic studies or annual reports, can produce a stratification of information. Considering long time series, it is possible to find some changes in the structure of reports that describe the same dataset. These changes could have limited the possible reconstruction of the whole time series. Thanks to the great effort of the region authority in the study of these phenomena, we had the opportunity to perform an in-depth analysis of the main critical points related to the availability of long monitoring time series and many detailed studies. These time series, acquired in a period characterized by fast technological improvements, suffered the fallout of these technological changes and the lack of a standardized modality of acquisition and description of the datasets.

3.2. Operative Monography Structure

To homogenize and integrate the available landslide data, we implemented a methodology for the redaction of OMs. OM is a document in which all the information and data acquired over time are organized and summarized in a standardized format.

As mentioned before, we considered the guidelines of Operation Manual proposed by Civil Aviation Organization (ICAO—document 9376) to define the structure of OM. This Operation Manual describes how an aviation company should organize internal procedures in order to manage all the activities related to the safe use of civil aircrafts. ICAO document defines explicitly the necessary chapters and their contents. In the case when information for a particular chapter are not available, the chapter should be left empty to satisfy required structure. Following the described approach, we divided the structure of landslide OM into four sections: (i) General information about unstable area; (ii) previous data analysis and organization; (iii) ground deformation time series analysis; and (iv) synthesis and eventual proposal.

As described in the ICAO, the sequence of the sections is a fundamental characteristic of operational documents. This guideline should be respected for each case study. Thanks to this, the identification of missing elements or the consultation of existing ones is facilitated. In fact, in OMs, some sections may remain empty when the specific data is missing. Such an approach emphasizes the possible lack of information. In the following sections, the OM subdivisions are presented and described.

3.2.1. OM—General Information

The first section of the OM refers to basic information of the considered landslide. In detail, this section briefly reports landslide geographical location, type, and state of activity. Additionally, this section provides short description of morphometric parameters, geo-lithological, geomorphological and structural settings, and land use setting.

When landslide interferes with elements at risk (e.g., linear infrastructure, road, path) a separate item is planned. This possible interference with human activities or infrastructure is, of course, a fundamental issue that should be carefully described. In this section, the results of hazard assessment and\or landslide collapse simulations are also presented.

3.2.2. OM—Previous Data Analysis

In this section, an in-depth analyses of the existing datasets are performed. These sets of historical information about unstable areas originates from diverse sources: Data stored in national and regional inventories, technical reports and studies associated with monitoring networks data (usually performed by private agencies), and Geological Survey's internal reports.

We developed a reiterative pattern, reporting only fundamental information of defined categories. We listed basic information like private agency name, month/year of delivery, topics covered, etc. to classify the numerous technical reports, field surveys and associated thematic maps, and technical annexes. All information are reported in tabular format. Due to this operation, the presence or absence of technical documents and information relative to specific topic can be quickly verified. The important difference between an ordinary copy of available material and OM is that, in the second case, only fundamental information are described. The objective of OM is not the simple copy of available material, but their brief summary and their source determination. In this way, readers who have to consult the OM can also recover the original position of reported information if detailed analyses of the original documents are necessary. We summarized the collected information in three main topics: (i) Geological-geomorphological setting, structural analysis, and hydrological-hydrogeological aspects, (ii) risk scenarios and landslide spatial prediction models, and (iii) monitoring network system. Representative images, photos, maps, and tables can accompany the brief description.

3.2.3. OM—Ground Deformation Time Series Analysis

As mentioned before, the study of active landslides, which may require the use of OMs is usually supported by monitoring systems. The acquisition and processing of monitoring data can be done by national and regional authorities or entrusted to private agencies. If we consider long time series, the lack of a specific guideline for the acquisition and elaboration of acquired data can hamper the data representation continuity. If several companies performed the acquisition of the same data in different moments, the risk that the same data were presented in different ways is very high. For long-term landslide evolution, the presence of discontinuities in the organization and elaboration of the same monitoring sequence can reduce the benefits coming from a detailed analysis and comparison of data, in particular if raw data were not included in the report. Therefore, the standardization of acquisition and presentation of information, and the availability of raw data is fundamental.

In this OM section, the collected monitoring datasets from monitoring network and /or near-real time system of an unstable area are re-organized and pre-analyzed. We used MATLAB® [51] environment to manage monitoring data. First, raw data were filtered and validated by removing inconsistent data, noisy measurements, and spikes. Then, eventual gaps are closed using the best approach that depends on the characteristics of the dataset. Later, specific mathematical functions were applied to these pre-elaborated data sets (e.g., moving average, local regression using weighted linear least squares and a 1st degree polynomial model or its robust version that assigns lower weight to outliers in the regression), in order to obtain an overall representation of landslide behavior.

The measured physical quantity depends on the technical specification of the instrumentation used. For example, RTS, GPS receivers, or extensometers can provide the same physical parameter but the dataset of each instrument has a different organization and different data. For example, in the case of GPS receivers, the measured quantity is a displacement in three-dimensional space (x, y, and z); for RTS it is vertical and horizontal angles and line-of-sight distance. However, we generated, for both cases, the time-series plot of the same variable, i.e. planimetric and altimetric displacement, which is the most convenient and representative way to describe landslide behavior. Moreover, the smoothing techniques were tested in order to adapt the suitable type to each dataset. In this way, especially for long-time plots, the evidences of seasonal accelerations or other patterns were not omitted. Such complete time series are used to synthesize the overall landslide behavior over time.

As described in the ICAO operational manual and in OM, the document should be updated every time when there is an important event and/or information. This means that continuous update of information according to the availability of new monitoring data is fundamental. According to the landslide risk level, the time series should be updated with a certain frequency that can be, for example, every 6 months or every year.

3.2.4. OM—Synthesis and Final Proposals

The final part of the OM corresponds to a brief synthesis of the general framework of the analyzed phenomenon. Here, the eventual strengths and the observed lacks and/or inconsistencies were highlighted.

The goals of this section are: (i) To provide a short summary as comprehensive as possible of the available data, (ii) highlight possible missing data or information, and (iii) provide several suggestion for definition of the new activities aimed to improve the comprehension of the studied landslides. Here a concise comment of the OM contents points out also possible weaknesses, on which should be oriented future interventions and actions. In the proposed structure of OM, this final section is important because it makes the difference between a simple resume of available information and an operative document that is also aimed to provide indications for future analysis and actions.

4. Operative Monographies Application in Aosta Valley Case Studies—Results

We applied our methodology to the data of some slow moving complex landslides of Aosta Valley region, providing OMs to the Regional Geological Survey. For example, in Annex 1 (Supplementary material), we report a simplified version of one of the case studies, the Bosmatto landslide, in order to show the general OM structure.

The Bosmatto case study is located in Gressoney-Saint-Jean municipality, Lys Valley, within the Letzè catchment. Based upon the geological and geomorphological studies, two old landslides have been recognized on the left side of the basin. In connection with the old landslide named "paleofrana 1" (vd. Annex 1), a complex landslide, evolving in an impressive debris flow, affected the Letzè basin during October 2000, involving the alluvial fan [52]. For the Bosmatto landslide, a thickness of about

25 m was estimated, with a computed volume of 2,000,000 m^3. The landslide is monitored by a manual GPS network since 1997, and by automated GPS since 2002, and by extensometers for a limited period from summer 2006 to autumn 2010. Moreover, a GBInSAR monitoring has been performed from October 2016 to November 2017. The long-time series allow synthesizing the overall landslide behavior over time, displaying an independence from the rain and snow regime.

On the right side of the Letzè basin, another phenomenon occurred during the summer 2002. Field survey, also associated with seismic analysis, reveals that this phenomenon, the Stadelte landslide, has variable thickness from 5 m to 20 m. From the GSP measurements analysis, a cross-correlation from snowmelt and seasonal reactivation has been assumed. In the Bosmatto OM first section, the general information of this landslide are reported, with a one-page summary with a brief description of the type of landslide, state of activity, geological and geomorphological setting of the unstable area (Annex 1, Section 1). This provides sort of "register tab" of the considered phenomenon.

In the following section "Previous works analysis", the examination of the available data reveals 22 documents, which include technical reports, maps and technical annexes, drafted by four private agencies. A summary of the topic of the document and the agencies that drafted it has been reported in tabular format (Annex 1, Section 2, Table 1), following the main categories occurred.

Of all this large amount of data, the key information have been reported in the OM in a synthetic format, associated with the meaningful maps and/or profile of the analyzed landslide (Annex 1, Section 2). By this way, we collect all the geological, geomorphological and structural information, the monitoring network status, and the eventual risk scenarios, describing the state of knowledge, in order to define a reference model for landslide behavior assessment.

The high number of studies and technical reports, associated with maps and geological profile, recurs also in the other case studies (Figure 3).

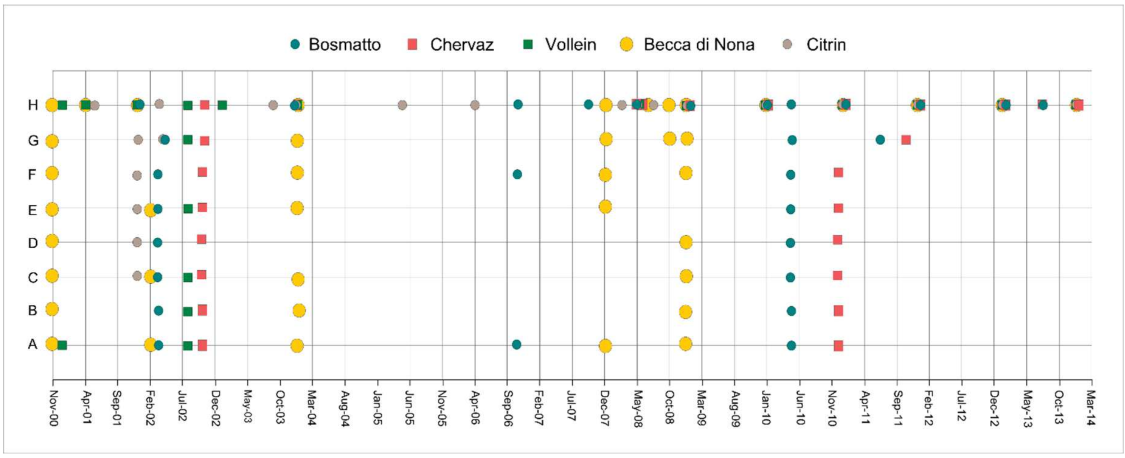

Figure 3. Time distribution of the data available for each considered landslide, divided in the eight recognized topics: (A) GeoGeomS; (B) GeoM; (C) GeomM; (D) SrtM; (E) GeoP; (F) Hyd/Hydg; (G) Rsk/Sc; and (H) MonNet.

Figure 4 reports the total number of available information, split into the eight principal categories and divided for each case study. The graph highlights the constant presence on the "MonNet" category for all the five landslides. Whereas, some variable are missing, as "StrM" and "Hyd/Hydg" for the Vollein case. Moreover, we can observe that, in the Chervaz, Becca di Nona and Bosmatto case studies, there are more than two geological-geomorphological survey reports, as well as for the risk scenarios and landslide spatial prediction models. Instead, in other cases like Vollein and Citrin, there is a shortage of products, with a brief internal technical report produced by the Aosta Valley regional authorities. In these cases, the total amount of information is limited with respect to the other case studies. In the Chervaz, Becca di Nona, and Bosmatto cases, the presence of different versions of the proposed geological model (Figure 3), which correspond to the evolution of the state of the art updated using new field data or geological/geophysical surveys results, is an important issue. These different interpretations (obtained in different times by different companies) could create a misunderstanding about the best model for the definition of scenarios and during emergencies. Instead, in the Vollein and Citrin cases, the mere presence of synthetic internal reports may limit a correct representation and characterization of the structure of the unstable area and their dynamic of deformations.

In all considered cases, the great work done by the regional authority is witnessed by the large amount of documents and reports draft during the years.

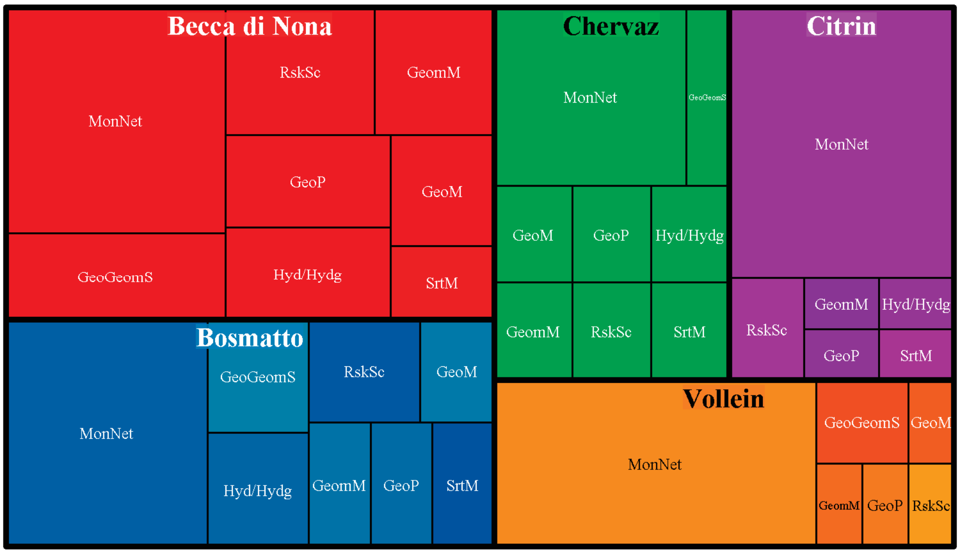

Figure 4. Three map chart shows the proportion of the eight original thematic variables recognized for each monitored landslide, highlighting which are the more frequent and which are eventually missing (Graph elaborated in R program).

The third section "Ground deformation time series", provides time series of collected monitoring measurements (Annex 1, Section 3). To produce such time series, we firstly pre-analyzed the raw data, handling missing values, noisy acquisitions, and by removing the outliers. Finally, specific smoothing functions were applied to the pre-elaborated datasets in order to obtain the adequate representation of landslide behavior. Figure 5 shows an example of elaborated data in the form of complete time series plots of Bosmatto landslide. The evolution of planimetric and altimetric displacement is presented. Additionally, an example of corresponding altimetric raw data is shown.

The choice of smoothing technique depends on features of raw data. For example, in the case of Bosmatto landslide, in order to preserve seasonal fluctuations, the moving average technique was applied to the raw datasets [51].

The generation of time series as a complete set provides a fast evaluation of landslide behavior over time. For example, eventual anomalies, seasonal patterns, reactivations and their magnitude can be easily localized with a long and complete time series. The organization of data provided in annual reports often limited the possibility to recognize seasonal or long-period trends. Another important point is that complete time series are fundamental instruments during the emergency conditions because can support the recognition of an anomalous evolution that can be a precursor of a collapse.

The last section "Synthesis and final proposal" of Bosmatto OM (Annex 1, Section 4) highlights the strengths and weaknesses of the actual state of knowledge. For the chosen case study, the main problem lies in the unclear definition of the landslide body. In fact, in the various technical reports more than one phenomenon is described, variably distinguishing the Bosmatto landslide s.s., located on the left side of the Letzebach river, and the Stadelte landslide, on the right side, in their turn divided into two portions, vegetated and non-vegetated. Those subdivisions became very clear only after eight years of technical studies and insights by more than one private agencies studies, passing through the identification of two old landslides to the designation of the Bosmatto and Stadelte landslides. This subdivision generates some difficulty also in the ground surface measurements presentation that sometimes are not clearly separated in the two landslide bodies. Therefore, among other suggestion, the Bosmatto OM recommended a noticeable separation of the Bosmatto and Stadelte cases, in order to provide a comprehensive overview of each one to be updated over time, also for the ground deformation time series elaboration. The reorganization of monitoring time series was important also to organize old records with the new subdivision of the monitored area in two landslides.

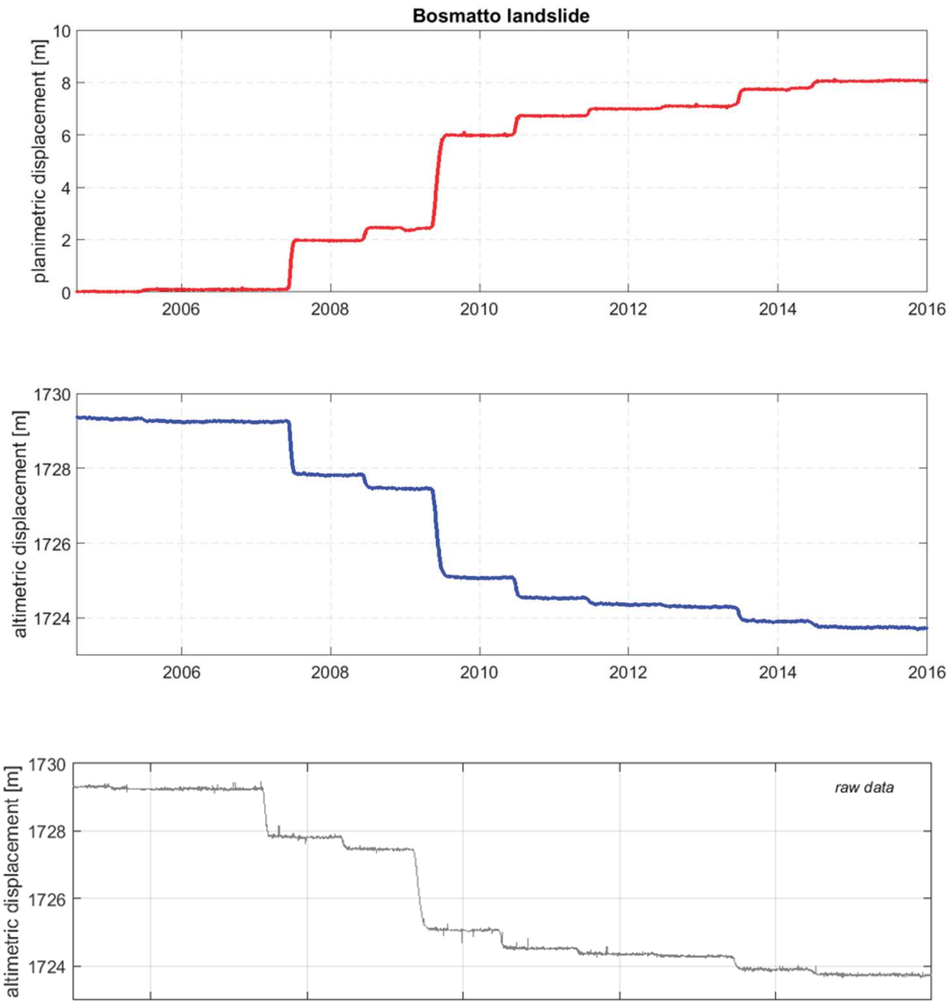

Figure 5. Bosmatto landslide elaborated time series of planimetric and altimetric displacement measured by global positioning system (GPS) for the entire monitored period. In the bottom, the raw dataset of altimetric displacement.

5. Discussion

In this paper, we want to analyze two underestimated topics in landslides studies: (i) The application of a usable science approach and (ii) the identification of a standard approach in data organization and management.

The concept of usable science, for the correct dissemination of scientific results, are sometimes considered a minor issue in landslide study and investigations. In particular during emergency, a proper dissemination of the available data about the observed landslide evolution can represent a key point for a good involvement of population, and an effective support to decision makers [24,26].

The scientific community usually focused on the improvement of methods and approaches for a more effective comprehension of landslide mechanism and for the identification, for example, of failure precursors [53]. However, it should be noted that, frequently, the main effort has been dedicated to the acquisition of valuable dataset of studied landslides. On the contrary, little importance are attributed to the way of mange available data, with the risk of using approaches not able to express the real capability of the available dataset. Commonly, scientific literature concerns on the application and implementation of WEB-GIS solutions for information and data management [22,25]. WEB-GIS are powerful solutions for the organization of information, but it is important to divide technical solutions aimed to display available data from more complex approach that are aimed to analyze and make a critical synthesis of these data.

Another important issue is the lack of a standard approach for landslide data collection. We analyzed the ICAO approach that can be considered one of the most standardized industrial sector. The safety of flights has been always considered one of the most important element for aviation, and the use of detailed standard approach represents one of the key element for the maintenance of high- safety levels. Starting from this example, we tried to transfer this approach in the organization of a pre-defined document that can be applied for the study of complex landslides. The high variability of landslides makes the possibility of the definition of a standard approach a critical challenge. According with our experience, we identified several macro-categories typically adopted for complex landslides analysis and description, representative for the structure of our standard document.

The OM is a site-specific document that collects all the available information of a studied landslide. It should be noted that, frequently, the monitoring data are performed and organized per year (e.g., a single report with monitoring results of many landslides in the same year). In addition, thematic studies often focus a single theme (e.g., geomorphological map or geotechnical characterization of a landslide). Instead, in our approach, all available information are re-organized in a single document referred to a single phenomenon.

The presented study attempted to provide the developed approach to five complex landslides studied and monitored for many years by the Aosta Valley Geological Survey. The considered case studies comprising active landslides that threaten urban areas, measured with near real time monitoring network.

The regional archive represents a case in point in the topic of large amount of data management. The archive is composed of numerous scientific and technical studies multi-sources, concerning diverse topics, repeated several time over a twenty year period, for each monitored landslide.

By the analysis of the results of the Aosta Valley monitoring network, we observed that there are some redundancies and contradictions in the considered case studies, mainly caused by the progressive availability of new investigation techniques during the years. In some cases, the acquisition of new data caused the elaboration of new geological models that could be in contradiction with the previous ones. It is worth noting that in many cases the development of contradictory models has been made possible by the lack, in the past, of direct investigations (e.g., core sampling boreholes) that could validate the geological interpretations.

The implementation of the OM allowed to an immediate access to the data and information relative to a specific phenomenon. The implemented method required the redaction of a standardized and iterative document, readily legible. The repeated structure, organized in specific sections, drops the reader to query the available data collected over the year about a single landslide or other phenomena. The OM do not want to be a mere catalogue, in which data are supplied in the extended version. Instead, the OM want to provide a reading guide of the available information, by providing a reasoned overview that highlights only the key elements relative to the analyzed phenomenon.

Jointly, the OM aimed to identify potential critical elements that are emerged from the analysis of all available material. It is important to point out that the OM has not a simply description of what are known about a landslide, but also a critical analysis of what we have to know. Thanks to this critical revision, it is possible to identify important missing information or weak points in the available dataset.

The presented standardized approach could also assure that future data will be organized with a compliant approach, limiting eventual mismatch or incorrect interpretation of previous studies. According to this purpose, the OM may represent a useful tool not only for policy-makers, but also for the scientific community, by providing reliable data, diverse technical and field information, and deformation measurements, able to describe a specific phenomenon and to define its behavior and evolution over time.

The activity undertaken with the implementation of the OMs give to the Geological Survey of the Aosta Valley Region a new and innovative method for a more standardized approach in landslide investigation and management of available data. The new document is scientifically validated by National Research Council that also made a periodical review of landslide monitoring data.

According to the results of this revision, the Geological Survey of the Aosta Valley Region plan the priority of maintenance activities of the monitoring network, and identify, for example, the need for a new geological model of some studied landslides. In the Bosmatto case, for instance, a core drilling campaign, allowing calibrating the previous geological hypotheses has been planned considering OM conclusions. Regional authorities plan also new boreholes with multi-parametric ground probes, in order to acquire in-depth data to re-evaluate the volume of monitored landslide.

This example shows how the definition of a review procedure and a correct management of available information can be used for the development of a "usable" document that can support decision makers for a better landslide hazard management. In addition, the codified procedure can also be considered a sort of audit process aimed to analyze the obtained results by the Geological Survey and suggest following inspections and analysis.

6. Conclusions

In this work, we considered the problem of the collection and organization of a large amount of information and data, relative to active complex and hazardous landslides. Usually, this is performed by the regional or national authorities, with the goal of ensuring safety of the managed territory and reducing landslide risk. Our purpose was to raise awareness of the potential hurdles that, often, these authorities have to deal with to build-up numerous technical and scientific reports and studies over time. In fact, this often leads to the creation of an extremely stratified and sometimes incoherent structure of available information. The availability of a large number of monitoring data and studies not quickly ready for use can reduce their effectiveness for the comprehension of landslide evolution and exacerbate the responsibilities of the technical staff and institutions, whose task is to administer a specific territory. This is therefore a serious issue, particularly during the emergency context. In this regard, the availability of not organized and not promptly accessible information can actually be a disadvantage element and not a benefit as it should be.

We proposed a solution based on the data analysis of the Aosta Valley region. We considered five large mass movements, which are monitored over many years. We had access to a large archive of different types of data, which were collected from one to two decades ago. In such conditions, a structured collection and a standardized organization of data appeared necessary. We generated an OM able to establish a synthesis of the landslide data in a standard format. An OM is a synthetic document that summarizes available information on a specific phenomenon. It also allows to identify missing elements and to verify existing ones. The OM facilitates the assessment of the state of knowledge, which is necessary step for a complete comprehension of each phenomenon. We recommended a periodical update of OM, in order to obtain the maximum efficiency of this document.

The OM can also represent a fundamental tool during the emergency, where effective access to the available knowledge is fundamental for the identification of anomalous behavior that can be precursors of the collapse.

By providing appropriate amendments, for example adding specific sections but also maintaining a standard structure, the OM could be easily applied in other contexts. For instance, in the case of a strategic infrastructure (e.g., pipeline), or a busy tourist path, the OM application could be a useful tool. By recognizing the potential critical sectors along the linear element, a single OM for each sector can be redacted, outlining the definition of the state of knowledge of each specific area, and defining with a specific focus the exposure and vulnerability of the element at risk, and delineating eventual mitigation strategies.

Supplementary Materials: The following are available online at http://www.mdpi.com/2076-3263/8/12/485/s1, PDF S1: Bosmatto Operative Monography.

Author Contributions: M.C. and A.W. collected the data available on the five considered case studies; M.C. organized data and information and drafted the fine OMs; A.W. elaborated and analyzed the data of monitoring networks of the five case studies; D.G. supervised the project and implemented the OM structure; D.G. and D.B. revised the paper. All the authors contributed to paper writing and revision.

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Article

Structure from Motion Multisource Application for Landslide Characterization and Monitoring: The Champlas du Col Case Study, Sestriere, North-Western Italy

Martina Cignetti [1,2], Danilo Godone [1,*], Aleksandra Wrzesniak [1] and Daniele Giordan [1]

1 National Research Council, Research Institute for Geo-Hydrological Protection, 10135 Turin, Italy; martina.cignetti@irpi.cnr.it (M.C.); aleksandra.wrzesniak@irpi.cnr.it (A.W.); daniele.giordan@irpi.cnr.it (D.G.)
2 Department of Earth Sciences, University of Pavia, 27100 Pavia, Italy
* Correspondence: danilo.godone@irpi.cnr.it

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Abstract: Structure from Motion (SfM) is a powerful tool to provide 3D point clouds from a sequence of images taken from different remote sensing technologies. The use of this approach for processing images captured from both Remotely Piloted Aerial Vehicles (RPAS), historical aerial photograms, and smartphones, constitutes a valuable solution for the identification and characterization of active landslides. We applied SfM to process all the acquired and available images for the study of the Champlas du Col landslide, a complex slope instability reactivated in spring 2018 in the Piemonte Region (north-western Italy). This last reactivation of the slide, principally due to snow melting at the end of the winter season, interrupted the main road used to reach Sestriere, one of the most famous ski resorts in north-western Italy. We tested how SfM can be applied to process high-resolution multisource datasets by processing: (i) historical aerial photograms collected from five diverse regional flights, (ii) RGB and multi-spectral images acquired by two RPAS, taken in different moments, and (iii) terrestrial sequences of the most representative kinematic elements due to the evolution of the landslide. In addition, we obtained an overall framework of the historical development of the area of interest, and distinguished several generations of landslides. Moreover, an in-depth geomorphological characterization of the Champlas du Col landslide reactivation was done, by testing a cost-effective and rapid methodology based on SfM principles, which is easily repeatable to characterize and investigate active landslides.

Keywords: unmanned aerial vehicle (UAV); structure from motion; landslide-infrastructure interaction; photogrammetry; deep-seated gravitational slope deformation

1. Introduction

Mountain regions have a remarkable exposure to landslide hazards, which are considered one of the most widespread natural disaster throughout the world [1,2]. In particular, in alpine regions, landslide types range from localized and sudden rock falls, to widespread and progressive rotational or planar slides, as well as large complex and in-deep landslides [3–5]. The occurrence of landslides of diverse types and size, and their local activation or reactivations play an important role in mountainous landscape evolution, often causing significant damage and casualties [6,7].

Active landslide inspection and monitoring are key elements in the assessment of landslide behaviour, specifically to support landslide emergency management and to identify areas with the highest damage. Usually, accurate landslide hazard evaluation needs consistent data concerning the extent of the unstable slope, detection of morphological features, deformation dynamics, triggers and historical records. This information is also useful to define landslide hazards and vulnerable areas [8–10]. Accurate landslide damage assessment and mapping requires time-consuming and costly methodologies by expert professionals (e.g., geologist, engineers) and field campaigns.

Remote sensing technologies, e.g., photogrammetry, terrestrial and airborne Light Detection and Ranging (LiDAR) are renowned techniques for landslide analysis [11,12]. The obtained orthoimages and Digital Terrain Models (DTMs) supply detailed representations of the topographic surface, which provide tools for recognizing landslide types and identifying related surface morphology signatures [12–15]. Aerial photogrammetry constitutes a suitable approach to obtain medium to high resolution datasets, enabling the definition of the geometric characteristics of the observed phenomenon [16] and multi-temporal analysis of the slope evolution [17–19]. Also, the LiDAR survey provides a useful instrument to study natural hazards through its high-resolution DTMs analysis [20–22]. However, these lengthy, in terms of data acquisition and processing, and costly procedures might not be suitable during an emergency when a more rapid overview of the current state is necessary. Therefore, straightforward and repeatable procedures that are able to provide reliable datasets in a very short time and in a safe manner are necessary.

Nowadays, the spread of unmanned aerial vehicles (UAVs) in natural hazards assessment and characterization has significantly increased [23–27], especially when there is a need to rapidly obtain very high-resolution airborne imagery of the area of interest. Recently, the use of UAV or Remotely Piloted Aircraft System (RPAS) has become more commonplace thanks to the improvement of autopilot or semi-autopilot systems, high-resolution digital cameras, and GNSS and inertial systems.

Captured images are geocoded by various approaches requiring on board and/or ground based approaches. In fact, UAVs are usually equipped with positioning apparatuses. In order to improve positioning accuracy, ground control points (GCPs) are positioned, surveyed and used in image processing. Additionally, on board GNSS can be coupled with ground receivers to measure the UAV position with an RTK approach [28,29]. Geocoded images are then used to generate a 3D point cloud, and consequently, a Digital Elevation Model (DEM) and orthoimage. These map layers are suitable for different mapping and analysis purposes by manual or automatic procedures that exploit image features (e.g., colours, texture) or DEM's geometrical characteristics (e.g., slope, height differences) by applying, respectively, image segmentation, classification or morphometry [30,31]. Obtained products are usually validated by comparison with previous datasets as LiDAR data or GNSS surveys in order to quantify the reliability of the procedure [32]. It is important to note that the employment of UAV must, in addition to technical requirements, meet local regulations in order to assure the security of the operation [33].

A well-established practice is observed in engineering geology, especially in landslide mapping [34–36], in slope stability analysis [23,37], as well as in a wide variety of natural hazards investigation, such as fluvial [38], volcanic [39] and glacial [40]. Moreover, UAVs are frequently employed during an emergency in order to provide information on structural damage and to define a preliminary impact assessment [41,42].

Focusing on the study of landslide hazards, the employment of UAVs is a useful solution for acquiring images at sub-decimetric resolution, especially for small active phenomena. They can be employed for a 3D model reconstruction by applying the Structure from Motion technique, and Multi-View Stereo (MVS) algorithms [43], a relatively new image processing technique based on computer vision algorithms, which obtain very high-resolution Digital Elevation Models and orthoimages.

The UAV survey, an accurate and cost-effective technique with a more streamlined process compared to the classic approaches such as aerial photogrammetry and field survey, provides high spatial and temporal resolution photographs of the area of interest [24]. The visual interpretation of orthoimages allows the implementation of landslide inventory and geomorphological characterization of the investigated sites [44]. With a multi-temporal analysis, the orthoimages time series provide the surficial of the unstable area, which is computed by the comparison of well recognizable features [45–47]. Instead, the DEMs time series provides detailed multi-temporal sets of 3D surfaces that are useful for vertical displacements investigation [48,49]. Moreover, the very high-resolution of these models allows the detection and mapping of all the geomorphological features due to landslide evolution [44,47].

Recent technological improvements allow the customization of UAV by equipping them with different cameras in order to acquire both RGB images and also different bands to be used in indices computation for the identification of anomalies in water content [50], and vegetation health anomalies [51].

In this paper, an image-processing workflow based on the use of Structure from Motion algorithm applied to UAVs datasets, old aerial images, and terrestrial photos have been implemented for a detailed characterization and monitoring of active landslides. The presented methodology has been developed and applied to the Champlas du Col landslide, Sestriere municipality, Piemonte Region, north-western Italy. Thanks to the availability of different datasets, we tried to achieve the following goals: (i) generation of a landslide inventory of the area of interest through aerial photogram interpretation and historical mapping of landslide activities; (ii) definition of the landslide boundary, (iii) geomorphological characterization of the investigated phenomenon, principally by exploiting RPAS products, and (iv) semi-quantitative analysis of the displacement that occurred between the two RGB acquisitions and by terrestrial photos processing.

The purpose of the proposed approach is to provide a rapid and low-cost solution for a multi-temporal and multi-scale analysis by exploiting multi-source datasets. It should provide a detailed geomorphological map of an active landslide and a temporal and spatial investigation of its behaviour, aimed to provide situational awareness immediately after the emergency phase and supply information for crisis management.

2. Study Area

The area of interest is located at the confluence of the Upper Susa Valley and the Chisone Valley (northern Cottian Alps), between the localities of Sauze di Cesana and Rollières, Sestriere municipality (Piemonte Region, north-western Italy). The study was carried out on the Champlas du Col landslide, located on the south-facing slope of Mt. Fraiteve (2700 m a.s.l.), close to the namesake hamlet (Figure 1).

The Champlas du Col landslide is a complex movement with a source area affected by a rotational component in the upper sector, which downhill, turns into an earth flow. The landslide extends between elevations of 1810 m at the crown, which involves the S.P. 23 national road, the principal way to reach the town of Sestriere, one of the most famous ski resorts in the north-western Italian Alps, and 1680 m, with an average slope of about 23°.

At the slope scale, the Champlas du Col landslide is embedded in an extensive instability phenomenon that corresponds to a Deep-seated Gravitational Slope Deformation (DsGSD) [5]. This DsGSD involves the majority of the valley south-facing flank of Mt. Fraiteve (515.15 ha), ranging from 2488 m, between the two peaks of Roccia Fleuta (2456 m) and Roccia Rotonda (2402 m), and down toto the bottom of the main valley. This huge phenomenon involves the metasedimentary successions of the Cerogne-Centiplagna unit, mainly constituted by heterogeneous calcschists. According to [52], the DsGSD movement corresponds to creep processes along discrete sliding surfaces, and along multiple listric surfaces. The movement rate, derived from high-resolution SAR images processing (i.e., COSMO-SkyMed (CSK) dataset from the WMS service of the *GeoPortale Piemonte* [53]) from 2011 to 2014, ranges from 20 to 35 mm/year along the LOS direction, for the area along the S.P. 23 way right above the Champlas du Col landslide. It decreases in the sector between the hamlets of Champlas du Col and Champlas Janvier, ranging from 5 to 10 mm/year. Generally, the SAR data coverage is poor with Permanent Scatterers (PS_s) distribution mainly located in urbanized areas and along the road network (Figure 2). No SAR data are available for the Champlas du Col landslide due to the phase decorrelation effect [54,55] caused by the large displacement of the slide. In addition, between Champlas Janvier and Champlas du Col hamlets, several geognostic surveys with in situ instruments (i.e., inclinometers, piezometers) were carried out and some GPS benchmarks have been installed (Figure 2).

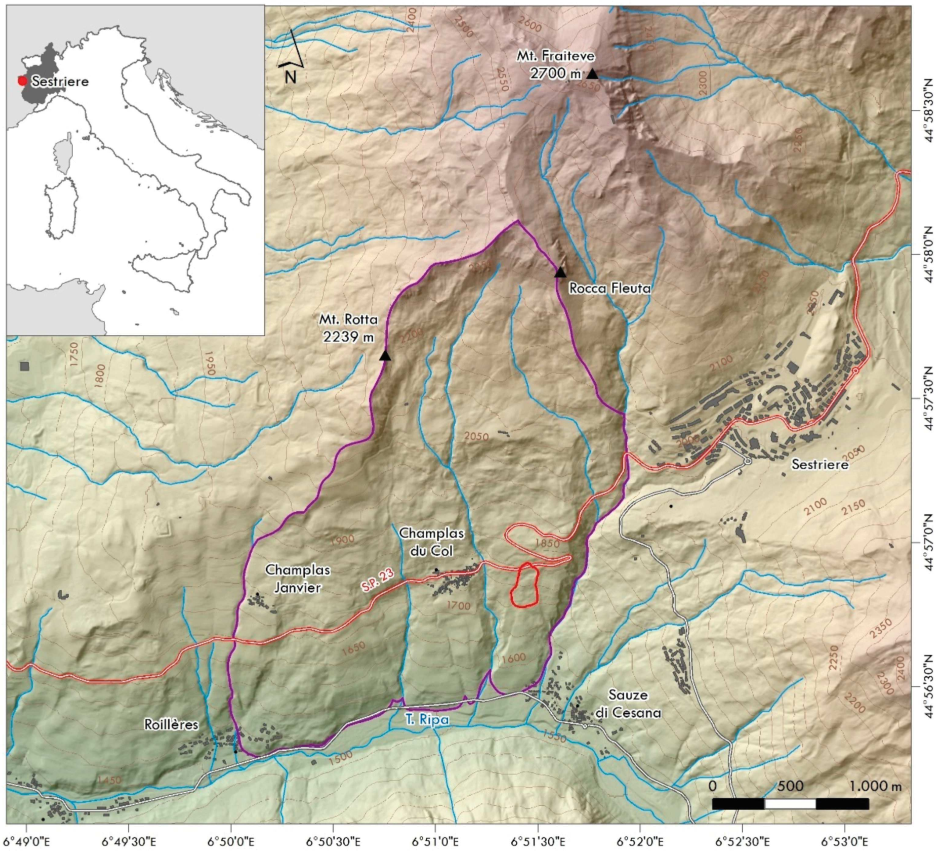

Figure 1. Geographic location of the area of interest, close to the Champlas du Col hamlet, Sestriere municipality (Piemonte, north-western Italy), red polygon corresponds to the May 2018 Champlas du Col landslide reactivation, while the purple one corresponds to the Champlas du Col deep-seated gravitational slope deformation (DsGSD).

The Champlas du Col landslide has been known since the beginning of last decade, with repeated reactivations that are principally related to snow melting in early spring. In the spring of 2017 (April–May), a noticeable reactivation was observed, with evident damage on the surface road (S.P. 23) and to the water regulation infrastructure. In this framework a GPS benchmark was installed by the Regional Environmental Protection Agency (Arpa Piemonte) at the base of the retaining wall of the S.P. 23. The movement rate, measured from the end of May 2017 to October 2017, corresponds to about 10 cm for the observed period. The last reactivation, recorded during late April–early May 2018, was more intense and severe if compared to the previous one, with a prevailing component of movement as earth flow. This movement seriously endangered the S.P. 23, causing the interruption of the national road with damage to the road surface (e.g., fractures, steps) and to the remedial facilities (e.g., upstream and downstream retaining walls). During the emergency phase, the Metropolitan City of Turin (MCT) (the owner of the street) performed an in situ measurement campaign by the employment of a Robotic Total Station (RTS). A total displacement, from May 2017 to May 2018, of about 1.8 m was recorded, of which 1.3 m was recorded in the 2018 reactivation, with a deformation rate of 5 cm/day (data derived from SiFraP [56] Champlas du Col landslide schedule).

The Champlas du Col landslide, on the basis of the present state of knowledge, mainly seems to involve Quaternary deposits, primarily represented by the glacial deposits of the "Supersintema of Moncenisio" [57], and the ophiolitic unit of the "Cerogne-Ciantiplagna unit" (Cretaceous Inf.) [57].

Glacial deposits consist of *Diamicton*, poorly sorted unconsolidated sediment with clasts and blocky suspended in an abundant silty, silty-sandy matrix. Instead, the Cerogne-Ciantiplagna unit is part of a complex system of tectonostratigraphic units of different paleogeographic origin, forming the Pennidic system, bordered and/or crossed by important post-metamorphic fault systems that are variably oriented [52]. This unit consists primarily of monotonous sequences of calcschists with Epidote and micaceous marble including lenses of serpentinites and serpentionischists.

Morphologically, tectonic features strongly influenced the drainage network and landscape morphology, as testified by the Dora Riparia and Chisone rivers and tributaries pattern, which is controlled by NE-SW and NNW-SSE fault systems. Moreover, glacial morphodynamics prevail and influenced the past and actual slope setting, principally related to the debuttressing caused by glaciers retreat, strictly related to the development of large slow-moving instability, i.e., $DsGSD_s$ [58,59].

From a climatic point of view, the study area is characterized by a temperate cold climate [60] typical of Alpine areas with a low rainfall regime (600–900 mm/year), and two peaks in autumn and spring [61]. During winter seasons, abundant snowfalls are recurrent.

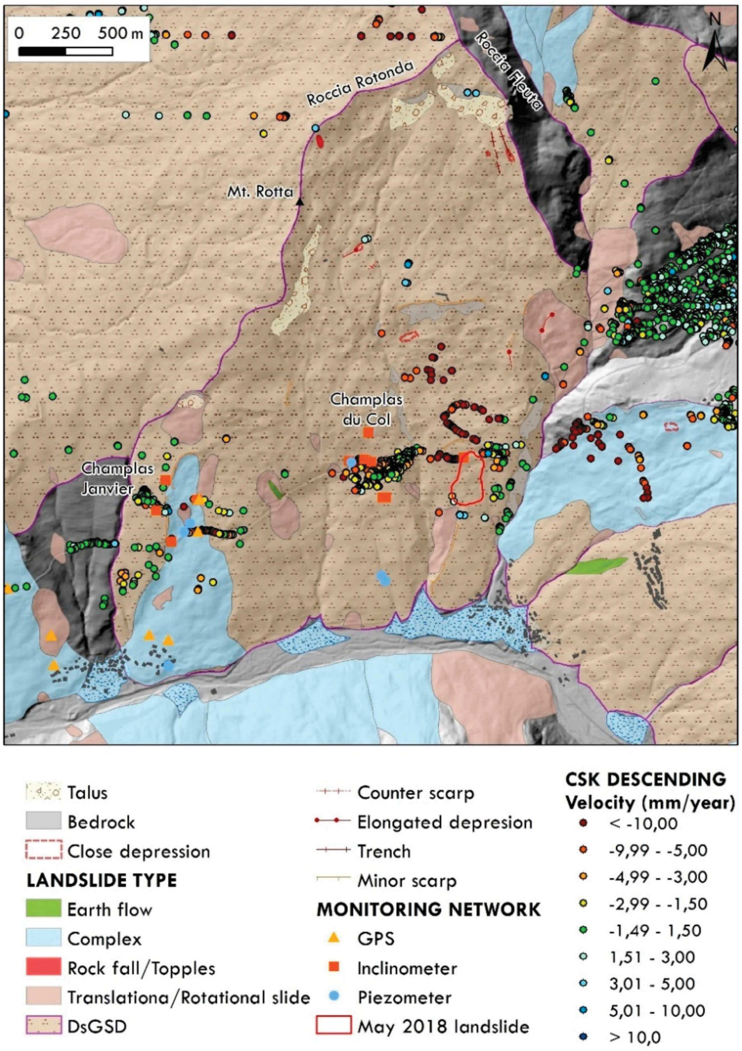

Figure 2. Geomorphological map of the Champlas du Col Deep-seated Gravitational Slope Deformation, landslides associated (landslide polygons source: SiFraP, Arpa Piemonte web-site [62]), in situ instruments (data source Arpa Piemonte web-site [62]) and remote sensing Cosmo-SkyMed (CSK) SAR data distribution (data source: Portale Cartografico Nazionale [63]); red polygon corresponds to the May 2018 reactivation and the purple one to the Champlas du Col DsGSD.

3. Materials and Methods—Structure from Motion Multisource Approach

In this paper, the low-cost photogrammetric Structure from Motion (SfM) method was employed to characterize and monitor an alpine landslide, starting with the integrated use of multisource images an acquisition approach, and also taking advantage of low-cost solutions.

3.1. Data Acquisition

Through a multiscale analysis, we developed a methodology that combines terrestrial and aerial image acquisitions (Figure 3). We generated a series of datasets composed of high-resolution images suitable for the SfM reconstruction process by using the Remotely Piloted Aerial System (RPAS), smartphone camera, and historical aerial photograms collected from diverse regional flights. The collected datasets are processed with Agisoft Photoscan, a commercial software that uses SfM to reconstruct the scene.

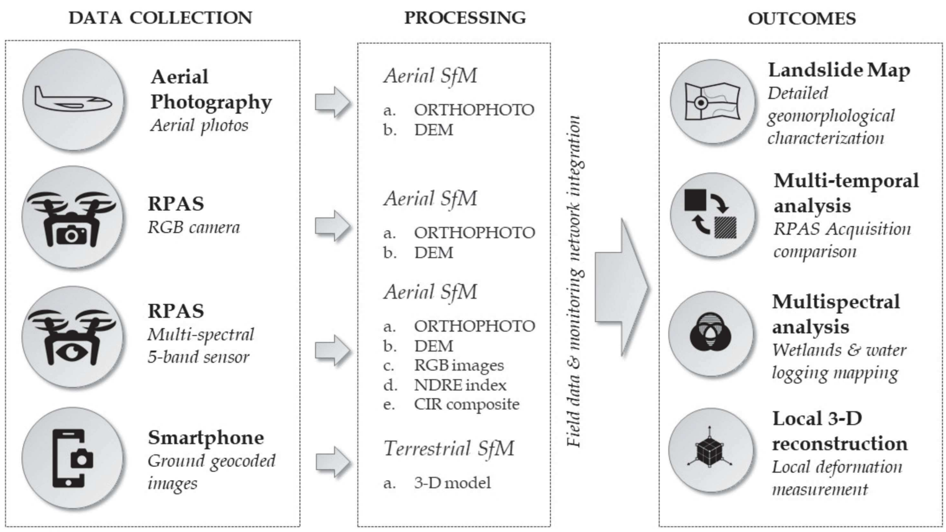

Figure 3. Flow chart of the Structure from Motion (SfM) multisource application methodology for landslide investigation.

First, the aerial photograms derived from available aerial flights (IRPI internal picture library [64]) were collected. Five datasets from 1954 to 2008, with variable scales from 1:38.000 to 1:10.000 are shown in Table 1. Each dataset was than processed by SfM in order to obtain both orthoimages and digital elevation models (DEMs) of the area of interest. A set of markers (discernable points, e.g., a road crossing, a building) were selected in order to geocode the processed raster data. The obtained orthoimages and associated DEMs resolution ranged from 25 cm/pixel to 1.2 m/pixel.

Table 1. Aerial photos datasets.

Operator	Year	Number of Images	Dimension [pixel]	Resolution [cm/pixel]	Scale
IGM	1954	3	7269 × 7360	100	1:33.000
Aer-foto	1963	4	4864 × 3898	60	1:18.000
Rossi	1975	4	4864 × 4052	77	1:14.000
Avioriprese	1991	4	7451 × 7977	120	1:38.000
Hansa Lufbild—German Air Survey	2008	9	7680 × 13824	25	1:10.000

Upon request of the Civil Protection Agency of the Metropolitan City of Turin, the CNR-IRPI carried out two RPAS surveys, performed by two different quad-rotor UAV-systems (Table 2). On 15 May 2018, 81 aerial photos were taken by the UAV equipped with an RGB camera, flying in the most affected area across the S.P. 23. Flight planning was carried out on site (Figure 4) in order to pick a safe location for take-off and landing and define the area to be observed. The flight altitude was about 70 m to provide a ground resolution of approximately 5 cm per pixel. Before the UAV survey, 12 square reference targets (GCPs) were placed outside the unstable area for georeferencing purposes.

Table 2. Unmanned aerial vehicle (UAV) survey specifications.

UAV Type	Data Survey	GSD [cm/pixel]	Number of Photograms	Overlap [%]	Sidelap [%]
Sensefly Albris	15/05/18	5	81	80	60
DJI Phantom-4	14/0618	1.65	383	80	60

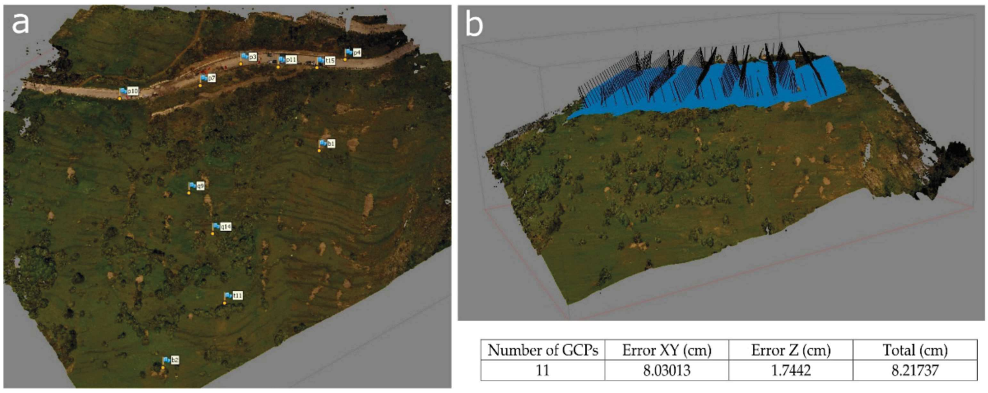

Figure 4. 14 June 2018 UAV flight planning: (**a**) Ground control points (GCPs) distribution, with XY and Z errors associated, and (**b**) camera positions.

A second RPAS survey was planned on 14 June 2018 to acquire RGB and multispectral images. In this case, the UAV was also equipped with a 5-band (i.e., Blue, Green, Red, Red-Edge and near-IR) multispectral camera (REDEDGE [65]). In this case, 383 aerial photos were taken by the UAV-system flying over the whole unstable area. Eleven GCP_s were placed (Figure 4). The obtained orthoimage has a final resolution of 1.65 cm per pixel.

The GCP_s were surveyed using a Leica 1200 GNSS receiver in VRS-RTK mode (accuracy ±3 cm). The SfM approach, thanks to the GCPs collimation, allowed the generation of orthorectified and mosaicked images. The first identification of the landslide border was based on this first RPAS survey combined with field survey observations.

Prior to the flight, the sensor was calibrated with the panel provided with the camera, then the acquired images were processed with the same approach as the RGB ones in order to compute an orthomosaic for each acquired band as the Agisoft Photoscan software is capable of processing multiband images in a unique procedure.

Finally, we used the same processing approach for 38 images (2976 × 3968 pixels) taken manually with a 3.95 mm focal length camera. These pictures were taken in a local sector of the landslide along the lateral landslide limit. Nine benchmarks of 20 × 20 cm were placed within the scene to implement the SfM approach and make the 3D-reconstruction geometrically measurable.

3.2. SfM Data Processing

We used the generated dataset to identify slope landforms and define the landslide surface area through an analysis of morphological features and their variations, and a semi-quantitative analysis of the landslide deformation rate.

Taking advantage of the historical photograms (Table 1), we carried out a qualitative analysis of the landscape evolution over a 54-year period. Specifically, a landslide inventory of the whole area of interest was created by the interpretation of the multiple sets of aerial photographs, using stereo interpretation and directly digitalizing polygons in the GIS environment [66]. For the generation of this inventory, we used the geo-referenced orthoimages obtained by SfM processing. We analyzed each set of aerial photograms by identifying landslides in the 1954–2008 time span. We started by analyzing the 1954 dataset in order to identify the long-standing landslides. Then, by combining all the diverse sets of images, we analyzed all the subsequent landslides that occurred and the potential reactivation of the already identified phenomena. We distinguished the relative age of the identified phenomena, defining a landslide hierarchy by discriminating between the oldest phenomena, i.e., ancient landslides and the possible variation identifiable in the period between two subsequent flights. Landslides were also classified according to their type of movement, according to Cruden and Varnes [67] classification, and subsequently, Varnes [68] and Hungr [69], combining photogram analysis with the information retrieved from the public regional inventory of Piedmont, i.e., SiFraP [56]. After the identification of landslides based on the analysis of aerial images, we also used the regional digital terrain model, and the available information in the regional landslides inventory [56].

The availability of very high resolution RPAS imagery allowed a thorough depiction of the morphological features resulting from the May 2018 landslide reactivation and its extension. Moreover, the availability of two subsequent RPAS surveys allowed a multi-temporal analysis of the unstable area, to evaluate its changes.

Thanks to the possibility of equipping the UAV with a multi-objective camera featuring 5 band acquisition, multispectral analysis was done. In an open source GIS environment, diverse indices and RGB composites were computed by applying raster algebra tools, in order to detect anomalies in water content and vegetation health. As in previous works [50,70], we took advantage of the sensor features by computing the Normalized Difference Red Edge (NDRE) index, which uses the ratio of Near-Infrared and the edge of Red, and Color Infrared (CIR) composites [51] to identify water springs, wetlands and soil saturation within the unstable area.

Moreover, three field surveys were carried out between May 2018 and March 2019 to detect the main geomorphological features of the active landslide. We also focused on and mapped the presence of wetlands and sources. The field data acquisition was supported by the use of "LocusMap", an app dedicated to recording and collecting geocoded points and images.

During these surveys, we acquired different datasets along the main lateral. The SfM processing of these terrestrial images was used to create a 3D terrestrial model, and an expeditious evaluation of the displacement was recorded referring to a local sector of the unstable area by a low-cost solution.

3.3. Additional Information

The obtained dataset has been improved using monitoring data available for this area. In particular, inclinometer and piezometer monitoring results were granted by the MCT. These instruments were installed by MCT after the 2018 spring reactivation. The inclinometer showed the presence of two shear surfaces at the depths of 3.5 m and 24.5 m. The availability of this data was very useful in the calibration of the 3D model of the slope and the definition of the landslide geometry.

4. Results

In this section, the results obtained by the application of the multisource and multiscale approach are presented as follows: (i) Landslide inventory map and multi-temporal analysis by aerial images acquired by aerial photography; (ii) Multi-temporal analysis acquired by RPAS; (iii) Multi-spectral analysis by RGB camera mounted on RPAS; (iv) Terrestrial images for 3-D reconstruction; and (v) Overall temporal evolution.

4.1. Landslide Inventory Map and Multi-Temporal Analysis by Aerial Images Acquired by Aerial Photography

The 54-year aerial photography analysis allowed us to generate a landslide inventory of the entire study area. The observed landslides reveal a typical alpine landscape, characterized by a number of $DsGSD_s$ that involve entire valley flanks, e.g., the Champlas du Col DsGSD (515.15 ha), which are associated to other subsequent phenomena, mainly represented by complex and translational/rotational landslides.

All the landslides, activated on the $DsGSD_s$, were recognized by combining all the multiple sets of images. A landslide hierarchy was established that distinguishes four different generations on the basis of geomorphological criterion. The $DsGSD_s$ bodies have been considered separately. The oldest landslides correspond to the first generation of landslides. These phenomena are generally large in size, exhibiting signs of severe reshaping from watercourse actions and from the ongoing slope instabilities over time. They partially preserve the typical morphologies of landslides (e.g., concave-convex shape, scarps, counter scarps) identifiable on each of the available flights. However, these landslides are partially obliterated by ancient agricultural practices and others human activities. Considering only the Champlas du Col DsGSD, all of the first-generation landslides covered an area of about 71.4 ha, prevalently involving the downstream portion of the DsGSD of Champlas du Col, sometimes crossing the road network and the Champlas Janvier hamlet.

Figure 5 portrays the inventoried landslides spatial distribution on the whole area of interest, in association with some geomorphological features that are well recognizable and related with the evolution of the slope and prevalently due to landslides (e.g., main scarp, trenches, elongated depression). Within the first-generation landslides, we recognized two additional generations of landslides that have progressively altered or partially erased the morphology of these previous ones. The fourth generation is represented by the May 2018 landslide activation, who interrupted the main road.

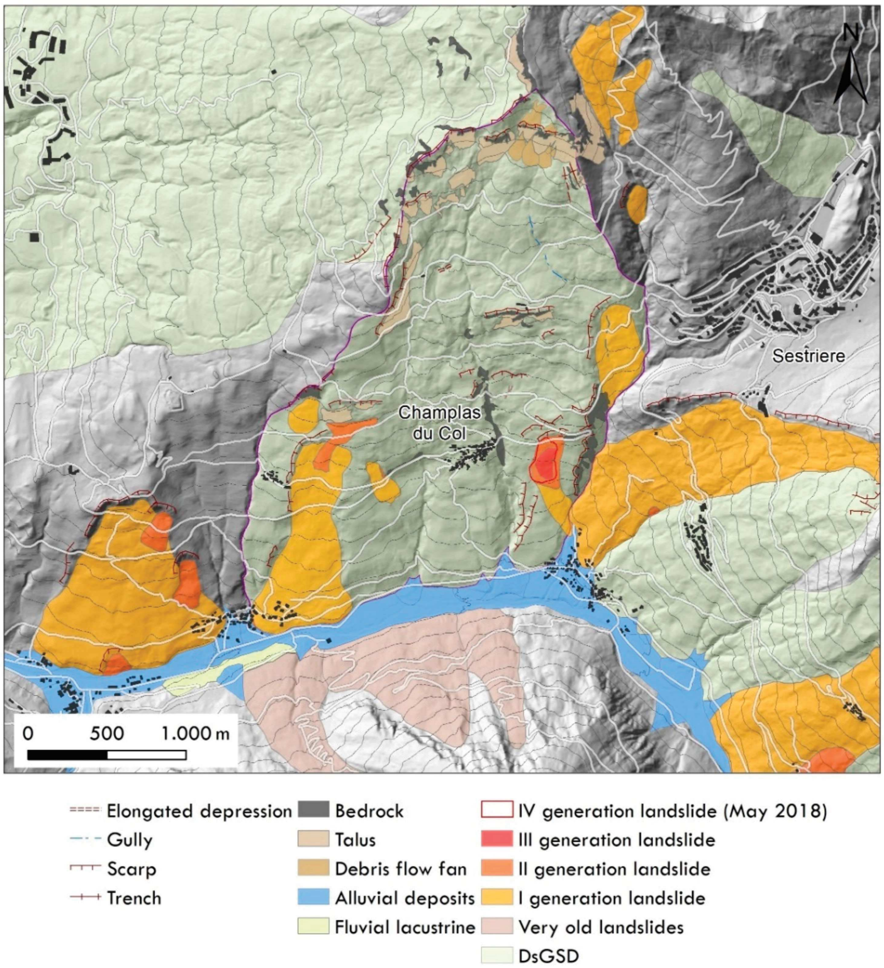

Figure 5. Landslide map of the area of interest distinguished on the basis of temporal hierarchy.

Focusing on the Champlas du Col sector (Figure 6), plotting the aerial photos allowed us to distinguish three chain-linked landslide bodies: (i) first-generation Champlas landslides; (ii) second-generation Champlas landslides; and (iii) third-generation Champlas landslides. The first and the second-generations bodies are already well recognizable in 1954 images, while the third-generation bodies were clearly detected in the 1963 aerial photos (Figure 6). Until 1963, the air photos clearly depict the complexity of the field pattern, which are mainly represented by agricultural land (i.e., pastures). In general, the agricultural parcels' orientation is regular, following the contour lines, while in the Champlas du Col landslide bodies, an irregular and uneven orientation is clearly visible. From the 1975 orthoimage, we can note a general abandonment of land in terms of agricultural practice. The most prevalent land use is pasture featuring the absence of tree cover. Only in correspondence to the landslide sector, small bushes and sparse trees are present. It should be noted that the 1975–1991 inter-period variation of the second-generation Champlas landslide, highlighted by a new 'fresh' scarp set in the downstream portion of the S.P. 23 road, is clearly visible in the 1991 orthophotos.

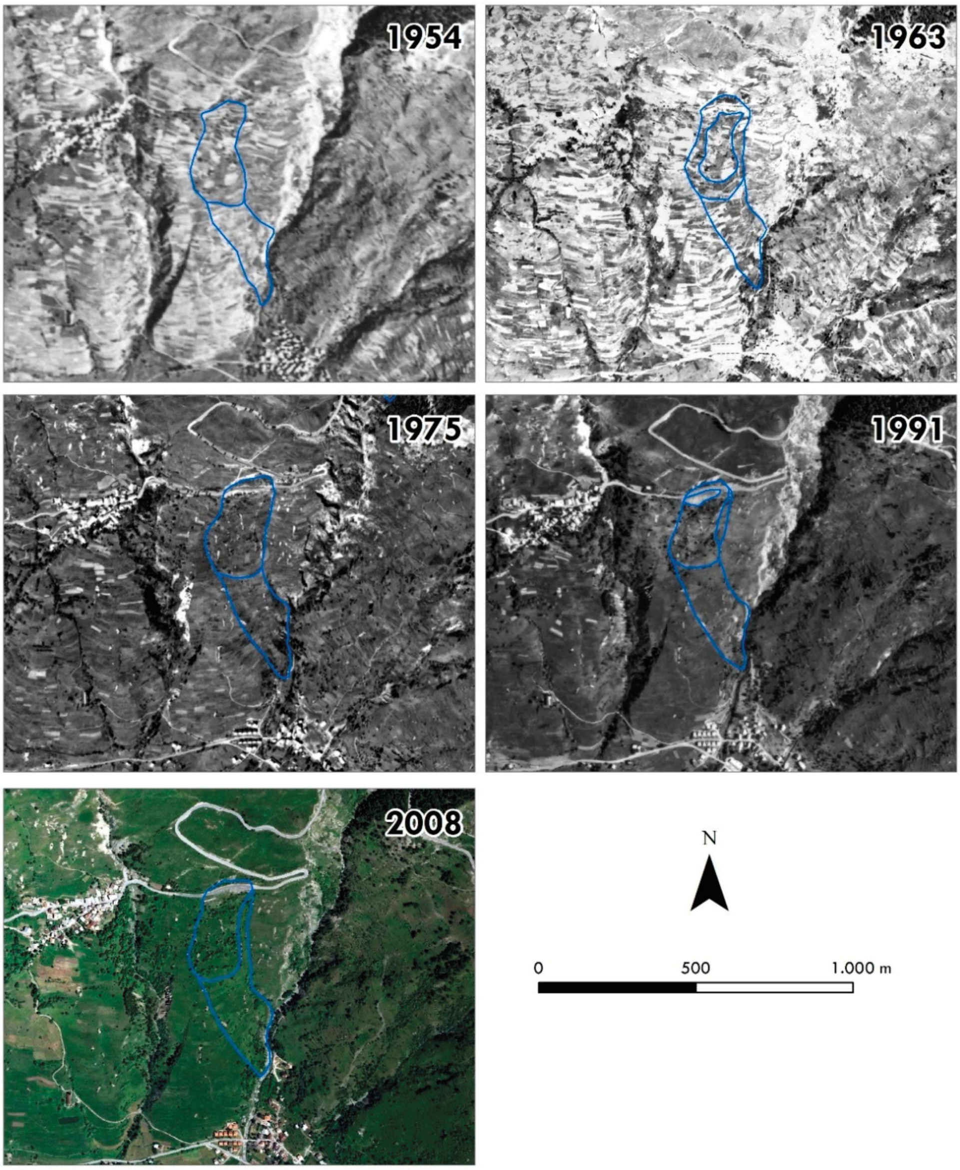

Figure 6. Orthoimages processed by SfM for the Champlas d Col area; the blue polygons represent the photo-interpreted Champlas du Col landslide bodies.

4.2. Multi-Temporal Analysis Acquired by RPAS

The Champlas du Col landslide reactivation in May 2018 led to heavy damage, causing the closure of the national road (S.P.23). During the emergency, two UAV surveys were performed: one immediately after the reactivation, occurred at the beginning of May and the other after a month. The RPAS ensured fast processing, was able to provide highly accurate digital elevation models (DEMs) and provided very high resolution orthophotos of the Champlas du Col landslide. The orthophotos analysis, which was associated with the DEMs derivative products (e.g., shaded relief, slope) led to the mapping of all the geomorphological features of the slope due to the landslide and its evolution, and definition of the landslide boundaries. Furthermore, to exploit the multi-temporal acquisition, a semi-quantitative analysis of the potential changes that occurred between the two flights was computed.

4.2.1. Champlas du Col Landslide Mapping with RPAS High-Resolution Images

The geomorphological evidence and the potential dynamics of the unstable area have been visually investigated by taking advantage of the two UAV imagery sets. The high-resolution RGB orthomosaics (5 cm resolution) supplied a detailed view of the surveyed area, and enabled us to map all the morphological features visible on the 15 May and 14 June orthoimages. In addition, the high-resolution DEMs supplied a detailed representation of the surface. The comparison of the DEMs derivative products such as shaded relief, slope, and contour with orthoimages allowed investigation and mapping of the morphological features that occurred due to the landslide evolution.

The crown area is evidenced by an ENE-WSW trending scarp extended around a hundred meters in length (Figure 7a), and it ranges from 1800 m to 1820 m a.s.l. in elevation. In correspondence of this scarp, there are outcrops of the highly schistose calcschists of the Cerogne-Ciantiplagna unit. The zone of visible depletion involves the surface of the S.P.23 national road, causing noticeable fractures and steps on the pavement. In the downstream sector, a series of transverse fissures with variable extension (from 5 to 30 m) were recognized. Across the slope, starting from the downstream sector of the road, two main lateral fissures of around 100–150 m in length and a noticeable gap in the range of decimeters were observed (Figure 7b).

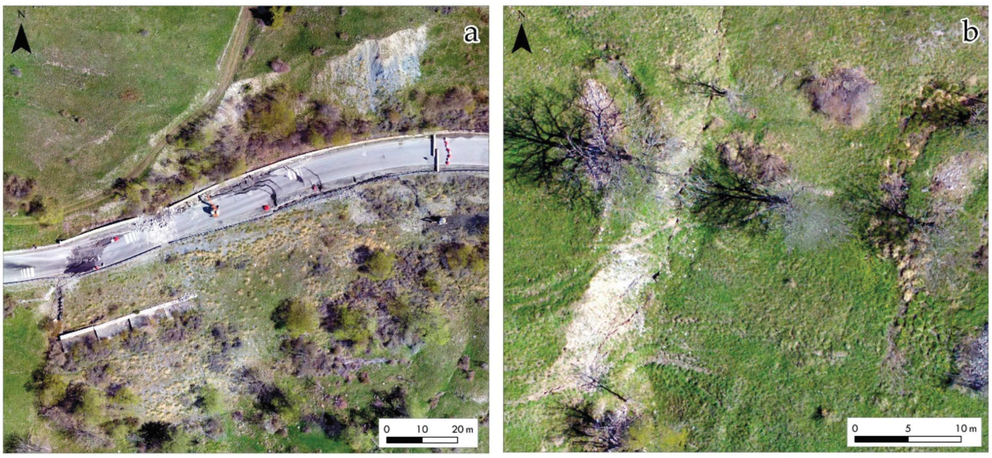

Figure 7. 15 May 2018 UAV orthoimage detail: (**a**) Main scarp of the crown area and road damage; (**b**) clearly visible latera fracture associated with a local fresh scarp, in the middle portion of the right-limit of the unstable area. On the right of the picture one of the wetlands is vividly discernible.

These evident fractures are associated to en-echelon tensional cracks, related to the drag of the slide. The right-side fracture involves the already in-place retaining wall, which shows clearly visible deformations. In the halfway sector, this main fracture is associated to a "fresh" scarp, that extends from 1750 m a.s.l., for about 20 m and about 3 m in height (Figure 7b). On the left-side, at about 1760 m a.s.l., two NNE-SSW trending minor scarps with variable extension of 30–40 m and an average height of a few meters were recognized. They are located in the proximity of the left-side lateral fracture.

Within the unstable area, diverse wetlands highlighted by bright green grass and characterized by hummock-and-hollow surfaces were identified. The distribution of the wetlands area mainly corresponds to the outer limit of the toe bulging portion, clearly evident on the shaded relief and also highlighted by the trend in the contour lines. Figure 8 shows the map of all the morphological features and road damage recognized in the UAV orthoimages of the unstable area.

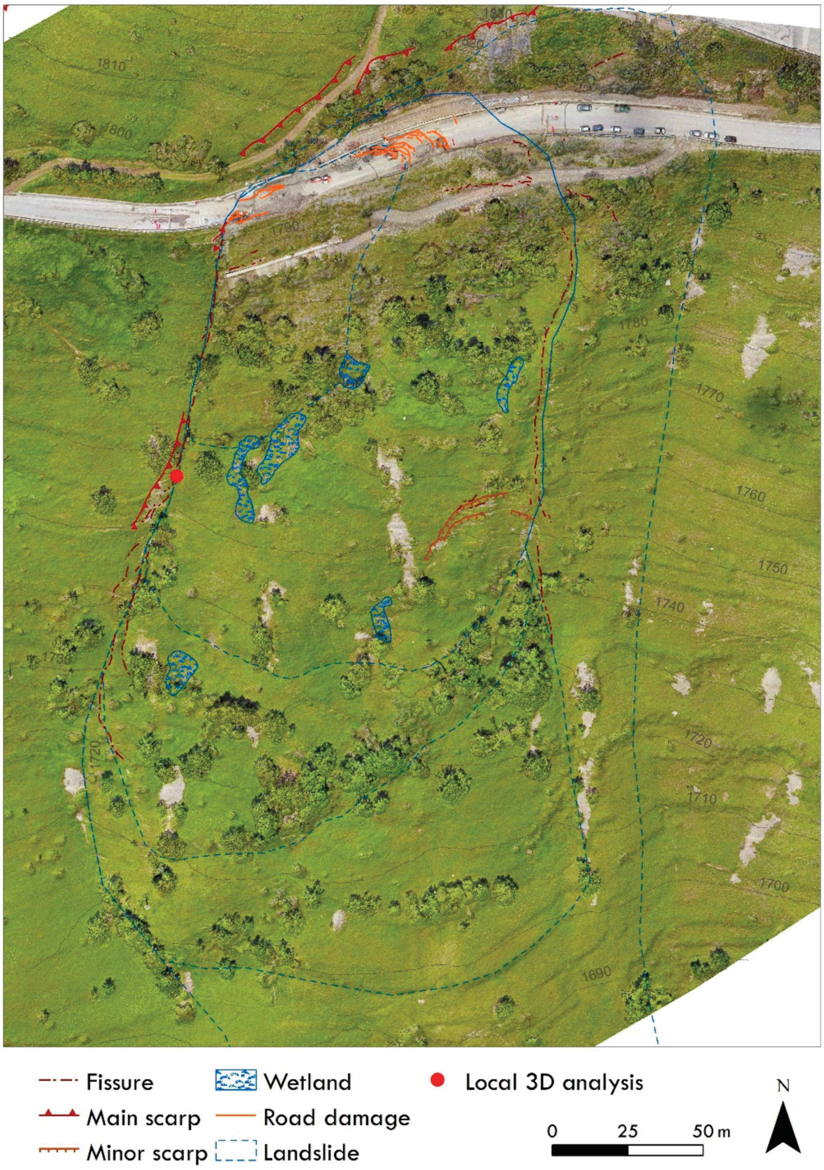

Figure 8. Map of the geomorphological evidence of the unstable area (Orthophoto source: 14 June 2018 UAV survey).

Based on the observations made by the visual interpretation of the UAV products, we were able to define the boundary of the unstable area. In particular, more than one landslide body has been recognized (Figure 8). Specifically, three main landslide bodies are identifiable and distinctively recognizable in the shaded relief obtained from the DTMs. The smaller one extends between elevations of about 1800 m a.s.l., close to the upstream-side of the S.P. 23, to 1730 m a.s.l., close to the terminal part of the two recognized lateral fissures that distinctively demarcate the landslide boundary. Within this first accumulation body, a minor rotational slide of about 0.43 ha, involving the right side of the S.P. 23 and the retaining wall located at 1786 m a.s.l., is recognizable. By analyzing the distribution of the wetland sectors, which are located in the outer limit of the main bulging portions and testify to permeability variations, the two other landslide bodies were delineated.

These three landslide bodies are embedded in a more extensive one, of about 9.04 ha with the toe at about 1575 m a.s.l. close to the tributary of the Ripa River. This more extensive phenomenon corresponds to that recognized by the aerial photograms' analysis, and named first-generation Champlas landslide. Instead, the second-generation one corresponds to the outer limit of the series of embedded rotational slides that occurred in the 2018 reactivation.

4.2.2. Evidences Derived from RPAS Datasets Comparison

The multi-temporal analysis carried out on RPAS data allowed us to analyze the potential changes that occurred between the 15 May 2018 and the 14 June 2018 flights. It is important to note that both the UAVs flights followed the paroxysmal event and occurred in late April-early May. Therefore, at the time of the flights the main deformation has already occurred. For this reason, by a first visual inspection, we can appreciate that a weak variation occurred between the two UAV acquisition DEMs (Figure 9). The figure illustrates that in about one month, material was removed from the north-western portion of the unstable area, specifically, in correspondence to the pre-existing retaining wall (ENE-WSW oriented) and located in the sector just downstream of the main road. The digging on the road pavement and that for the creation of a runway for the remedial work activity is clearly visible.

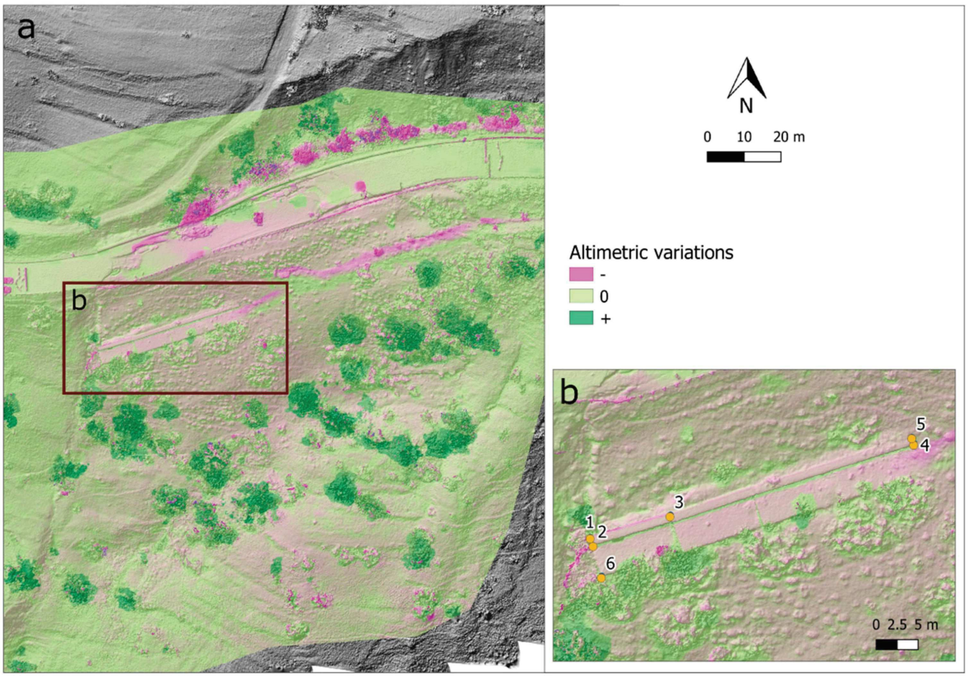

Figure 9. (**a**) Comparison of the altimetric changes from the 15 May 2018 and 14 June 2018 DEMs, illustrating the surface variations in the most damaged area, (**b**) with a focus on the retaining wall, highlighted by the red box, showing the selected points for the planar and height variations computation (see Table 3).

We also focused on the pre-existing retaining wall by selecting some well-recognizable features and extracting their three-dimensional coordinates in order to compute both the planar and height variations (Table 3) between the two DEMs.

Six points were selected on the wall. The computed planar dislocation displays a southwest movement, with a displacement ranging from 15 to 25 cm over a period of 30 days. However, considering the variation in altitude a downgrading of about 40–50 cm was detected.

Table 3. Planimetric and height differences computed in correspondence to six points across the retaining wall (see Figure 9) located within the Champlas du Col landslide, between the two DEMs of 15 May 2018 and 14 June 2018, obtained by UAV survey.

Point	Planimetric (cm)	Height (cm)
1	19.8	−39.6
2	16.5	−37.6
3	26.1	−47.3
4	23.0	−50.9
5	19.0	−49.4
6	26.9	−46.6

4.3. Multispectral Analysis by RGB Camera Mounted on RPAS

The interpretation of multispectral layers (NDRE and CIR maps) and its comparison with RGB data and field surveys revealed a complex pattern of springs and wetlands in the studied area (Figure 10). In particularly, the RGB and CIR composite has highlighted areas featuring hummock-and-hollow texture where, in the field surveys, the presence of springs has been confirmed. Moreover, in the NDRE layer, areas of long leaf grass are emphasized. Their colour suggests their vigor and their pattern indicates the abundance of water and the presence of a surficial flux causing plant lodging.

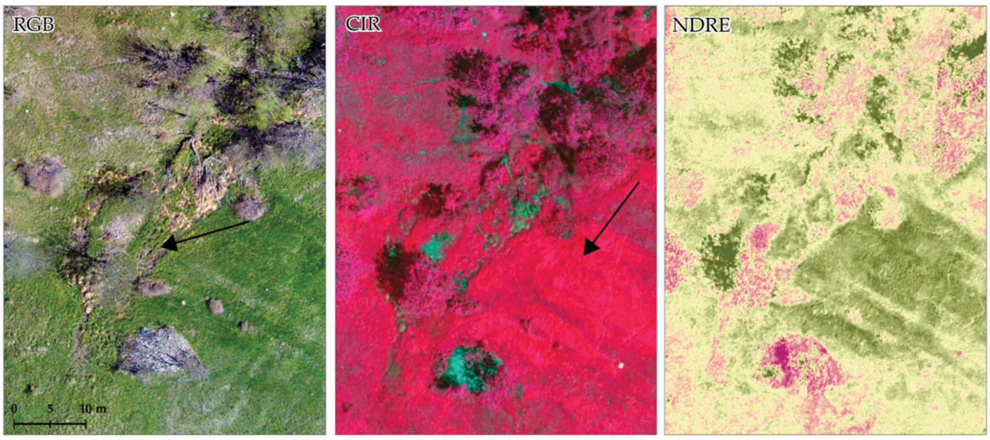

Figure 10. RGB (**left**), CIR (**center**) and NDRE (**right**) of a portion of the investigated landslides revealing hummock-and-hollow pattern (←RGB) and long leaf grass lodging (←CIR) as indicators of water abundance.

4.4. Terrestrial Images for 3-D Reconstruction

Local 3-D reconstruction on a sector located along the main lateral scarp on the right side of the studied landslide was generated by taking a sequence of images by smartphone (Figure 11). We processed the acquired images, taking advantage of references of known size (20 × 20 cm) located within the scene. After aligning photos, we used the bench-markers as scale bars for the known distance, in meters, between the targets' edges. By updating the dataset geometry, the tool refines the scale of the entire model, thus allowing metric measurement.

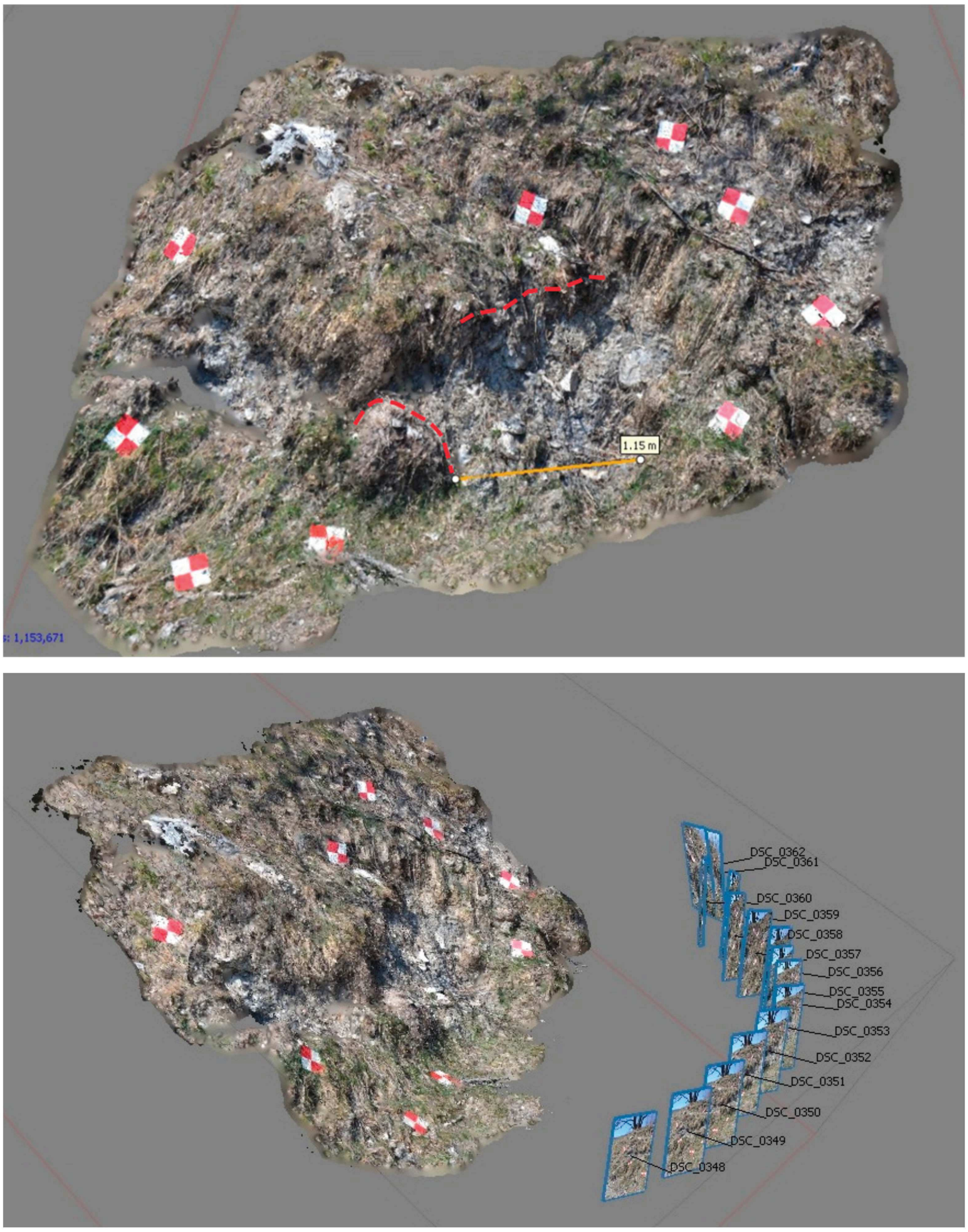

Figure 11. 3D-reconstruction of a local portion of the right-side fissure (see Figure 9 to locate the site), processing terrestrial photos (**Up**: manual displacement measure; **down**: positions of image captures).

The lateral fissure in the halfway sector (from 1750 m a.s.l.), is associated to a "fresh" scarp, along which local roto-translational movements are visible, and are materialized in small sods detached from immediately neighboring local scarps. The local displacement was measured in correspondence to a clearly recognizable sod, shown in Figure 11, by measuring the distance between its scarp and the top of the sod. A displacement of about 1.15 m was estimated, mainly due to the dragging effect of the landslide movement.

The displacement computed with this rapid methodology is comparable with the total displacement computed by the RTS, of about 1.3 m recorded during the 2018 reactivation.

4.5. Overall Temporal Evolution

The obtained results were combined with the orthophotos available on the *Portale Cartografico Nazionale* web-portal [63] (i.e., 1994, 2006, 2010 and 2012 orthophotos) in order to reconstruct the overall temporal evolution of the area of interest, with a specific focus on the Champlas du Col landslide (Figure 12). A time line created through the combined analysis of the historical aerial photos, the on-line orthophotos and the high-resolution UAV-orthoimages traces the evolution of the area of interest over a 64-year period (from 1954 to 2018), showing the four recognized landslide generations.

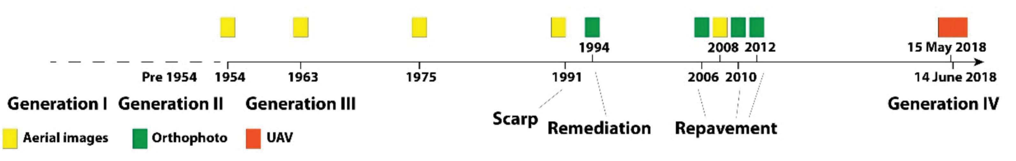

Figure 12. Time line of the Champlas du Col landslide evolution from 1954 to 2018.

Evidence of road damage, e.g., road repaving (Figure 13) testifies to a long history of instabilities in the Champlas du Col area, which before the construction of the retaining wall involved the entire curvy road (see 1994 orthophoto in Figure 13). Currently, the area involved corresponds to the May 2018 reactivation.

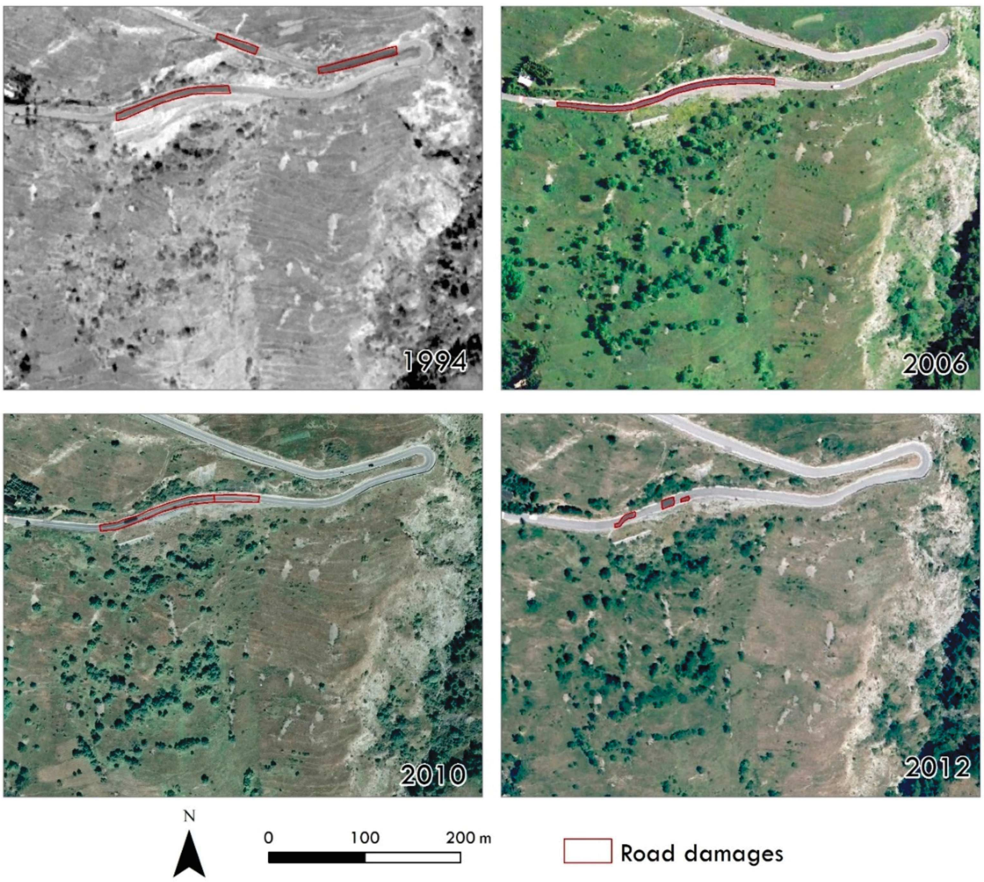

Figure 13. a. Evidence of road repaving visible on the orthoimages available on the "*Portale Cartografico Nazionale*" web-portal [63].

Figure 14 shows the preliminary geomorphological model of the investigated landslide, highlighting the preferential distribution of springs and wetlands in the outer limit of the bulging portions, outlining the series of overlapped landslides, clearly bounded laterally by very open fissures.

The existence and the location of many sliding surfaces was confirmed by the inclinometer (S1 in Figure 14) measurements in the period 8 June–13 November 2018. The S1 located one sliding surface at a depth of about 3.5 m, with an initially high speed that gradually decreased almost to zero from early August; a second surface was observed at about 24.5 m, with an initial deformation of about 3.6 cm/year, although this decreased at the beginning of August and settled on values of about 1.4 cm/year.

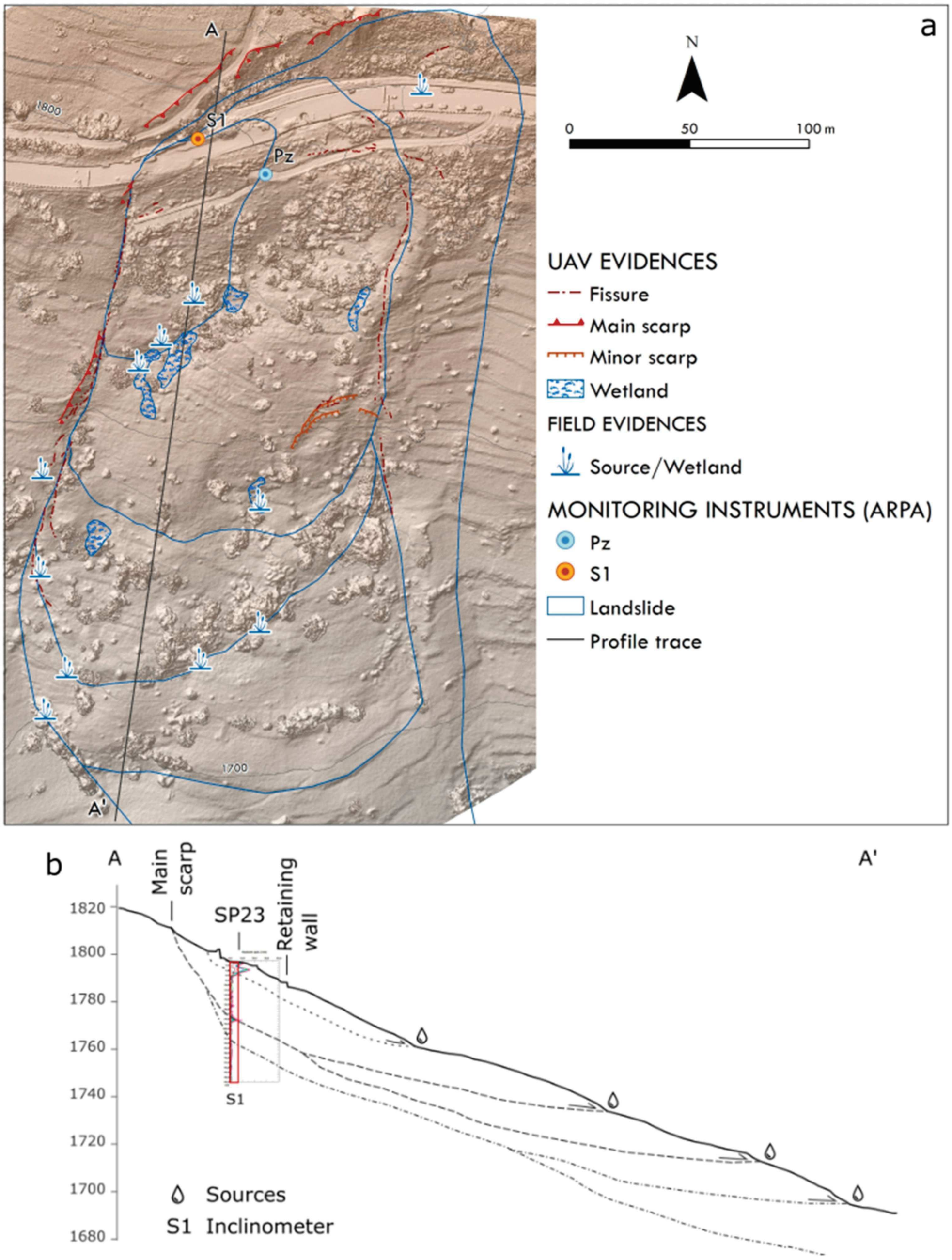

Figure 14. (**a**) Map of the Champlas du Col observed landslides associated with the main morphological features due to the spring 2018 reactivation, and (**b**) longitudinal profile associated with the resulting displacement graph calculated during June–November 2018.

5. Discussion

With regard to the geomorphological framework of the investigated site, the landslide setting is spatially and temporally complex. At the slope scale, the south-facing flank of Mt. Fraiteve is affected by a wide, mass movement known as the Champlas du Col DsGSD, in which a series of minor landslides are set. Thanks to the overall analysis of the final results, we discerned four generations of landslides (Figure 12). The first and the second generation are readily recognizable in the 1954 aerial photograms, and always visible in the following photos. In 1963, a third generation is detectable, located within the body of the second-generation landslide. However, in 1991 photograms, a reactivation of the second-generation landslide was observed and evidenced by a new scarp visible in the sector downstream of the S.P.23. A series of reactivations of the same landslide are recognizable in the orthophotos available on the web. Since the nineties, a series of serious damage to the road network have been observed, as testified by the repaving of the main road surface and the building of the retaining wall just downstream of the S.P.23 national road (Figure 13). After the paroxysmal phenomenon that occurred during the spring of 2018, corresponding to the fourth-generation landslide (see Figure 5), new aerial photos were taken by UAV surveys. The very high-resolution DEMs and orthoimages have led to the recognition and characterization of a series of landslide bodies (Figure 14). The two larger bodies correspond to the oldest phenomena, already recognized in historical reconstructions, within which a series of embedded landslide bodies were recognized on the new UAV images, and which are related to a progressive activation in spring of 2018. In the reactivation, it is important to note that the landslide reactivation starting from late April–early May was a result of the snow melting, which was related to the abundant snowfall during the 2017–2018 winter. The internal data acquired by the Metropolitan City of Turin reported peaks of 5 cm/day from 23 to 30 May 2018 (datasheet 001-76803-00 [56]), with a total displacement of about 1.3 m for the 2018 reactivation. By the 3D-model reconstruction of the terrestrial images taken by smartphone, we could locally estimate the overall landslide deformation (about 1.15 m), which was confirmed by the comparison with the RTS measurements acquired by the MCT. The comparison of the 15 May and 14 June 2018 flights highlights the damage that occurred along the road surface and the remedial work interventions, as well as the pluri-decimeter planimetric and altimetric shift along the retained wall, just downstream of the national road, and which is comparable to the recorded deformations.

This study demonstrates the productive use of the SfM technique applied to multisource images and multi-period acquisition by leveraging historical aerial photograms, high-resolution UAV-images, and terrestrial photos taken by smartphone.

The use of Structure from Motion (SfM) to process aerial and/or terrestrial images constitutes a practical and economic method that is useful for immediate, very high-resolution and detailed mapping in small (0.01–100 km^2) unstable areas. For landslide hazard analysis, this low-cost photogrammetric method has usually been applied to reconstruct very high-resolution topographic 3D-models, primarily starting from aerial imagery acquired by RPAS [23,25] where the distance of the object is the main factor that influences the accuracy [44]. However, generating DEM and orthoimages by UAV survey associated to flight orientation, based on GCPs measured by GNSS, can generally provide satisfactory results [46,49].

Commonly, multi-source and multi-period DEM/DTM data are a useful tool to characterize and research the mechanism of landslides. In the literature, in comparing the DEM/DTM acquired by diverse sensors and/or instrument at different times, they have been exploited to investigate landslide activity, volume estimation and its variations [71–74]. It should be noted that by combining information with various precision and resolution methods, collected in different periods, the acquisition scale and the subsequent error estimation of data becomes crucial [49]. In our case, we generated DEMs and orthoimages with highly variable resolution, mainly due to the acquisition scale. The ground resolution of historical aerial photos, ranging from 25 cm/pixel to 1.2 m/pixel is insufficient to be accurately co-registered with the recent UAV dataset (1.65 cm/pixel of resolution). Similar considerations have also been made for the terrestrial images and UAV-images comparison.

As highlighted in previous scientific works [17,18], the availability of historical aerial photograms allows the reconstruction of the previous morphological state, which is useful to the overall temporal evolution assessment of a specific area of interest, and for analyzing the geomorphic framework at regional scale. On the contrary, higher spatial resolution and submeter accuracy of the UAV-images ensures an accurate investigation at local scale, and the topographic information collection [23,44,75].

Theoretically, when the entity of displacement of the gravitational process is particularly remarkable and morphological modifications are highly visible, historical images can be employed in order to reconstruct past geometrical setting on the slope. In these cases, a comparison between diverse sources of data with different resolutions is possible and suitable [76].

The great availability of historical and recent images of the area of interest allowed us to prepare an overall reconstruction of the Champlas du Col landslide. By combining historical aerial photograms, RGB images and multispectral data from UAV surveys, local 3D-reconstruction from terrestrial photos, with field campaign information, and in situ measurement reported by ARPA Piemonte [56], we delineated an initial assessment of the Champlas du Col landslide (Figures 12 and 14).

In our work, the entity of slope change is of the same order of magnitude of the accuracy of aerial photos. For this reason, it is possible to make a direct comparison between old aerial image results and new UAV acquisition. The processing of historical aerial photograms ensured a qualitative analysis of the landscape evolution over a 54-year period (from 1954 to 2008), and allowed the generation of a landslide inventory and the historical reconstruction of the study area. Additionally, the DEMs and orthoimages obtained from the two flights are characterized by adequate resolution for the identification of the main morphological features of the unstable area, as well as of the damage displayed on the road surface of the main road.

6. Conclusions

In this paper, a low-cost and repeatable methodology based on SfM to derive valuable information to investigate and characterize active landslides from heterogeneous and multi-scale data sources is presented and discussed. SfM is a valuable tool that is able to compute a 3D point cloud from a sequence of images taken from different points of view. RPAS can be considered an effective solution for high-resolution image acquisition for active landslide analysis. Along with RGB camera equipment, the UAV system can be empowered with other sensors to perform, for instance, multispectral and hyperspectral images. The use of smartphones represents another valid and low-cost approach for capturing terrestrial, RGB images. Likewise, historical aerial images acquired by aerial photogrammetry constitute a relevant information source that can be treated with an SfM approach.

A methodology that combines the use of multiple set of images, acquired from diverse instruments and sensors on various scales has been implemented. This methodology is applied to the Champlas du Col landslide (Sestriere municipality, north-western Italy), for which two UAV surveys were carried out after the spring 2018 reactivation and a series of terrestrial pictures were taken. A multiple set of aerial photogrammetrical images is also available.

The orthophotos obtained from aerial photogrammetric images processed by SfM allowed us to generate a landslide inventory for the area of interest, which was associated to the historical analysis of landslide activity, and is useful to define the evolution of slope instabilities over a 54-year period (from 1954 to 2008). The DEMs and orthoimages obtained from UAV surveys enabled identification of the main geomorphological features due to the recent reactivation and the geological model of the unstable area and characterization of the landslide extension that occurred, in association with the executed field survey and the available in situ data (i.e., inclinometer). Several considerations on the variations that occurred between the two UAV flights products were done for a characterization of the source area up to the area close to the retained wall within the unstable area. In addition, the SfM applied to terrestrial images allowed us to estimate the local deformation rate of the May 2018 re-activation, which resulted in a value comparable to the displacement rate computed by RTS.

Our strategy shows that it is possible to obtain reliable and useful data for landslide hazard definition, employing a cost-effective and rapid methodology based on SfM principles that is easily repeatable to characterize and investigate active landslide in other contexts.

Concerning future improvements, the proposed methodology could be enriched by multi-temporal, multispectral flights in order to monitor the presence and abundance of water in the site. These findings should then be related to the geometrical evolution of the landslide with the purpose of investigating the possible relationship between landslide dynamics and water.

Author Contributions: D.G. (Daniele Giordan) and D.G. (Danilo Godone) collected all the UAV datasets. M.C. and A.W. carried out the field survey. M.C. and D.G. (Danilo Godone) processed all the imagery including the historical aerial photogrammetry data, creating DEMs and orthophotos using AgisoftPhotoScan. M.C. and D.G. (Danilo Godone) analyzed and interpreted all the datasets. M.C. wrote the majority of the manuscript, and D.G. (Daniele Giordan) and D.G. (Danilo Godone) contributed to several sections and revised the manuscript.

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Article

An Open-Source Web Platform to Share Multisource, Multisensor Geospatial Data and Measurements of Ground Deformation in Mountain Areas

Martina Cignetti [1,2], Diego Guenzi [1,*], Francesca Ardizzone [3], Paolo Allasia [1] and Daniele Giordan [1]

1 National Research Council of Italy, Research Institute of Geo-Hydrological Protection (CNR IRPI), Strada delle Cacce 73, 10135 Turin, Italy; martina.cignetti@irpi.cnr.it (M.C.); paolo.allasia@irpi.cnr.it (P.A.); daniele.giordan@irpi.cnr.it (D.G.)
2 Department of Earth Sciences, University of Pavia, 27100 Pavia, Italy
3 National Research Council of Italy, Research Institute of Geo-Hydrological Protection (CNR IRPI), Via della Madonna Alta 126, 06128 Perugia, Italy; francesca.ardizzone@irpi.cnr.it
* Correspondence: diego.guenzi@irpi.cnr.it

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Abstract: Nowadays, the increasing demand to collect, manage and share archives of data supporting geo-hydrological processes investigations requires the development of spatial data infrastructure able to store geospatial data and ground deformation measurements, also considering multisource and heterogeneous data. We exploited the GeoNetwork open-source software to simultaneously organize in-situ measurements and radar sensor observations, collected in the framework of the HAMMER project study areas, all located in high mountain regions distributed in the Alpines, Apennines, Pyrenees and Andes mountain chains, mainly focusing on active landslides. Taking advantage of this free and internationally recognized platform based on standard protocols, we present a valuable instrument to manage data and metadata, both in-situ surface measurements, typically acquired at local scale for short periods (e.g., during emergency), and satellite observations, usually exploited for regional scale analysis of surface displacement. Using a dedicated web-interface, all the results derived by instrumental acquisitions and by processing of remote sensing images can be queried, analyzed and downloaded from both expert users and stakeholders. This leads to a useful instrument able to share various information within the scientific community, including the opportunity of reprocessing the raw data for other purposes and in other contexts.

Keywords: digital archive; spatial data infrastructure; monitoring network; synthetic aperture radar data; GeoNetwork; GeoServer; NextData project

1. Introduction

Thanks to the development of increasingly meaningful monitoring technologies and sensors, the scientific community is undergoing a data-rich period with respect to the Earth's surface. Nowadays, the amount of monitoring network acquisitions, both in-situ and by remote sensing techniques, is constantly increasing [1,2]. Recently, a lot of web approaches for monitoring measurements analysis and dissemination have been developed [3–5] jointly as new tools for the effective management of huge archives of multisource data [6]. In addition, the high availability of satellite images from different sensors (e.g., ERS-1/2, Envisat ASAR, RADARSAT) and the latest free images of the ESA's constellation (i.e., Sentinel-1A, 1B), have significantly enlarged the surface information, both in space and time. From the processing and the analysis of geospatial data (GD) and surface information, new archives of multisource data are created, specifically in the framework of scientific projects to support environmental and climatic data sharing [7–9], project results management and visualization, all applied to natural hazard risk management.

The development of large archives of multisource data is functional to the investigation of geo-hydrological processes' evolution over time [10]. With this purpose, the integration of GD and ground deformation measurements, derived from remote sensing and in-situ acquisitions, has become necessary. However, only the memorization of data does not meet all the needs and expectations of the different stakeholders in terms of data access, retrieval, investigation, visualization and analysis.

Web service technologies, as the spatial data infrastructures (SDIs), enable the scientific community to set up large and heterogeneous data infrastructures, developing reliable methods of representing and mapping information [11–13]. SDIs are useful to implement a framework of geographic data and metadata, constituting an efficient and flexible way to discover and manage geospatial information. Moreover, SDIs are able to reply to the increasing demand for processing geospatial information and discovering of knowledge, for both scientists (e.g., researches, social scientist, geographers) and all the other stakeholders (e.g., government institutions, public authorities, citizens).

To cope with the interoperability management of heterogeneous GD-integrating sensors, instrumental data and geographic information, the SDI must agree with well-known standards like the ones sponsored by the Open Geospatial Consortium (OGC). This demand finds a useful answer in new technologies, especially with the development of web services structured according standard protocols that guarantee a simple access to the whole scientific community and all stakeholders.

The GeoNetwork open-source software (https://geonetwork-opensource.org/) entirely fulfils the requirements previously described, using the principles of free and open-source software (FOSS) and international standards about services and protocols (International Organization for Standardization Technical Commission, ISO/TC211 and the OGC). This platform implements both a portal and a database, referring to an SDI defined in the "OGC Reference Architecture". GeoNetwork provides an easy to use web interface to manage different resources at the same time, by ensuring the spatial exchanges and sharing, managing and publishing metadata and spatial data. This system allows data querying using a huge volume of metadata from different environments and provides a web-based interactive map viewer. Moreover, using this software allows anyone to independently discover and exploit the dataset, without any intermediary. Concerning huge information in terms of number of test sites, number of sensors, instruments and relative measurements, an interesting approach, easily integrable with the GeoNetwork, is represented by deep-learning approaches and convolution neural networks (CNNs), in particular related to landslides and slope failure detection [14].

Inside the NextData Project (http://www.nextdataproject.it/) framework, an Italian project of National Research Council for retrieval, storage, access and diffusion of environmental and climatic data, a special project named HAMMER (relationsHips between meteo-climAtic paraMeters and ground surface deformation time sEries in mountain enviRonments) was developed. The main objective of this special project was to promote the collection and implementation of a long-term series of ground deformations, focusing on high mountain regions spread over different physiographic and climatic environments. In this framework, time series acquisition and reconstruction have been realized by applying both traditional field monitoring techniques, obtaining short-term surface movements with high accuracy, and differential interferometry with synthetic aperture radar (DInSAR) techniques [15–17], ensuring wide-area coverage (e.g., thousands of km^2), with a monthly temporal sampling.

The possibility of obtaining a long-term series of deformation relevant to several geo-hydrological processes in different physiographic and climatic regions may open the possibility of understanding the complex and largely unknown relationships between climate and its variation [18–20]. A more effective combination and integration of DInSAR and in-situ measurements can be considered a convenient approach to analyze different phenomena at different spatial (regional, local) and temporal (months/weeks, days/hours) resolutions. The collection and organization of multisource data of surface deformations is a key element in finding eventual relationships between meteorological and climatic variables and slope instabilities over time.

In large projects, such as NextData, the use of a dedicated GeoNetwork suits well with the integration of several subprojects, and becomes useful for the integration of different types of data. In our proposal, we focused on the implementation of the SDI dedicated for the HAMMER sub-project (H-SDI), adopting, among other software, the GeoNetwork platform predisposed for the main project. The H-SDI includes multisource data of mountainous regions and has been implemented in order to share, manage and disseminate all the acquired knowledge and information. Such SDI not only provides the postprocessed ground deformation time-series, but also the raw data from monitoring network measurements of specific landslides, carried out by expert geologists and engineers, and remote sensing data from satellite surveys. Seven study areas have been considered: five located in Italy (Western Alps and Northern and Central Apennines), one located in the Spanish Pyrenees and other one in the Atacama Desert (Chile).

The main aim of this paper is to show the structure developed for the management and sharing of monitoring data of active geomorphological processes. The paper also points out the functionalities of the GeoNetwork system as a tool for geospatial data and metadata organization and standardization inside the project. Moreover, we briefly present the selected study areas and the relative multisource data collected within the project. Then, we discuss the adoption of a dedicated GeoNetwork to manage and share the metadata and geospatial data, illustrating the hierarchical architecture of the heterogeneous information and time series of the different test sites. After that, we show a brief presentation of the web-interface and its potentials while, in the final section, we focus on the exploitation of the web-interface and the employment of the obtained results.

2. Data Collection

The generation of GD suitable for publishing and linked with descriptive information (i.e., metadata) arises from the need to collect and organize the results of the HAMMER project. This project focuses on the collection and generation of ground deformation time-series of several geo-hydrological processes located in high-mountain regions, in different geographic and physiographic settings, as a key issue for the correct analysis of slope hazards.

Little is known on the effects of environmental and climate changes on the frequency and the intensity of landslides [20,21]. Taking advantage of ground deformation time-series, as long as possible, derived from multisource instruments or sensors, we can analyze the eventual changes in deformation trends, useful to assess landslide behavior over time. This should also support effective ways of land use, planning and risk management. According to this purpose, an SDI was designed to incorporate and integrate multisource data from some settlements distributed in high mountain regions. The types of data source can be summarized in two main groups, based upon the instrument or sensor employed for the time series production:

i. In-situ: surface and sub-surface instruments providing ground deformation time-series with very high temporal sampling (e.g., hourly/daily), suited for local scale analysis, eventually with early warning purposes;
ii. Satellite: active space sensors above Earth collecting synthetic aperture radar (SAR) images exploited by the DInSAR techniques, like PSInSAR [15] or SBAS [16], to obtain ground displacement time series with monthly temporal sampling and regional scale analysis of surface displacement.

Data collection and time series reconstruction refers to the seven study areas of the project. Figure 1 shows the areas of interest (AOI) distribution, while Table 1 summarizes some information of the selected areas. For each AOI, we specify the type of slope instability threatening the area, the instruments and/or sensors employed to ground deformation time-series acquisition, the corresponding acquisition time and the institution who acquires and processes the surface measurements. All these metadata are stored into the GeoNetwork.

Figure 1. Areas of interest and their geographical location: (**a**) European study areas; (**b**) South America study area (orthoimages from BING—https://www.bing.com/maps).

Table 1. Area of interest data summary, reporting geographical information of each test site, the monitoring network adopted, the duration of data acquisition and the source of the data. (Glossary: IREA—Istituto per il rilevamento elettromagnetico dell'ambiente; Envisat ASAR—Environmental Satellite Advanced Synthetic Aperture Radar; ERS-1/2—European Remote-Sensing Satellite; G-POD—Grid Processing on Demand; P-SBAS—Parallel-Small Baseline Subset; PSInSAR—Persistent Scatterer Interferometric Synthetic Aperture Radar; HR—high resolution; LR—low resolution).

Test Site	Monitoring Network	Observation Period	Data Source	Temporal Sampling Rate
GRANGE ORGIERA Landslide (Varaita Valley, Sampeyre, Piedmont, Northern Italy), Western Italian Alps	Robotic Total Station	August 2009–October 2010	CNR IRPI of Turin internal data.	hourly
	Robotic Total Station	July 2010–September 2010	CNR IRPI of Turin internal data.	hourly
	Envisat ASAR Descending	April 2005–October 2010	G-POD service, 21 images processed by P-SBAS algorithm by the CNR IRPI of Turin.	monthly
GARDIOLA Landslide (Germanasca Valley, Prali, Piedmont, Northern Italy) Western Italian Alps	Robotic Total Station	March 2004–April 2009	CNR IRPI of Turin internal data [22,23].	hourly
MONTALDO di COSOLA Landslide (Cabella Ligure, Alessandria, Piedmont, Northern Italy) Apennine	Automated Inclinometer System	2002–2001	CNR IRPI of Turin internal data [24].	daily
	Automated Inclinometer System	2002–2004	CNR IRPI of Turin internal data [24].	daily
IVANCICH Landslide (Assisi, Perugia, Umbria, Central Italy) Central Apennine	Inclinometer	November 1998–December 2006	CNR IRPI of Perugia internal data [18].	yearly
	Cosmo-SkyMed Descending HR	December 2009–February 2012	CNR IRPI of Perugia internal data [18]. 39 images processed by SBAS technique in low resolution by CNR IREA of Naples.	monthly
	Cosmo-SkyMed Descending LR	December 2009–February 2012	Perugia internal data [18]. 39 images processed by SBAS technique in low resolution by CNR IREA of Naples.	monthly
	ERS-ENVISAT HR	April 1992–November 2010	Perugia internal data [18]. 130 (91 ERS-1/2, 39 Envisat) images processed by SBAS technique in low resolution by CNR IREA of Naples.	monthly
AOSTA VALLEY (Northern Italy) Western Alps	Envisat ASAR Ascending	June 2004–November 2010	G-POD service, 38 images processed by P-SBAS algorithm by the CNR IRPI of Turin [25].	monthly
TENA VALLEY Portalet Landslide (Upper Tena Valley) Spanish Pyrenees	Envisat ASAR Ascending	October 2002–July 2007	Framework Agreement between NextData Project and Terrafirma. ERS-1/2 and Envisat images processed by PSInSAR technique.	monthly
	ERS-1/2 Ascending	June 1995–July 1999		monthly
	Envisat ASAR Descending	July 2001–September 2007		monthly
	ERS-1/2 Descending	April 1995–December 2000		monthly
SALAR de ATACAMA (Atacama Desert, Chile) Andes	Envisat ASAR Descending	March 2003–September 2009	G-POD service, 18 images processed by P-SBAS algorithm by the CNR IRPI of Turin and the CNR IREA of Naples.	monthly

3. Infrastructure Design

The requirement of managing different data formats (e.g., vector, raster, text), visualizing time series information derived from multisource instruments or sensors, querying the catalogue and portraying the data on a map made the implementation of a cataloguing system necessary. By using a geospatial catalogue service, we structured a web-based metainformation repository with a web-interface to advertise and query the available geospatial data. The H-SDI is managed and integrated in an open-source software like the previously cited GeoNetwork supported by a dedicated GeoServer. Figure 2 sketches the different data types stored in the GeoNetwork/GeoServer structure and the web-interface facility.

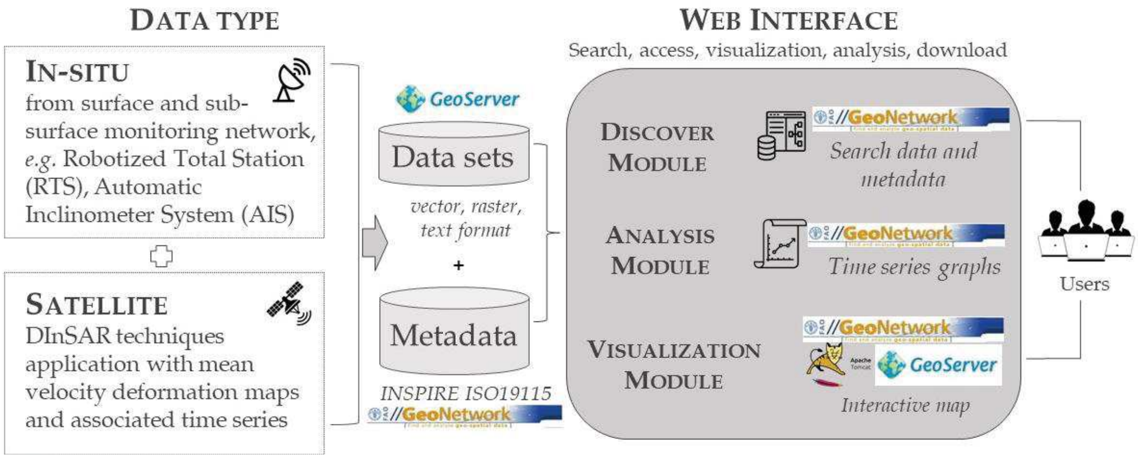

Figure 2. HAMMER spatial data infrastructure (H-SDI) architecture based on the GeoNetwork open-source software.

GeoNetwork is a software for the management of geographic datasets, jointly developed between the Food and Agriculture Organization of the United Nations (FAO), the United Nations World Food Program (WFP) and the United Nations Environment Program (UNEP) in 2001 [26]. It provides an easy-to-use web interface that allows managing different resources at the same time by ensuring the spatial information exchange and sharing. It offers metadata editing and search functions, in addition to a web viewer of georeferenced maps, highly suitable to SDI implementation. The GeoNetwork has been implemented to allow the shared access to data, supporting the communities that deal with geographic datasets through a modern distributed architecture that is both powerful and cheap. It is as a catalogue of metadata, indexing different geo-services and spatially referenced resources hosted by different societies. Using this free software (distributed with GPL license) it is possible to improve data access, integrate different spatial data and easily share geographically referenced thematic information between different organizations, since it is a catalog of location-oriented information. The GeoNetwork architecture and protocols are based on standards, offering a spatial information management environment designed to enable access to georeferenced datasets, cartographic products and related metadata from a variety of sources, using the capabilities of Internet. Using standard protocols (e.g., OGC CSW, OAI-PMH, OpenSearch, Z39.50, RDF), it both accesses remote catalogs and makes its data available to other catalog services, completely embracing the five star principles proposed by Tim Berner Lee for Linked Open Data (https://www.w3.org/DesignIssues/LinkedData.html), even if you can also choose to use it as a stand-alone product. GeoNetwork is a cross-platform software that works on any server that is able to run a Java web container (e.g., Tomcat, JBoss) since it is distributed in a WAR (Web Application aRchives) file, making it completely independent from the operating system. Main advantages of using this software, in addition to the previously cited standardization of formats, are that the GeoNetwork could be seen as a single point of access to all georeferenced data. Several related tools are packaged with GeoNetwork, including GeoServer, which is normally associated to the GeoNetwork platform in order to store the data and to create an SDI. The GeoServer is a web mapping server for the dissemination of GD. GeoServer is a FOSS server written entirely in Java that allows users to store, view and edit geospatial data. Designed for interoperability, it publishes data from any major spatial data source using open standards. With GeoServer, it is possible to display spatial information using the Internet. Implementing the Web Map Service (WMS) [27] standard (or even its extension with time series support, WMS-T), GeoServer can create maps in many output formats. OpenLayers, a free mapping library, is integrated into GeoServer, making map generation quick and easy. GeoServer also conforms to the Web Feature Service (WFS) [28] standard, which permits the actual sharing and editing of the data that is used to generate the maps, letting others to incorporate your data into their website and applications with greater transparency. Among other standard protocols, it also supports Web Coverage Service (WCS) [29], Web Processing Service (WPS) and Catalog Services for the Web (CSW), just to cite main ones. In our project, GeoServer could be thought of as a store for the raw data, with accurate publishing and visualization features, while the GeoNetwork can be seen as a catalogue that helps understanding the information stored and presented by the GeoServer.

4. Dataset Component

To analyze the landslide behavior of the AOI, we employed a wide spectrum of in-situ and remote sensing instruments and sensors to monitor surface and deep-seated deformation of the considered active geomorphological processes.

Generally, the short-term analysis of surface movements is obtained through quantitative or semiquantitative analysis of three-dimensional topographic data and high accuracy measurements, obtained by exploiting different monitoring techniques. The analysis of surface movements is primarily carried out by traditional field monitoring systems: (i) robotized total station (RTS) [30]; (ii) global navigation satellite system (GNSS) [31]; (iii) extensometer [32]; (iv) inclinometer [33]. All these instruments provide measurements with high temporal sampling (daily/hourly), useful for the reconstruction of the evolution of single phenomena over time [24].

Alongside, remote sensing techniques such as DInSAR [15–17] are used to process the huge archive of SAR images continuously acquired by radar satellites constellation (e.g., ERS-1/2, Envisat ASAR, Radarsat). The most recent constellations (e.g., Cosmo-SkyMed, Sentinel-1A and Sentinel-1B) also improve capabilities in terms of resolution and revisit time. The application of these techniques allows obtaining a wide-area coverage (thousands of km^2) and millimetric-accuracy time series.

The in-situ GD are mainly vector and text files, consisting of monitoring network information relative to specific activation and/or reactivation of a landslide, acquired by expert researchers of the National Research Council of Italy. Time series are characterized by limited temporal acquisition, usually during the emergency phases, with high temporal sampling and high accuracy, provided in comma-separated values (CSV) format.

The satellite GD products are both raster and vector files, consisting of mean velocity deformation maps, with distinct spatial and temporal resolution derived from the adopted radar sensors. The data source varies from internal data and previous project results to a fresh SAR data processing, taking advantage of the ESA G-POS free service [25] based on the parallel-SBAS technique [34]. The derived time series have monthly sampling and a precision of few millimeters, always provided in CSV format.

5. Data and Metadata Hierarchical Structure

All the data hosted in the dataset are associated with semi-automatically-compiled metadata. In order to join different phenomena distributed in mountainous regions in the world that include multisensor acquisitions from multiple sources, a structural metadata archive is implemented. A hierarchical structure is developed, where any element of the chain depends on the element from which it derives. This dependency is based on a logical link named "Parent/Child" link (Figure 3). All information always follows the same logical sequence:

- Test site;
- Instrument and/or sensor;
- Raw data.

This means that, frequently, in the first two levels of the structure we have mainly metadata (information on the site and the sensors adopted) and only some time we have raw data (i.e., a shape file of the full site) while, in the last layer, we have always both data and metadata (i.e., time series and information on them).

Besides the hierarchical structure, metadata uses a specific format that has to be filled in. The metadata format is made of specific fields like abstract, keywords, purposes, constraints on data, lineage and responsibility (creator, point of contact, distributor). In order to validate the metadata published in the GeoNetwork catalogue, the metadata follow the ISO19115 standard (INfrastructure for SPatial InfoRmation in Europe—INSPIRE directives). Throughout the time, updates are possible if metadata are modified or new data are added.

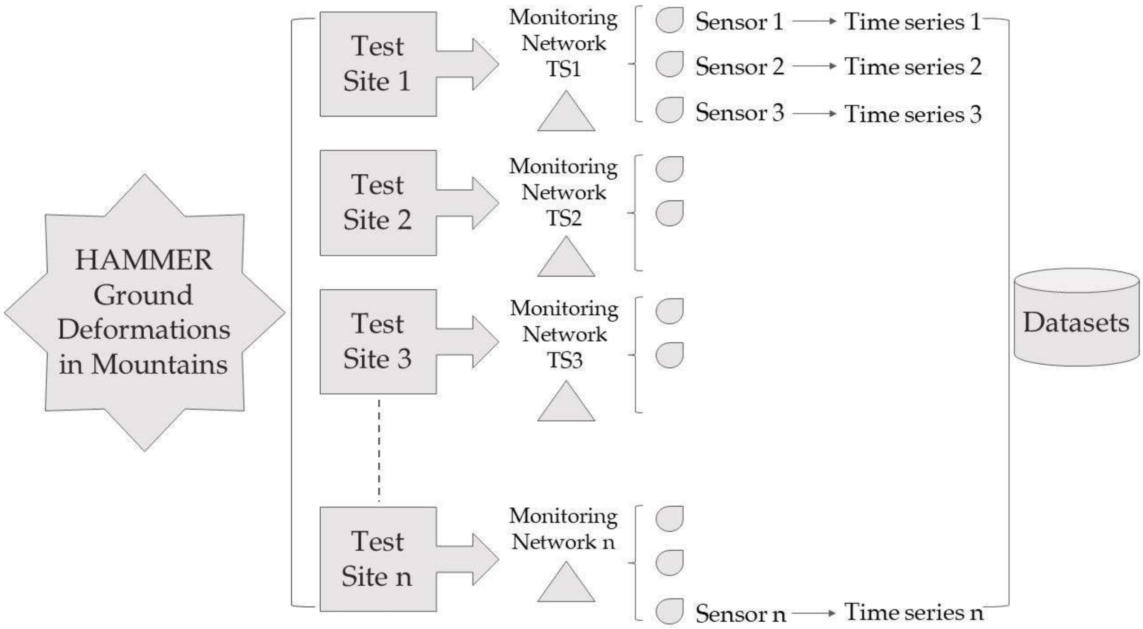

Figure 3. Data and metadata hierarchy structure with Parent/Child link, following the reiterated pattern "Test site (rectangular box)—Instrument/Sensor (triangles)—Raw Data (drops)".

6. H-SDI GeoNetwork Web Interface

The implemented H-SDI in GeoNetwork consists of three main services, all obtained exploiting native features of the platform:

- Data querying service;
- Data analysis service;
- Data visualization service.

This interface guarantees an open data format that is freely and widely available to the scientific community and to any users. The dissemination data are published using a standard format, such as CSV and TXT files while, for the geospatial vector data, the use of shape format (e.g., SHP, SHX or DBF) is recommended. This is very useful to exploit and visualize data in a geographic information system (GIS), for the data publication in a web mapping software and/or for sharing it using web services (WMS, WFS and WCS).

6.1. Data Querying Service

An advanced system of data querying allows users to access information through multivariable queries. The data search is divided in two principal domains "Metadata" and "Dataset". Choosing the metadata domain, the user can query the metadata available for the collected data and measures relative to mountainous regions selected (Figure 4). This selection can be done based on different criteria such as keywords, title, geographic coordinated, time and so on, showing the data location on an interactive map.

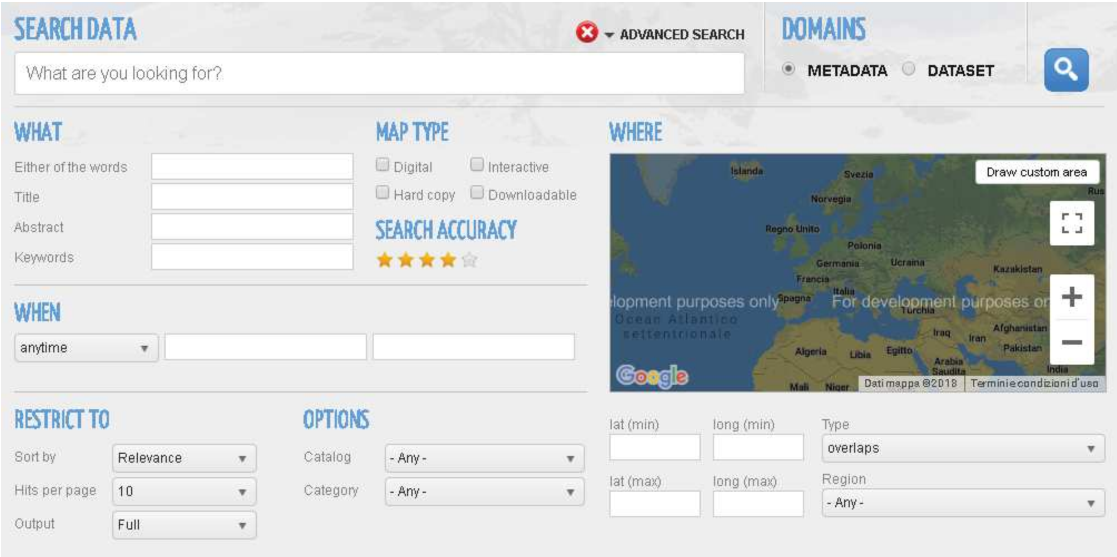

Figure 4. Web-interface data query [35].

Choosing the dataset domain, instead, the interface has a sequential activation of the fields, starting from the selection in the "Dataset" field, followed by "Data provider", "Location", "Parameter" and "Reference time", guiding the user in the data selection based upon spatial and temporal criteria. Three possible output of the data search are available: (i) table; (ii) plot; (iii) CSV file. Therefore, the user can obtain results in tabular and graphical format, choosing site, instrument and time period.

6.2. Data Analysis Service

The GeoNetwork web interface gives the opportunity to the users to analyze and acquire collected data from the H-SDI. As we said previously, two distinct domains for visualizing and analyzing the dataset are available: (i) dataset and (ii) metadata of dataset. Both domains are linked to the web mapping features offered by GeoServer to visualize vector and raster data in WMS format.

The information we manage in out H-SDI is about seven different study areas distributed in mountain regions (see Table 1). The majority of the test sites focus on landslides affecting urban areas in the Alpines, Apennines and Pyrenees chains. Only in the case of the Salar de Atacama, the uplift in correspondence of the Salars has been analyzed.

In the Italian test sites (see Table 1), the observation instrumentation includes an in-situ monitoring network, used in the past by the CNR IRPI in the framework of other scientific projects. The monitoring networks include the Grange Orgiera and Gardiola topographic network (RTS) [22,23], the Montaldo di Cosola automated inclinometer system (AIS) [24] and the Ivancich inclinometer system [18]. The instruments aim to characterize the slope instability of the study area, generating ground deformation time-series for a limited time span. Based upon the employed instruments, the time series have a different structure.

Usually, the topographic network time-series reports, for each prism of the network, the east, north and elevation coordinates and the differential and total displacement, with an hourly/daily acquisition range.

Inclinometers probe tilt for two orthogonal axes conventionally named "A" and "B". In particular, they read a measure corresponding to the axes inclination (θ), returning the graph of the cumulative displacement computed by the sum of the incremental displacements. Figure 5 shows an example of inclinometer data representation, relative to one of the Ivancich inclinometers' cumulative displacement [18].

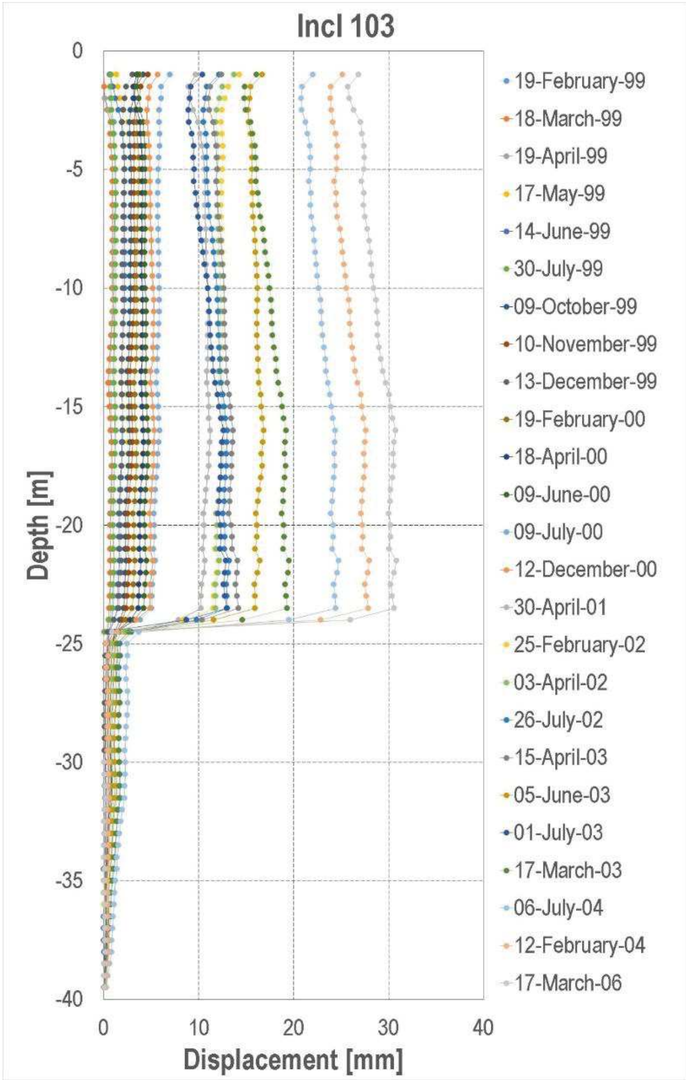

Figure 5. Ivancich landslide inclinometer data (I103). Inclinometer displacements refer to the ground level (cumulative displacement).

In the case of SAR data, several satellites have been considered, including ERS-1/2, Envisat ASAR and Cosmo-SkyMed. The output of SAR data processing, in addition to the ground deformation time-series, also includes other information, such as: (i) geocoded coordinates; (ii) coherence; (iii) mean velocity; and (iv) standard deviation. Several SAR data were already available from previous projects, as in the case of the Pyrenees and Central Apennines test sites. Instead, in the Salar de Atacama, Grange Orgiera and Aosta Valley Region case studies, new SAR data-processing has been carried out from scratch, taking advantage of the ESA G-POD service [25,36], based on the parallel-SBAS chain [34].

All the technical information relevant to the employed instrument and/or sensors, as well as the description of the surface deformation measurements, are largely reported in the metadata abstract. Most of the data are available as a free download and can be represented by graphs directly in the GeoNetwork portal (Figure 6).

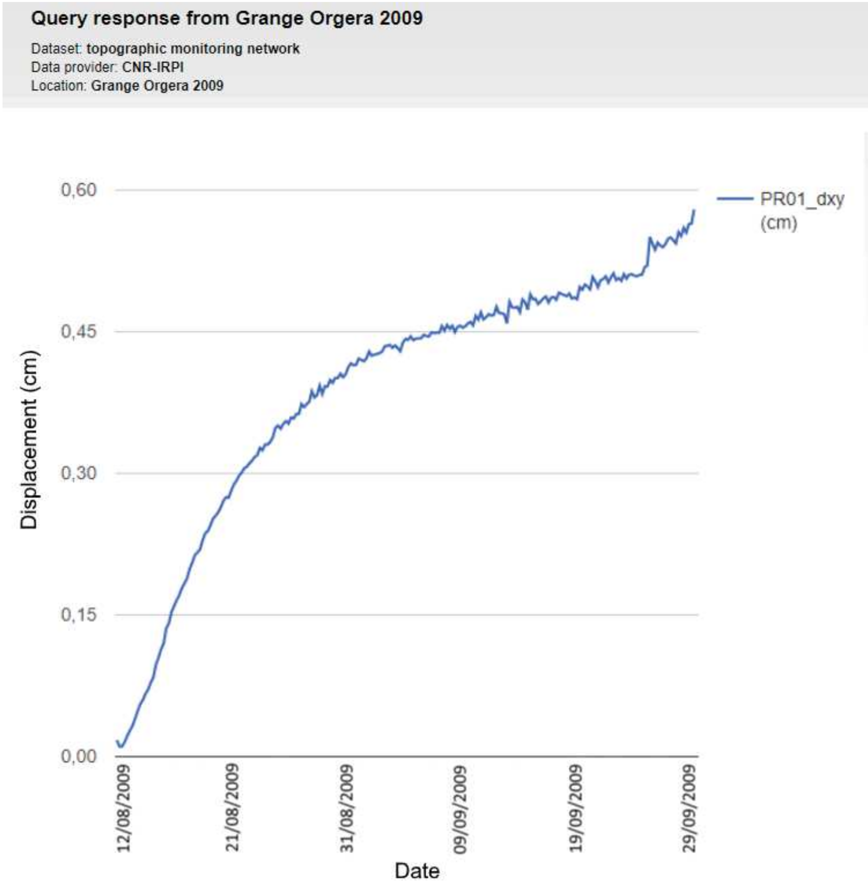

Figure 6. Example of planimetric ground deformation time-series graph (dxy), relative to the prism PR01 belonging to the Grange Orgiera topographic network.

The catalogue of metadata of the dataset follows the Parent/Child link hierarchy, where the project metadata are the upper hierarchical unit (Figure 7). The first series of metadata refers to the seven selected study areas, connected to monitoring network/sensor metadata and, in their turn, with the raw data. In some cases, more than one monitoring network metadata are connected with a single test site (e.g., Grange Orgiera, Ivancich), and consequently more raw data metadata are available.

Here are show all 40 metadata that constitutes the H-SDI. Each element of this hierarchy contains all the information required by INSPIRE metadata regulation, with some common characteristics, such as the point of contact, inherited from the upper level of the hierarchy. Moreover, each metadata configuration in the web interface of the GeoNetwork has buttons linked to (i) dataset; (ii) keywords; (iii) KML file; and (iv) XML information (Figure 8). This versatility is a powerful feature of the GeoNetwork platform, allowing the user to choose between many download and visualization formats. The metadata can be also downloaded in XML format.

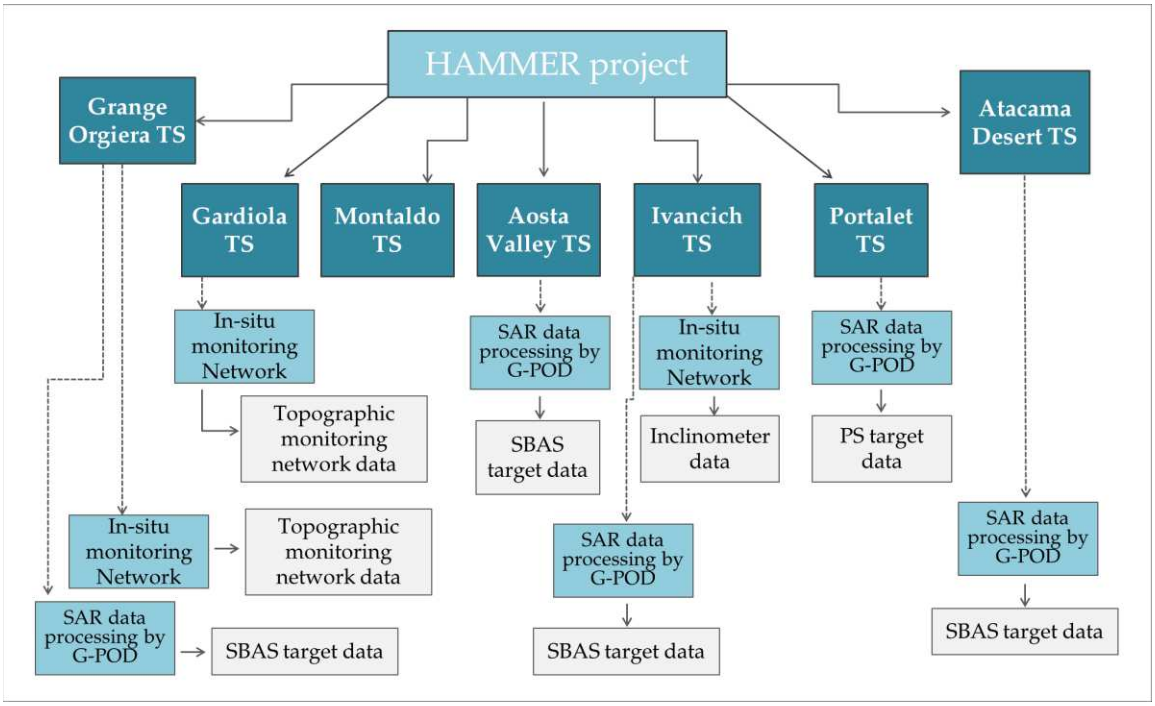

Figure 7. H-SDI metadata hierarchy scheme based on "Parent/Child" links; in dark blue are the test sites of the Hammer project; in blue are the available sensors and/or in situ instruments for each test site; in light grey are the raw data of ground deformation measurements.

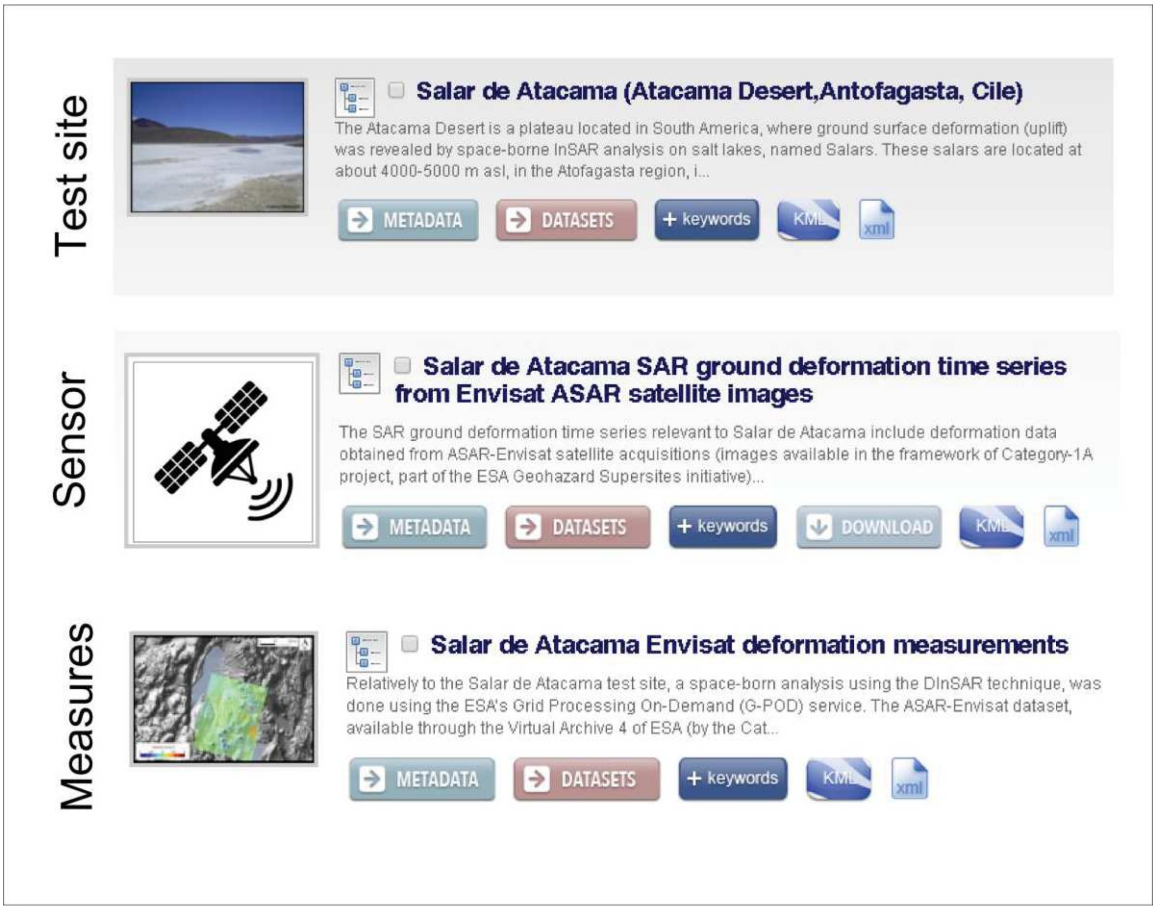

Figure 8. Metadata configuration in the H-SDI GeoNetwork platform relative to the Salar de Atacama test site.

6.3. Data Visualization Service

Data visualization is possible with the adoption of the previously described GeoServer that is integrated in the GeoNetwork. With this software, it is possible to publish and edit geo-referred information on the web. Data can be stored into common relational/spatial datasets or file systems and exported as a web service. Many clients could use those services. Some visualization tools are integrated in the GeoServer software (i.e., a fresh installation comes with OpenLayers libraries and a web mapping interface to preview the data loaded into the system), others could be chosen by the final users thanks to the adoption of standard protocols and formats defined by the Open Geospatial Consortium (OGC). i.e., WMS, WFS, WCS. As an example, GeoServer can display data on any of the popular mapping applications, such as Google Maps, Google Earth, Yahoo Maps, and Microsoft Virtual Earth (Figure 9). Moreover, GeoServer can connect with traditional GIS architectures such as Earth ArcGIS and QGIS (Figure 10). This flexibility makes GeoServer interoperable with many different platforms, making it one of the best FOSS for data visualization (Figure 11).

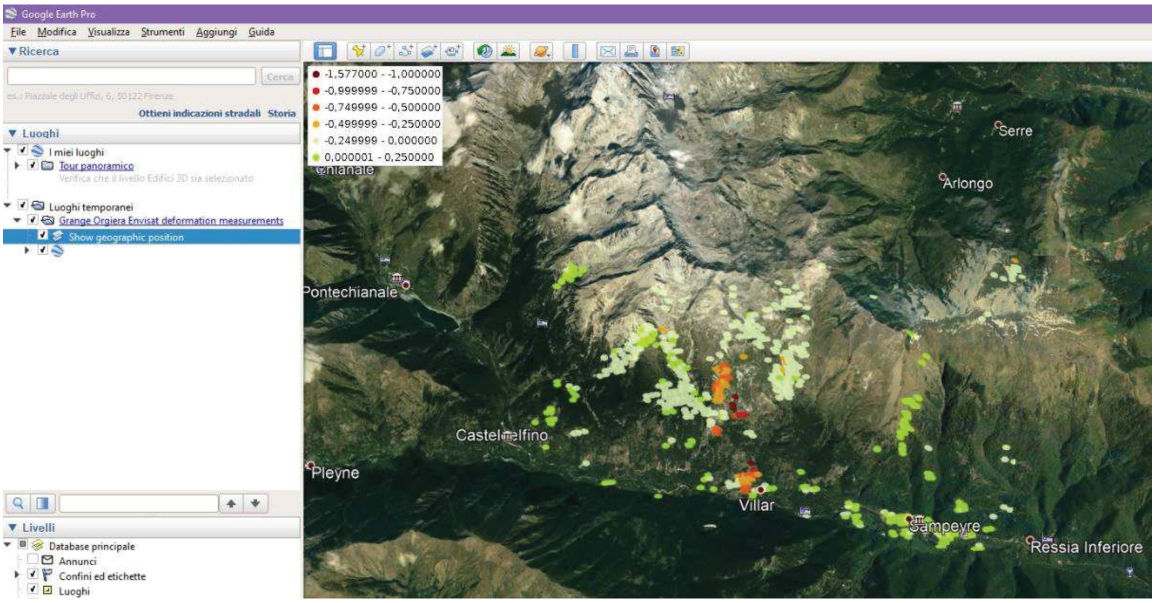

Figure 9. SBAS targets visualization in KML format on Google Earth for the Grange Orgiera test site.

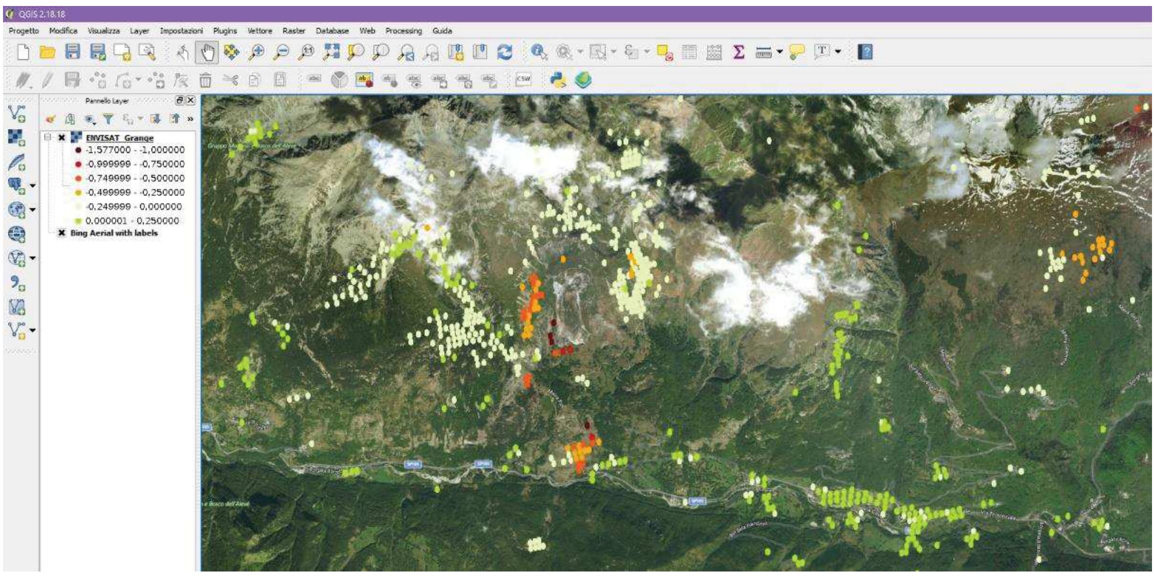

Figure 10. QGIS platform connected to the WMS offered by the GeoServer showing Grange Orgiera SBAS targets.

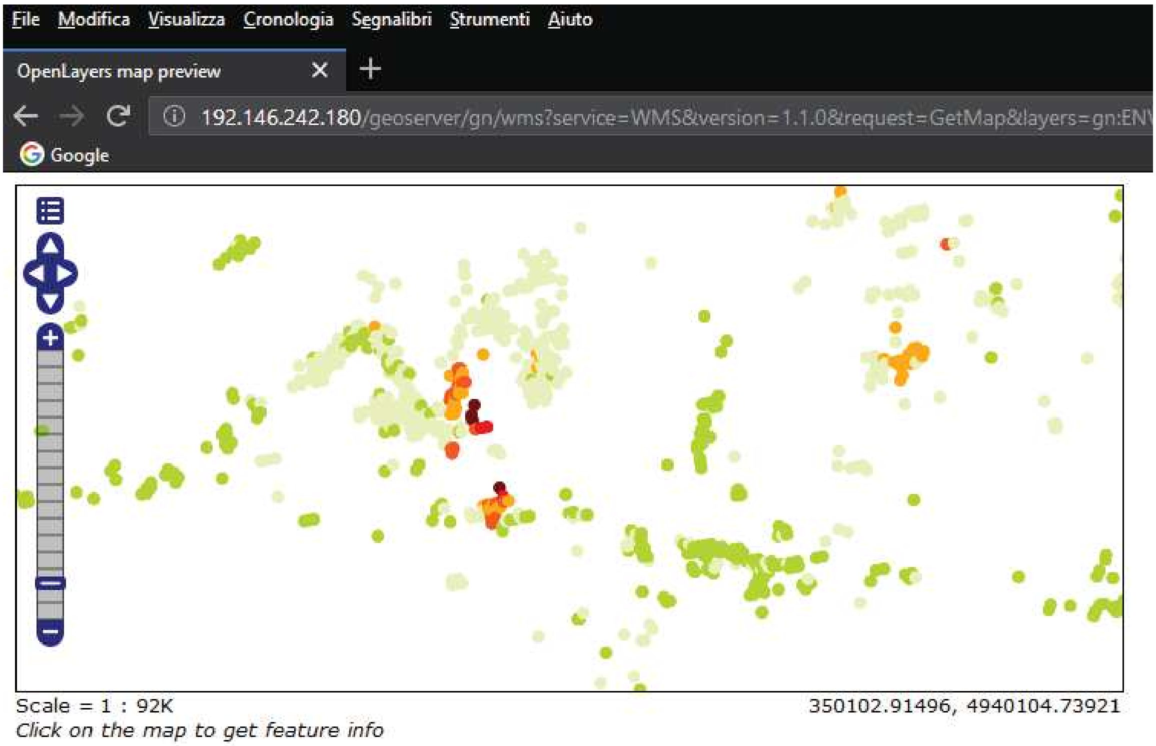

Figure 11. OpenLayers preview of the SBAS targets of the Grange Orgiera test site.

7. Discussion

Cataloguing wide, multisource and heterogeneous geospatial data, published at the same time with a metadata link, has become an ever more common practice, especially for scientific project results management [12,26,37,38]. The problem becomes more complex with the generation of archives to investigate geo-hydrological processes and to assess their behavior; this increasingly demands the use of multisource and heterogeneous data acquisition and efficient tools and software.

Our SDI has been defined inside a framework based on institutional arrangements and technologies, with specific policies on metadata and data sharing and use. This guarantees the sharing and the effective utilization of geographic information, exploiting standard formats and protocols, focusing in particular on the accessibility and the interoperability. Moreover, with the employment of an SDI, different users can access, retrieve and disseminate spatial data in a friendly and secure way.

The presented work attempts to show an effective approach to catalogue heterogeneous geospatial data and metadata, acquired by the observation of different geo-hydrological processes, all located in mountainous environment of different geographic and physiographic settings. A great effort has been made to meet the demand of cataloguing high elevation environmental data and metadata in an integrated platform. This has been done both to effectively access postprocessed data (as usually happens) and to supply the original raw data acquired by in-situ and satellite sensors.

Frequently, many national and international projects exploit open-source GIS software, such as PostGIS and PostgreSQL for a WebGIS design [11,39], to provide to public users a practical data sharing and mapping service. With respect to these ones, an important additional feature is represented by the data association with metadata. Software as GeoNetwork and GeoNode appear more complete in this sense, providing a valid technology compliant with the internationally recognized standards (e.g., OGC) to improve managing, sharing and also analyzing data and metadata in a unique way [7,40]. A great added value is also represented by the possibility of producing graphs of the raw data, allowing an in-depth analysis of the collected measurements.

Here we focused on the exploitation of the GeoNetwork open-source software to provide an integrated platform to gain access to the data resulting from the HAMMER project. This software guarantees a solid basis and has been slightly modified and customized according to the project needs. Main modifications, besides the one to the front-end GUI, are related to the structure of the link between metadata and raw data.

The H-SDI is structured to collect multisource, multisensor geospatial data and measurement of high-altitude environments, following the specification of the main project (NextData). The test sites cover areas with different extensions (from local to regional scale) that are characterized by different geo-hydrological processes (e.g., landslide, uplift) and analyzed by different in-situ instruments and/or by satellite sensors. Overall, the ground deformation measurements cover wide time periods, up to decades, freely providing exceptionally long time series to everyone. Currently, all the project data are stored inside a single-node GeoServer (located in Turin, Italy) or a dedicated file server (hosted in Pisa, Italy). The whole GeoNetwork is also hosted inside a single-node server but, as a good practice, we are planning the strengthening all our infrastructure by adopting a redundant solution.

Taking advantage of the GeoNetwork platform, we were able to provide multiple services:

- Dataset management and advanced structure of data query of multisource information aimed to collect and analyze ground deformation time-series both from in-situ and remote sensing observation measurements;
- Metadata catalogue linked with the dataset, with a hierarchical structure based on "Parent/Child" structure, validated in accordance to the ISO19115 standard;
- Web mapping features used to collect the georeferenced data obtained within the project, supported by a dedicated GeoServer.

By exploiting the GeoNetwork, we achieve a monitoring data management structure, with free access, relevant to active geomorphological processes, that commonly is not made available to users and usually treated as private data. The resulting system can be easily exploited following the open data principles resulting in an architecture that could be used by third parties and customized for different needs, even for those users not familiar with using such kinds of data. Scientific users and other stakeholders can discover the predisposed web-portal and explore processed and validated data, including the use of the web mapping features. This guarantees the availability of well-prepared geospatial time-series for environmental and climatic investigation, partially overcoming the challenge for a nonexpert user to process the data independently. In our case, the added value is the availability of both processed and validated data with raw data (always in CSV or other standard formats), stored and managed on a standard platform, as requested by the main project directives. Moreover, taking advantage of a geographic information system such as QGIS, the user may simply link or download the collected data in order to portray it on a georeferenced map (Figure 12a). In this way, any user can analyze and independently process data acquired both in-situ and by remote sensing measurements, obtained by expert geologists and engineers, and generate plots for a specific area of interest (Figure 12b). By exploiting in-situ measurements and radar sensor acquisitions, every stakeholder can access the raw data in order to reprocess any single ground deformation time-series, by applying the same reference parameters or by modifying them, if required.

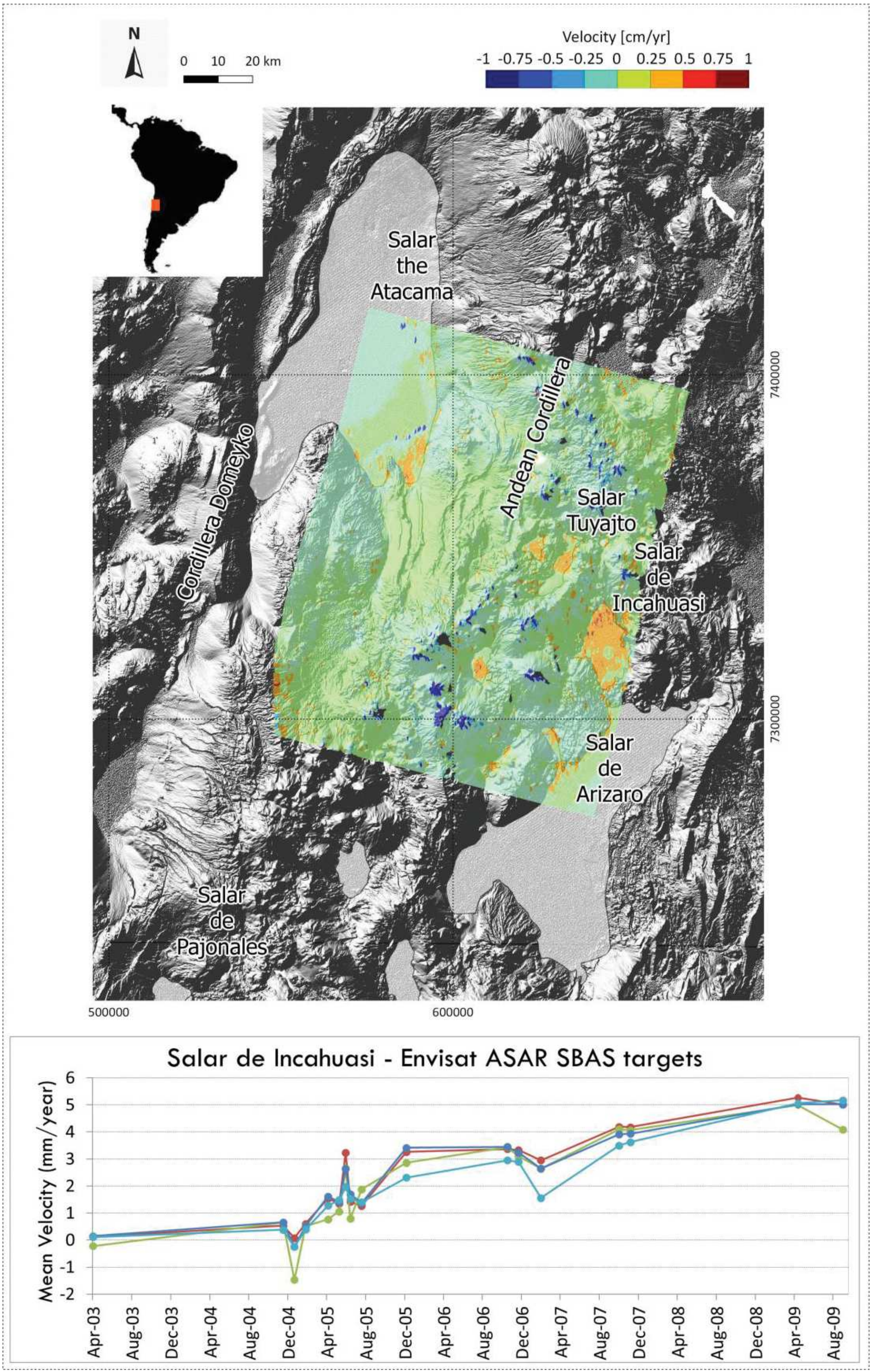

Figure 12. Example of data usage: (**a**) map of the SBAS targets, processed by G-POD, generated in GIS environment for the Salar de Atacama test site; (**b**) plot of the ground deformation time-series relative to some SBAS target of the Salar de Incauasi, located in the Salar de Atacama AOI.

The employment of GeoNetwork guarantees a structure in accordance with internationally recognized standards, useful for sharing data in the scientific community. This platform ensures an easy way of reading, downloading and browsing interactively any single resource of the H-SDI by expert users and stakeholders. We decided to avoid any particular restrictions to access the information, and the data are freely downloadable, with only one minor exception to this that is covered by an intellectual property right. Instead, only authenticated users can create, import or edit data and metadata included in the platform.

Another important aspect is the possibility of analyzing, managing and sharing multiple datasets with a single instrument, allowing the exploitation of validated data mainly related to landslides and ground deformation analysis distributed in high mountain regions.

Currently, after a project remodulation, we did a migration from the previous GeoNetwork to a new one; this migration has been made in collaboration with the Institute of Geosciences and Georesources of the National Research Council (CNR-IGG). The employment of GeoNetwork guarantees the adoption of recognized standards, essential for sharing data in the scientific community, allowing the creation, management and analysis of huge amounts of information, composed by a multisource heterogeneous database and time series, easily adaptable for managing large amounts of data from both national and European projects.

8. Conclusions

The H-SDI was made to meet the demand of collecting, managing and sharing the HAMMER project data and metadata, in order to improve the knowledge of geo-hydrological processes occurring in high mountain regions. This information is focused on the test sites selected for the project that are inserted into a main project, aimed to share environmental and climatic data. The HAMMER data, related to hard-to-reach areas of high mountains (e.g., Andes, Western Alps), are acquired, collected and processed by expert geologists and engineers from in-situ monitoring networks and satellite sensors. The access to a collection of preprocessed and validated ground deformation measurements, as well as the related information of instruments and sensors used to acquired them, is the most important added value that this project is giving to the scientific community and other stakeholders.

Taking advantage of the combined use of GeoServer with a partially customized GeoNetwork, we could jointly organize in-situ measurements and satellite sensor observations related to the project test sites distributed in the Alpines, Apennines, Pyrenees and Andes chains, focusing on active landslides. In this way, we propose an infrastructure totally based on free software and internationally recognized standards, following the main project directives. We provided a valuable instrument to manage, collect, visualize and share multisource and multisensor data, that could be downloaded and exploited by anyone, including the uncommon possibility of reprocessing the raw data for other purposes and in other contexts.

Through the adoption of such software, it is possible to develop other platforms aimed to facilitate the convergence of multisource and multisensor information, following recognized policies for the access management and allowing the re-use of data even in other strategic projects. Moreover, it is important to underline that the adoption of open data principles enables the exploitation of the information contained inside the system in both research and industrial fields.

Author Contributions: Conceptualization, Martina Cignetti, Francesca Ardizzone and Daniele Giordan; Data curation, Diego Guenzi and Paolo Allasia; Formal analysis, Paolo Allasia; Funding acquisition, Francesca Ardizzone; Methodology, Martina Cignetti, Francesca Ardizzone and Daniele Giordan; Project administration, Francesca Ardizzone; Resources, Francesca Ardizzone; Software, Diego Guenzi; Supervision, Francesca Ardizzone, Paolo Allasia and Daniele Giordan; Writing – original draft, Martina Cignetti and Diego Guenzi; Writing – review & editing, Martina Cignetti and Diego Guenzi. All authors have read and agreed to the published version of the manuscript.

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4

Shallow landslide

Shallow landslides are rainfall-induced landslides triggered by high-intensity and short duration rainfalls, or precipitation of medium-intensity and high duration. This type of landslide affects small thickness (less than 2-3 m), involving slopes with impermeable bedrock and shallow permeable layer (Caine, 1980). Despite the small volume, due to high velocity and high-impact forces of these phenomena, strongly conditioned by morphological and geological settings, recurrent casualties and damage are described in the literature (Borga et al., 2004; Galve et al., 2015; Tarolli et al., 2013). After a meteorological alert, released as a result of heavy rainfall occurrence, a shallow landslide inventory constitutes a reliable instrument to define the distribution, type and patterns in relation to morphological, geological and land use setting, and also related to anthropic elements distribution. This provides the primary data for better awareness of the potential interrelationships between shallow landslides occurrence and natural and human land use characteristics. By exploiting a territory highly characterized by shallow landslides as the Liguria Region one (northwester Italy), in the Phase I of the reiterated structure proposed in the thesis (Figure 4.1), a dedicated landslide inventory of the rainfall-induced landslides occurred in Autumn 2014 rainfall events (Faccini et al., 2015), developed in previous research project within the GMG group (Giordan et al., 2017b) (Appendix B), has been exploited. The results of this research have been published in a scientific paper immediately before the start of the PhD research, for this reason the paper is not included in the thesis papers. However, the paper is annexed in the Appendix B. Leveraging on a very high-resolution LiDAR survey, carried out by the CNR IRPI of Turin, an event map and an in-depth analysis of the relationships between shallow landslides occurrence and a human-made environment, as the Liguria one, was available. Previous data availability primarily consists of a shallow landslide inventory relating to the areas most affected by the Autumn 2014 rainfall events and its analysis, have formed a sound knowledge base for the subsequent studies.

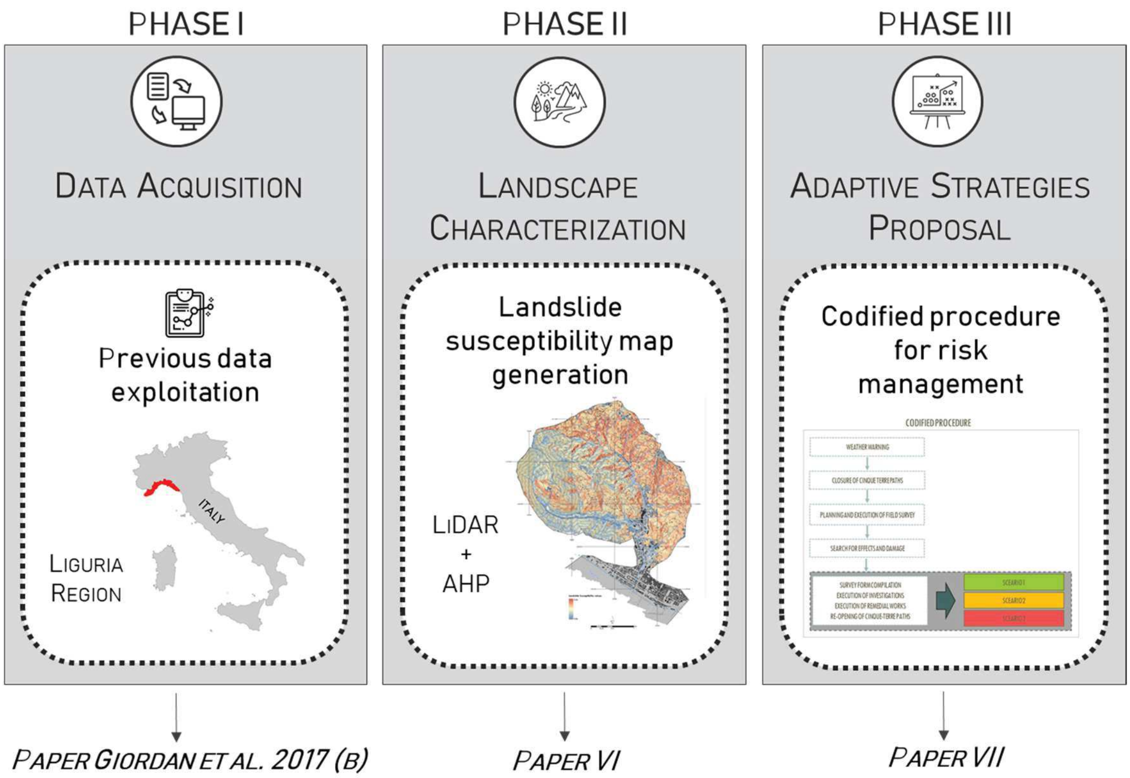

Figure 4.1 – Reiterated structured proposed for the shallow landslide typology.

This first stage constituted the preliminary step toward landslide susceptibility definition, whit a focus on high-human modified landscape, like the Ligurian one. Considering this aspect, Phase II focused on landscape characterization and the shallow landslides susceptibility map generation, by exploiting the available high-resolution Lidar survey and applying the Analytic Hierarchy Processes of Saaty (1977). In particular, a shallow landslide susceptibility map of a small catchment within the Chiavari municipality (northwestern Italy, Liguria, La Spezia province), almost entirely occupied by anthropic terraces (*i.e.* anthropic element highly widespread in the Liguria territory, for agricultural practices) has been computed. The landscape characterization obtained with the definition of those areas more susceptible to landsliding represents a useful source for landslide risk assessment and land use planning management. The generation of landslide susceptibility map, based on a highly anthropized territory as the Liguria Region one, by applying the AHP method has presented in *Paper VI*.

In steep-slope mountainous territory highly affected by rainfall-induced landslides, an effective slope instability risk management, represents a great challenge, specifically for the policy-makers. In particular, in those touristic areas with significant cultural and geological heritage (*e.g.* UNESCO sites), the identification of the potential impacts of the newly or existing landslides, and the implementation of a dedicated procedure for the identification of rainfall-induced landslides and related damage should represent an effective response in landslide risk management, specifically in the phases of an emergency.

The Phase III consisted in the improvement of a dedicated codified procedure, based on the combined use of the Operative Monographies and Survey Forms, to slope instabilities identification, characterization and relative impact evaluation, useful for decision-makers in land use planning, and in particular in the emergency and post-emergency phases. Leverage on a renowned UNESCO site as the Cinque Terre National Park (Liguria, northwestern Italy), the non-structural measure for landslide risk mitigation, represented by a standardised procedure for a suitable and sustainable administration of the territory, as well as to schedule the appropriate management measures to guarantee the safeguard of human life and landscape, has presented in *Paper VII*.

The full version of the published scientific papers is available below.

Paper VI: Cignetti, M., Godone, D., Giordan, D. (2019) *Shallow landslide susceptibility, Rupinaro catchment, Liguria (Northwestern Italy)*. Journal of Maps, **15(2)**, 333-345. DOI: 10.1080/17445647.2019.1593252

Paper VII: Giordan, D., Cignetti, M., Godone, D., Peruccacci, S., Raso, E., Pepe, G., Calcaterra, D., Cevasco, A., Firpo, M., Scarpellini, P., Gnone, M. (2020) *A new procedure for an effective management of geo-hydrological risks across the "Sentiero Verde-Azzurro" trail, Cinque Terre National Park, Liguria (north-western Italy)*. Sustainability, **12(2)**, 561. DOI: 10.3390/su12020561

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Shallow landslide susceptibility, Rupinaro catchment, Liguria (northwestern Italy)

Martina Cignetti [a,b], Danilo Godone [a] and Daniele Giordan [a]

[a]National Research Council, Research Institute for Geo-Hydrological Protection, Turin, Italy; [b]Department of Earth Sciences, University of Pavia, Pavia, Italy

ABSTRACT
The shallow landslides assessment is a hard task in territories featuring composite influence of natural and anthropic factors. In Liguria region (northwestern Italy), the landscape presents widespread human intervention prevalently represented by terraces. The assessment of predisposing factors in such landscape deserve a multidisciplinary approach. We implemented a classification methodology based on the Analytical Hierarchy Process. In GIS environment we overlaid several layers: (i) slope, (ii) land use, (iii) lithology, and (iv) aspect. Slope and aspect have been computed on a filtered (based on TPI) high-resolution DTM with the removal of terraces, in order to obtain the pristine slope pattern. Each spatial data was then reclassified according to the weighting procedures thus producing a landslide susceptibility map. This methodology represents a starting point for the correct assessment of shallow landslides occurrence, capable to generate a map, taking in account of the peculiar features of this extremely man-made territory.

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High-resolution digital terrain model; analytic hierarchy process; anthropic terraces; topographic position index

1. Introduction

Shallow landslides constitute a widespread phenomenon in Liguria region (northwestern Italy) mostly due to the unique combination of steep slope and heavy rainfall, enhanced by human interferences.

Hillslope morphology of the Ligurian hinterland, characterized by catchments with limited extension, high relief that abrupt descent to the coastline makes it particularly susceptible to shallow landslides and flash floods (Brandolini, Faccini, Robbiano, & Terranova, 2008; Faccini, Luino, Sacchini, Turconi, & De Graff, 2015). This setting, associated with modification on land use, leads to an increase on landslides occurrence (Brandolini et al., 2018; Bruschi et al., 2013; Glade, 2003; Lasanta-Martínez, Vicente-Serrano, & Cuadrat-Prats, 2005). In this region, human intervention represented noteworthy morphogenetic impact. The current landscape is the result of a long-term land use history, arising from the extensive building of terraces, already in the Middle Ages, and their level of maintenance work over time (Brancucci & Paliaga, 2006; Cevasco, Pepe, & Brandolini, 2014; Tarolli, Preti, & Romano, 2014).

In this strongly human-influenced environment, with high socio-cultural heritage, the mitigation of landslides hazard become a crucial issue in risk management and in land-use planning. Landslide hazard is defined as the probability of occurrence of a potentially damaging phenomenon within a given area and in a given period of time (Varnes, 1984). In the Ligurian territory, due to numerous natural and human-induced environmental factors (e.g. topography, geology, land cover), the assessment of the shallow landslides occurrence it is not a simple issue. The use of landslide susceptibility maps gives information on the potential areas that are landslide-prone, identifying the most probable initiation areas, on the basis of local terrain condition (Brabb, 1984; Corominas et al., 2014), and states the degree to which a territory can be affected by future slope failure (Guzzetti, Carrara, Cardinali, & Reichenbach, 1999). Furthermore, in some cases, landslide susceptibility zonation is extended in order to cover areas from which landslides may travel on to or regress into the area being zoned (Fell et al., 2008).

Our study aims to assess the landslide susceptibility of a hilly-mountainous highly human-influenced areas, using a semi-quantitative index-based method. This method is the Analytic Hierarchy Process (AHP), developed by Saaty (1977), able to organize and analyze multi-criteria decisions. This is highly useful in landslide susceptibility analysis that depends on a multiple-knowledge of all the causative factors in landslides occurrence (Kayastha, Dhital, & De Smedt, 2013; Thanh & Smedt, 2012; Yalcin, 2008).

At the base of landslides susceptibility computation, there is the selection of thematic variables. In literature, various factors are employed, considering diverse geo-lithological, morphological, land use aspects. We

CONTACT Danilo Godone danilo.godone@irpi.cnr.it National Research Council, Research Institute for Geo-Hydrological Protection, 73 Strada delle Cacce, Turin, Italy

specifically take care of morphological variables considered relevant in susceptibility model assessment (Reichenbach et al., 2018), and in our case affected by human impact. The Ligurian landscape brings with it widespread anthropic geometrical elements represented by terraces. These features strongly modify the natural morphometric aspect, constituting a forcing able to create a misleading effect affecting the topographic variables. High-resolution Digital Terrain Model (HR-DTM) usage are highly recommended (Corominas et al., 2014), since the smaller a cellsize is, the more have enough resolution to support slope stability characterization and provide adequate quality on the input data. The availability of an HR-DTM should be considered an added value, but poses also new issues relative to the landslide susceptibility map computation concerning the proper exploitation of such dataset. Conversely, previous susceptibility models have been generated using only medium or low-resolution DTMs, approximating the effective terrain profile (Persichillo et al., 2016). In a complex environment as a terraced area (Tarolli, Calligaro, Cazorzi, & Dalla Fontana, 2013), the effectiveness of an HR-DTM become evident. In this paper, we leverage on a very HR-DTM with 25 cm cellsize available in an area strongly human modified in last centuries with the construction of anthropic terraces. To properly consider the effect of terraces on morphometric aspect definition, we developed and tested an *ad hoc* filtering procedure based on the TPI index (Tagil & Jenness, 2008). The presented methodology is based on the use of open source Geographic Information System (e.g. QGIS), and statistical programming languages (e.g. R), which facilitate the computation of these variables and the generation of susceptibility maps (Carrara, Guzzetti, Cardinali, & Reichenbach, 1999; Chacon, Irigaray, Fernández, & Hamdouni, 2006; Van Westen, 2004).

The considered case study is a shallow landslides prone area of the Liguria region (northwestern Italy), corresponding to a small coastal basin named Rupinaro catchment. During the autumn 2014, this area was affected by a series of intense rainfall events, causing numerous shallow landslides inventoried in Giordan, Cignetti, Baldo, and Godone (2017), leveraging a very high-resolution digital terrain model from LiDAR survey. The availability of an adequate dataset of previous landslides and the event map related to the flood of 2014 make this basin a perfect test site for the application of the proposed methodology. In this work, we operated as follow: (i) analysis of the causative factors leveraging on the HR-DTM and on-field survey observation; (ii) computation of frequency analysis of the regional inventoried landslide (Trigila, Iadanza, & Spizzichino, 2008) in order to define the relation between the selected variables and landslides occurrence; (iii) implementation of a morphometric filtering of the DTM by the TPI method, in order to estimate the higher loyal landscape pattern, taking account of anthropic terraces; (iv) application of the AHP method computing the weights for each variable and relative classes, and finally (v) comparison and validation of the obtained susceptible map with previous inventoried landslides.

2. Study area

The Rupinaro catchment is a small coastal basin (11 km^2) of the Liguria region (northwestern Italy), within Chiavari municipality. The topographic relief of the catchment ranges from 547 m (Mt. Anchetta) elevation above sea level (Figure 1). The whole of the landscape is occupied by hills and mountains with a very steep slope, surrounding restricted flat areas. Generally, high acclivity and the proximity to the coastline reflect the typical tectonic setting of the Ligurian Apennines, with short channels with low-hydrographic order and high erosive action (Brancucci & Paliaga, 2006). Slope never exceed 45 –50° except for limited sectors, and aspect is prevalently south-southwest faces. Land use reflects a deeply human-influenced landscape, primarily represented by centuries-old anthropic terraces, entailing the creation of flat areas for farming. These structures consist of dry-stone walls, covering about 40% of the catchment (Godone, Giordan, & Baldo, 2018).

From a geological point of view, the study area is entirely within the Northern Apennines flysch succession (Marroni et al., 2002; Molli et al., 2010). The outcrop geological formation passes through the *Mt. Antola Unit*, constitute by the *Mt. Antola Limenstones*, to the *Mt. Gottero Unit*, constitute by the *Slates of Mt. Verzi*, the *Manganese rich Shales* and *Palombini Clays*. The Mt. Antola Limestones is localized in the western part of the basin, along the right side of the Rio Campodonico, tributary of the Rupinaro Stream. This unit prevalently consists of a turbiditic succession of marly limestone, and subordinated shales and slate (Scholle, 1971). The Manganese rich Shales, together with the Slates of Mt. Verzi, lie in the majority of the catchment. The Manganese rich Shales prevalently outcrops along the main stream axis, and consists of dark shales with intercalation of thick siltstones and calcarenites. The Slates of Mt. Verzi mainly lie in the left side of the Rio Campodonico, consisting of dark slates and marl (Marroni, Della Croce, & Meccheri, 1988). In the eastern sector of the basin, outcrops the *Palombini Clay* of the Giacopiane Lake, composed by an alternation of shales and siliceous limestones (Van Wamel, 1987).

2.1. Thematic data

For landslides susceptibility map generation, one of the most important element is the availability of past

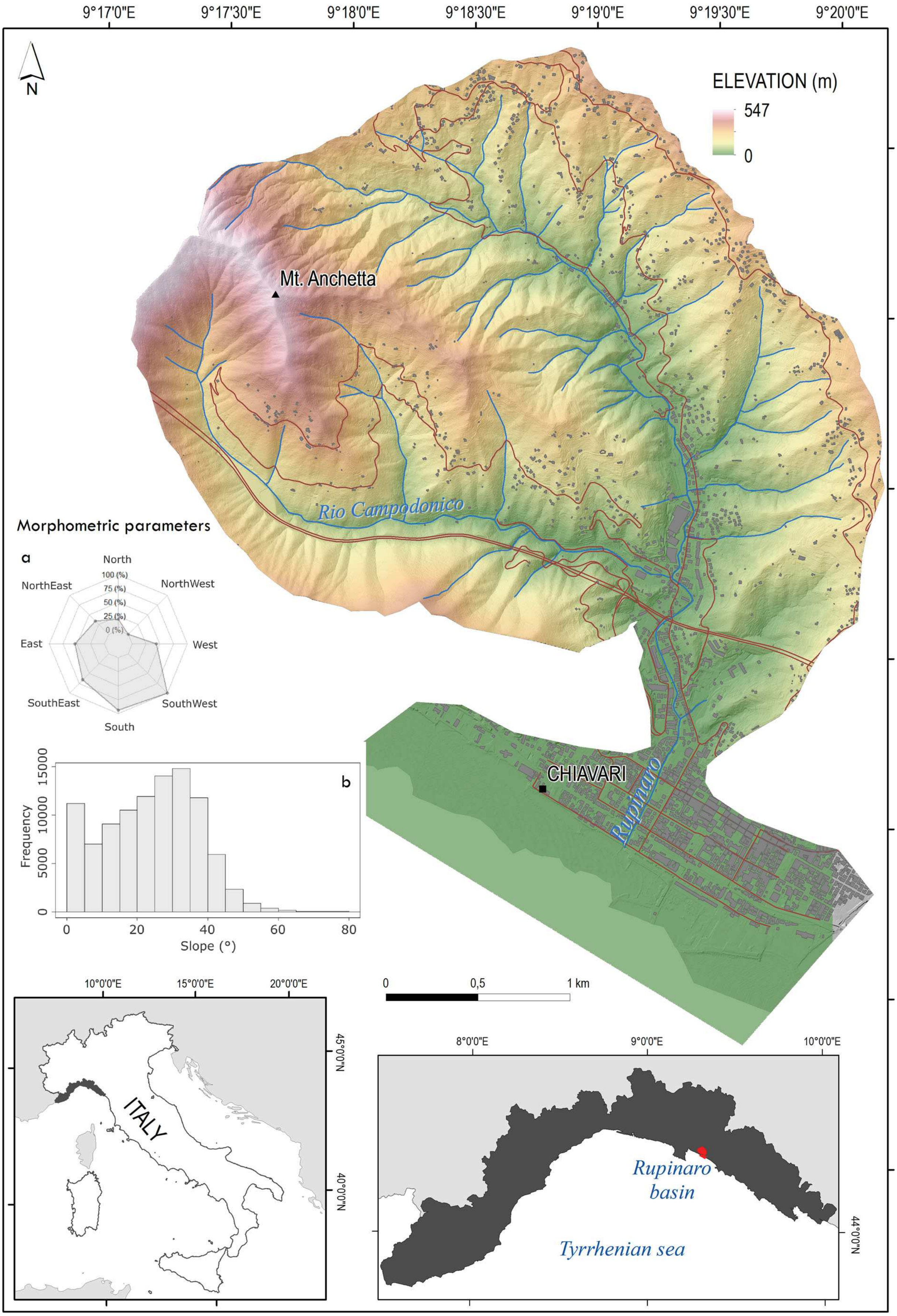

Figure 1. Relief terrain of the Rupinaro catchment, located in the eastern Liguria region (northwestern Italy): (a) aspect and (b) slope morphometric parameters.

landslides inventory. For the Rupinaro basin, two different inventories are available and employed in this work; (i) the National Landslide Inventory, achieved in the IFFI project (Trigila et al., 2008); (ii) the landslides inventory of the autumn 2014 rainfall event (Giordan et al., 2017).

The landslides inventoried in IFFI for the Rupinaro basin are in total 43, constituted by rainfall-induced landslides of limited size. Relative to the landslides inventoried in 2014, the study area has been hit by a series of rainstorm events occurred during the autumn of 2014 (Cevasco, Pepe, Avanzi, & Giannecchini, 2015; Silvestro, Rebora, Giannoni, Cavallo, & Ferraris, 2016). Specifically, in the 9–13th November, the Rupinaro catchment was affected by a prolonged rainfall with local rainstorm events, up to 100 mm per 3 h. The intense and prolonged rainfall generated the Rupinaro Stream flooding, triggered many shallow landslides and causing considerable damages and two casualties. After rainfall events, an helicopterborne LiDAR survey, coupled to photogrammetric acquisition of the damaged area was carried out by CNR IRPI.

The LiDAR data provided a means to identify all the rainfall-induced landslides, by exploiting its derivative products. The occurred phenomena have been mapped by a visual analysis methodology, employed combing high-resolution Digital Terrain Model (HR-DTM) and orthoimages (Giordan et al., 2017). Simultaneously, in the post-event phase, a field survey has been executed to define the main characteristics of the occurred phenomena. A total of 110 landslides have been inventoried (Figure 2). Landslides were

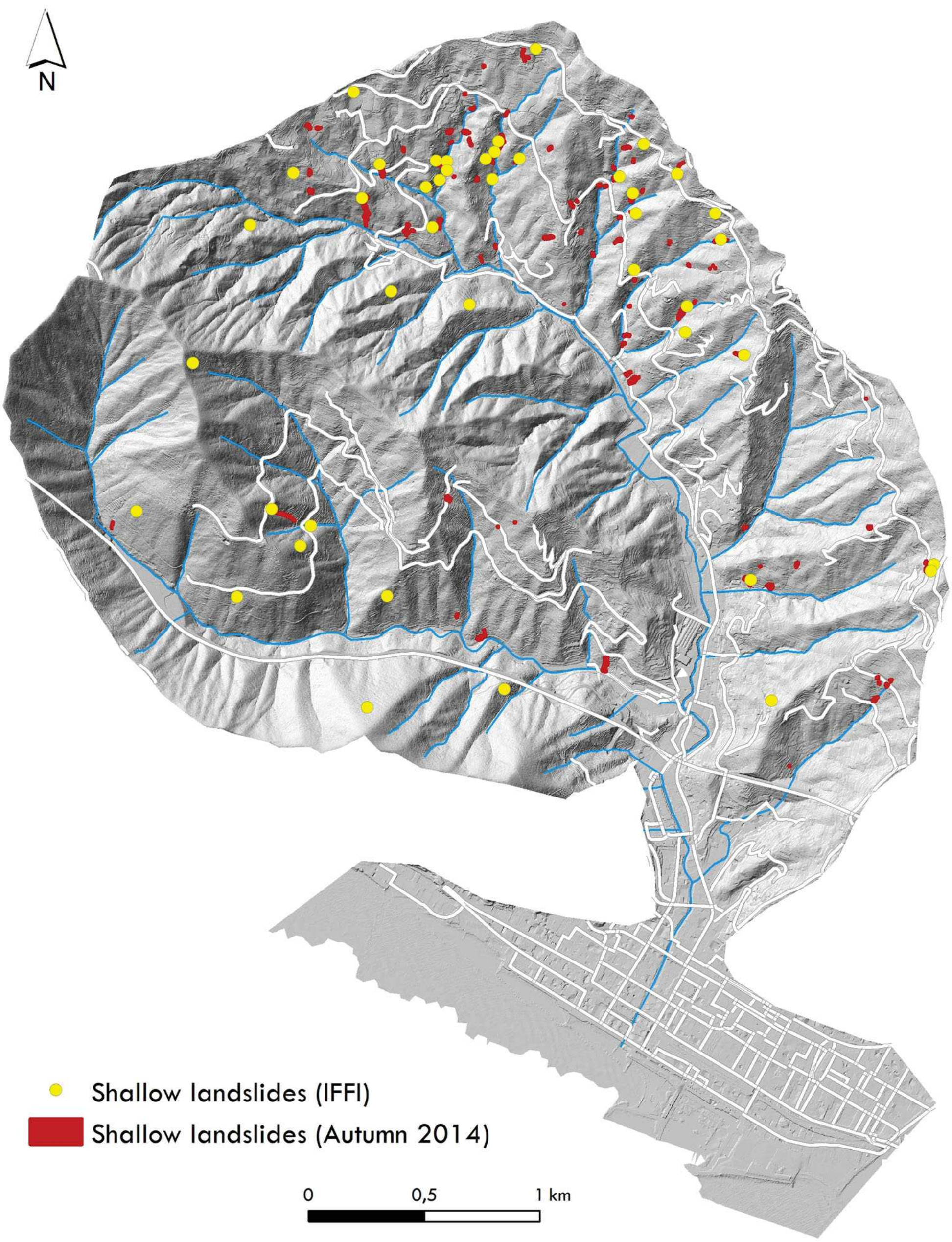

Figure 2. Inventory map of the IFFI (Trigila et al., 2008) and autumn of 2014 rainfall-induced landslides, affecting the Rupinaro catchment. The shaded relief derived from the high-resolution DTM obtained from the post-event LiDAR survey.

Table 1. LiDAR survey parameters.

Parameter	Value
Sensor	RIEGL LMS-Q680i
Vehicle	Eurocopter AS 350
Survey date	Jan 2015
Point density	4 and 9 points/m^2
DTM cellsize	25 cm
Orthoimage ground resolution	15 cm/pixel
Horizontal datum	ETRF2000 UTM zone 32N
Vertical datum	EGM2008

classified according to Cruden and Varnes (1996). All the phenomena correspond to shallow landslides, including soil slips, debris flows and debris avalanches, with size varying from less than 10 m^2 to more than 1000 m^2.

The LiDAR survey of 2014 was planned and realized considering the possibility to acquire a high-resolution dataset that could be used both for landslides mapping, and for a more detailed analysis of the anthropic terraces and slope instability relationship. For this reason the survey was performed acquiring high-density points (Table 1) in a period of the year when coverage of vegetation was limited (Giordan et al., 2017; Godone et al., 2018).

3. Methods

The methodology for landslide susceptibility map generation is structured according to the workflow showed in Figure 3. The methodology is structured in three phases:

(1) definition of variables influencing shallow landslides initiation;
(2) data preparation;
(3) analytical Hierarchy Process application.

3.1. Considered variables for landslide susceptibility estimation

An analysis of the causal factor is performed to define the main variables that influence the shallow landslides triggering in the study area. The selection of the parameters that influence landslides in susceptibility mapping do not have general guidelines. Usually, the causal factors selection is highly dependent on the characteristic of the study area and data availability. We based the variables selection on a comprehensive bibliography research, added to LiDAR data processing and field campaign carried out after the autumn 2014 rainfall events. Many authors, focusing their studies on different area among the Liguria region, analyzed the relationship between rainfall-induced landslides and factors such as land use, geology, soil properties, slope (Cevasco et al., 2014; Crosta, Dal Negro, & Frattini, 2003). In our case most relevant are the variables derived from HR-DTM that have a significant degree of affinity with landslides (Giordan et al., 2017), taking also into consideration the presence of terraces, such as (i) slope; (ii) aspect; (iii) land use, and (iv) lithology.

3.2. Data preparation

The availability of HR-DTM allowed to work with a detailed representation of the studied area. Morphometric and topographic layers are derived from the described HR-DTM, by the employment of GIS tools.

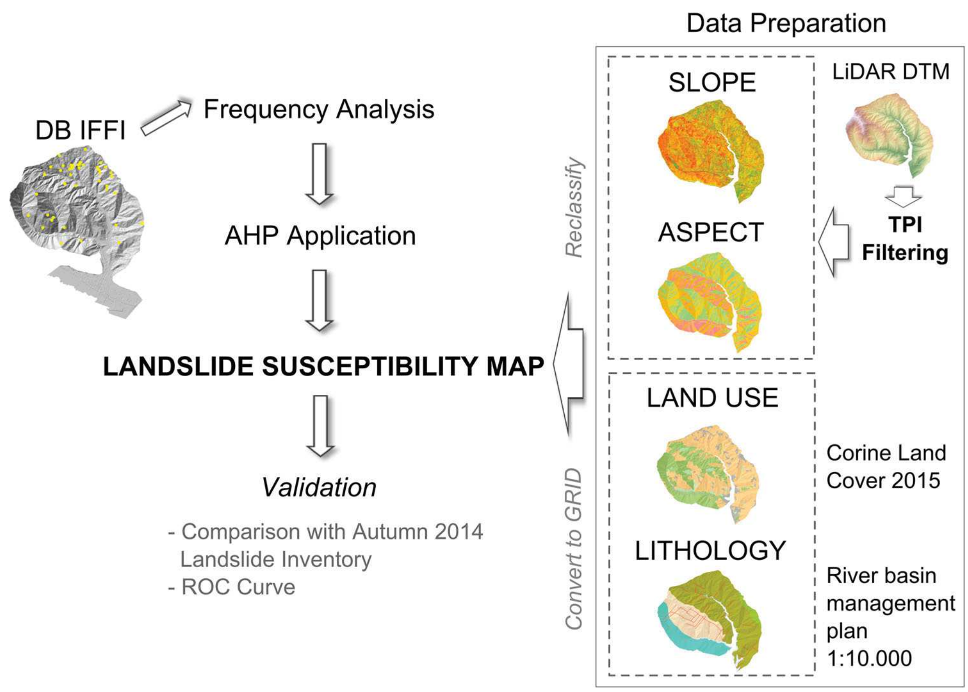

Figure 3. Scheme of the adopted methodology.

Taking into account the anthropic variable of this area, an *ad hoc* filtering procedure is created, based on the TPI index. Instead, the geological and land use maps are derived from the general land-use plan (Regione Liguria, 2017) and the web-portal of the Liguria region (Regione Liguria, 2016) both at scale 1:10.000.

In parallel, we carry out a frequency analysis of the inventoried landslides, within the National Landslide Inventory (IFFI, Trigila et al., 2008) in order to analyze the relationships between occurred landslides respect to the considered variables for landslide susceptibility computation. This step intends to strengthen the AHP usage, particularly in the allocation of the weights of each considered factors. The availability of two different datasets of landslides inventory (i.e. IFFI and Autumn 2014 events) are useful for the calibration (IFFI) and validation (Autumn 2014 events) of the presented susceptibility model.

3.2.1. TPI index-based filtering process

During data preparation, we operate a filtering on the HR-DTM, before computing slope and aspect layers. Several published researches have estimated the susceptibility map based on a low-resolution or resampled DTM (e.g. 5 m/10 m resolution) and from already existing topographic database (Ayalew & Yamagishi, 2005; Lee, Ryu, Won, & Park, 2004; Persichillo et al., 2016). Using this approach, relevant information of the ground pattern could be lost, particularly in a strong man-made modified landscape as in the case study. In our case, the HR-DTM clearly depicts the topographic pattern. Also, the anthropic terraces (average height of walls = 2 m), which cover an area of about 40% of the Rupinaro basin (Godone et al., 2018), are visible. It is important to note that shallow landslides commonly have a failure surface, which arises within soil or in correspondence of soil-bedrock interface (Beguería, 2006; Borrelli, Ciurleo, & Gullà, 2018). On the widespread terraced landscape, as the Rupinaro one, field observations highlight how shallow landslides mainly occurred in correspondence of the lower portion of the dry-stone walls. Considering, both theory and field observation, we decide to remove these anthropic features, by DTM filtering, in order to ensure, as far as possible, a realistic detection of landslide-prone areas. The Topographic Position Index (TPI) is computed to spot ridges (positive TPI values) and valley (negative TPI values) (Tagil & Jenness, 2008); in our case study, to spot wall bases and tops. The obtained raster layer is then queried by extracting only the minimum value (< 1^{th} percentile), with the aim to pointing out riverbeds and terraces wall bases. The filtered layer is then employed as a mask to extract DTM cells intersecting the described land features and interpolated again in a *terrace free* DTM.

3.2.2. Slope and aspect

Topographic information have a relevant role in landslide hazard analysis. In particular, slope represents one of the most relevant factors in shallow landslide occurrence (Lee & Min, 2001). Considering that the slope factor is directly related to the landslides, it is frequently used in preparing landslide susceptibility maps, by applying a variable number in slope gradient subdivision (Bui, Lofman, Revhaug, & Dick, 2011; Calvello & Ciurleo, 2016; Clerici, Perego, Tellini, & Vescovi, 2002; Wu et al., 2016; Yalcin, 2008).

The availability of HR-DTM represents a useful instrument to derive these information. In the study area, the slope is affected by a geometric forcing constituted by the dry-stone walls of anthropic terraces. The availability of very HR-DTM points out clearly the presence of these features. The distribution of slope classes is strongly influenced by the presence of these elements that can affect the result of the model. By the TPI filtering, we obtain a terrain profile filtered by these geometric elements, by removing the disturbance produced by terraces. Totally, five slope classes have been set up for the Rupinaro catchment case study: (i) less than 15°; (ii) 15–25°; (iii) 25–35°; (iv) 35–45°; (v) more than 45°.

Aspect is recognized as one of landslide conditioning factors and generally considered in the assessment of landslides susceptibility (Dai, Lee, & Ngai, 2002; Guzzetti et al., 1999). It has an effect on solar and rainfall exposure, thereafter on soil moisture and degree of saturation, which may influence the distribution and density of landslides occurrence (Eger & Hweitt, 2008; Yalcin, 2008). In literature, a linkage between aspect angle and soil formation and evolution has been observed, with a major correspondence in south-facing slopes (Sidari, Ronzello, Vecchio, & Muscolo, 2008; Stanchi, Freppaz, Godone, & Zanini, 2013). For this reason, we considered three aspect classes divide in north, south and east/west orientation indistinctly.

3.2.3. Land use

Land use, together with morphological factor, strongly conditioned rainfall-induced landslides initiation (Dai, Lee, Tham, Ng, & Shum, 2004; Galve, Cevasco, Brandolini, & Soldati, 2015). In accordance with the literature (Dai, Lee, Li, & Xu, 2001; Greenway, 1987), an improvement in slope stability, in terms of vegetation cover, should be linked to deep-rooting plants and to a soil moisture reduction by evapotranspiration.

Land use map of the Rupinaro catchment has derived from the vector data available from the geoportal of Liguria region (Regione Liguria, 2016), at 1:10.000 scale. Three classes of land use were generated for this area. We grouped all the urbanized areas, inclusive of road and rail network, industrial, commercial and public unit, in a unique class 'Artificial areas'.

All the cultivated sectors have been grouped in the class 'Agricultural areas', consisted primarily of 'Non-irrigated arable land', 'Pasture', 'Olive groves' and 'Complex cultivation patterns'. Instead, all those sectors with scattered vegetation and scrubs and wooded sectors have been included in the class 'Forest'.

3.2.4. Lithology

Lithology plays a relevant role in slope stability. As already described, bedrock of the Rupinaro catchment mainly belong to the Gottero Unit, and in the south-eastern part to the Antola Unit. Lithological data were available by the general land-use plan (Regione Liguria, 2017), at 1:10.000 scale. At the basin scale, more than half territory belong to an impervious bedrock mainly consisting of shales and/or shale associated to marl. Instead a bedrock permeable for fracturing has been recognized in the marginal southeast portion of the study area (Regione Liguria, 2017). Three classes have been set: (i) shGOT, corresponding to *Manganese rich Shales* and *Palombini Clay*, impervious bedrock, (ii) shmGOT, corresponding to *Slates Mt. Verzi*, impervious bedrock and (iii) mlFMA, corresponding to *Mt. Antola Limestones* permeable for fracturing.

3.3. Analytic hierarchy process

The data preparation allows to extract the all considered variables in a grid format, in order to apply the Analytic Hierarchy Process (AHP).

The application of this method requires the division of a composite problem and the organization of its factors in a hierarchic order. Once the hierarchy is structured, a numerical value (Table 2) is associated to the considered elements. These numerical values are based on subjective judgments on the relative importance of each factor. Therefore, the judgments are synthesized to determine the priorities to be assigned to these factors. Finally, a pair-wise comparison matrix is set up, and the normalized principal eigenvector is computed giving the weight of each factor (Saaty & Vargas, 2012).

Table 2. Scale of preference between two parameters in AHP (Saaty, 1977).

Scales	Degree of preferences	Explanation
1	Equally	Two factors contribute equally to the objective
3	Moderately	Experience and judgment slightly to moderately favor one factor over another
5	Strongly	Experience and judgment strongly or essentially favor one factor over another
7	Very strongly	A factor is strongly favored over another and its dominance is showed in practice
9	Extremely	The evidence of favoring one factor over another is of the highest degree possible of an affirmation
2,4,6,8	Intermediate	Used to represent compromises between the preferences in weights 1, 3, 5, 7 and 9
Reciproclas	Opposites	Used for inverse comparison

Notes: If the factors have direct relationship the scale ranging from 1 to 9, while if there is an in verse relationship the scale vary from 1/2 and 1/9.

In the proposed methodology we computed a frequency analysis to collect information concerning the relationship between occurred shallow landslides, as reported in landslide national inventory (Trigila et al., 2008) and the selected causal factors of the Rupinaro catchment. This procedure allows to allocate weights to the various conditioning factor classes, for AHP, in a less subjective manner.

In this study, such as in other previous works (Thanh & Smedt, 2012; Yalcin, 2008; Yalcin, Reis, Aydinoglu & Yomralioglu, 2011), the AHP approach is applied to assign weights to causative factors by pair-wise comparison and to classes within each factor, too. The comparison matrix of the four identified causative factors is reported in Table 3, together with their respective comparison matrix. All the pair-wise comparison matrices were structured ranking the established items with respect to their impact on slope instability. The normalized principal eigenvector matrix of each factor is calculated by a statistical opens source environment (R Development Core Team , 2011) and reported in Table 3. In order to verify the consistency of the weights and ratings, the consistency index (CI) was applied, calculated by (Saaty, 2000)

$$CI = \frac{\lambda_{max} - N}{N - 1} \tag{1}$$

where λ_{max} is the largest eigenvalue and N is its size, corresponding to the number of parameters. Next,

Table 3. Pair-wise comparison matrix and normalized principal eigenvector for landslide causative factors and for the classes within each factor, as required for applying the AHP method.

Causative factors and factor classes	Pair-wise comparison matrix [1]	[2]	[3]	[4]	[5]	Normalized principal eigenvector
Causative factors						
[1] Slope	1	2	5	6		0.52
[2] Land Use		1	4	2		0.26
[3] Lithology			1	1/3		0.07
[4] Aspect				1		0.14
Slope						
[1] 0–15°	1	1	1/4	1/5	3	0.10
[2] 15–25°		1	1/3	1/4	3	0.11
[3] 25–35°			1	1/2	5	0.29
[4] 35–45°				1	6	0.44
[5] 45–90°					1	0.05
Land use						
[1] Agricultural areas	1	5	9			0.75
[2] Forest		1	3			0.18
[3] Artificial areas			1			0.07
Lithology						
[1] shGOT	1	9	8			0.80
[2] shmGOT		1	1/2			0.08
[3] mlFMA			1			0.12
Aspect						
[1] 315–45°	1	1/6	1/5			0.08
[2] 45–135/225–315°		1	2			0.58
[3] 135–225°			1			0.34

the consistency index is compared to a random consistency index RI. The RI values were reported in Saaty (1977) as a function of N, and allows to calculate a consistency ratio CR, defined as

$$CR = \frac{CI}{RI} \times 100\% \quad (2)$$

When the consistency ratio is larger than 10% the subjective judgment in the pair-wise comparison is inconsistent and needs to be revised.

In view of factor weights determined by the AHP method a landslide susceptibility map was generated. We operated in GIS environment by the reclassification and rasterization of all the considered thematic layers. Applying a procedure based on the weighted linear sum (WLS), the combination of the causative factors and their classes was obtained, defining a landslide susceptibility index (LSI)

$$LSI = \sum_{j=1}^{N} W_j w_{ij} \quad (3)$$

where W_j is the weight value of causative factor j, w_{ij} the weight value of class i in causative factor j, and N the number of considered causative factors.

4. Results and validation

By applying the AHP method, we obtained the Landslides Susceptibility map of the Rupinaro basin (Main Map). The pair-wise comparison matrix was structured using four causative factors ranked in term of their impact on slope instability, also justified by the frequency analysis based on the IFFI national inventory analysis (Trigila et al., 2008). The normalized principal eigenvector of each comparison matrix portrays the presences applied in the hierarchic order, both between causative factors and between the classes of each causative factors (Table 3). For the study area, the slope factor corresponds to the most relevant considered variable getting the highest weight of 0.52, followed by the land use factor weighting 0.26. Table 4 reports the Consistency Ration (CR), calculated on the basis of the relative values of Consistency Index (CI) and Random consistency index (RI). These parameters confirm the consistency of the weights and rating of each considered causative factors. The resulting Landslide Susceptibility map presents LSI value ranging from 0.06 to 0.56. LSI values are then classified by manual classification according to Oztekin and Topal (2005) (Figure 4). Totally four classes resulting: (i) low, (ii) medium, (iii) high, and (iv) very high. The 'high' LSI values cover most of the analyzed territory (43%), principally distributed in the northern and eastern portions of the basin. 'Moderate' values occupy the 28% of the Rupinaro basin, whereas the 'very high' and 'low' classes respectively have 12.5% and 16.5% of the basin (Figure 4(a)).

Table 4. Consistency index (CI), random consistency index (RI) and consistency ratio (CR) values for the causative factors considered.

Factors	Number	CI	RI	CR
Causative factors	4	0.05	0.9	0.05
Slope	5	0.03	1.12	0.03
Land use	3	0.01	0.58	0.025
Lithology	3	0.02	0.58	0.03
Aspect	3	0.015	0.58	0.025

In the case of Rupinaro catchment, consideration has been done to the long-term history of human impacts, primarily represented by anthropic terraces. These structures are widely distributed in the Rupinaro catchment (Godone et al., 2018), constituting a sensitive element in slope stability, mainly in respect of their level of maintenance (Arnáez, Lana-Renault, Lasanta, Ruiz-Flaño, & Castroviejo, 2015; García-Ruiz & Lana-Renault, 2011; Koulouri & Giourga, 2007; Tarolli et al., 2014). This landscape brings with it anthropic geometrical elements, with an average size of 2 m in height and some tens of meters in length. In this way, those features deeply modify the natural terrain profile, constituting a forcing able to create a misleading effect in landslides susceptibility computation. As highlighted in literature (Corominas et al., 2014; Reichenbach et al., 2018), HR-DTM usage in morphometric variables computation allows to improve the susceptibility map generation. Even more in the case of the deeply human affected profile terrain of the Rupinaro catchment, distinguishing and extrapolating the terraces geometry. Thanks to the HR-DTM availability, and applying the TPI filtering, we remove the disturbance, due to the dry-stone walls of the anthropic terraces, on slope and aspect computation obtaining a homogeneous layer, that describes a terrain without terraces.

A verification of the obtained result has been done on the basis of prior landslides inventory. Specifically, we employed the available data relative to the landslides inventory of the autumn 2014 rainfall events (Giordan et al., 2017). The mapped landslides correspond to 110 shallow landslides. Considering the source area, the inventoried landslides prevalently occurred in the slope classes of 25 –35° and 35 –45°, respectively the 41% and the 28%, presenting east–west and south exposure. The highest number of landslide occurred on agricultural areas (more than 90%), particularly in correspondence of olive groves, in connection with an impervious bedrock mainly consisting of shales and shales associated to marl. In the Rupinaro basin, this crop typically lies with terraced areas. By field observation and DTM derivative products analysis, we have found that, in most cases (approximately 80%), the source area of the inventoried landslides fells in correspondence of the dry-stone walls bases. The overall quality of the landslide susceptibility map

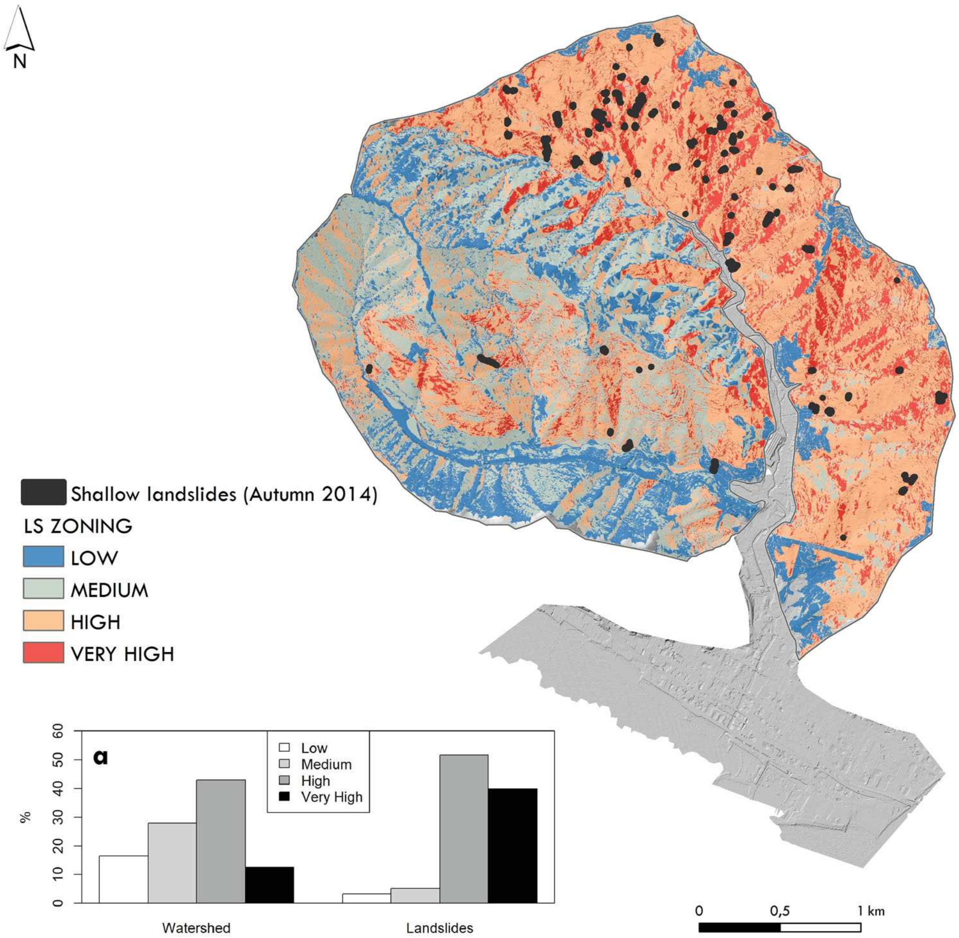

Figure 4. Landslide susceptibility zonation map of the Rupinaro catchment; dark gray polygons correspond to the shallow landslides occurred during the autumn 2014 rainfall events. (a) Histogram of percentage values of basin areas and landslide areas in the four susceptibility classes.

is confirmed by the inventoried landslides areas distribution in the four respective LSI classes (Figure 4(a)). Observing landslides distribution the 52% fall within 'high' susceptibility class and the 40% in the 'very high' class, prevalently in correspondence of agricultural areas, specifically olive groves, with a medium to high slope gradient. This result correctly predicts all known landslides inventoried for the autumn 2014 rainfall events.

In those areas with 'high' and 'very high' susceptibility that fall in correspondence of high vegetated areas, e.g. forested sectors, a limited number of shallow landslides have been observed. The landslides distributions could be related to the degree of slope degradation, and specifically to the level of terraced slope abandonment and recolonization by vegetation of these anthropic features. In fact, it is important to note that also forested sectors have a terraced slope, which are characterized by a high degree of vegetation cover such as to ensure a major slope stability. As demonstrated by Brandolini et al. (2017), a relationship between time of terraces abandonment, slope degradation and vegetation growth has been observed in other area of the Liguria Region, based on a detailed field campaign to define the degree of agricultural land abandonment. In our case, instead, the implemented methodology offers a procedure taking advantage of immediately available and validated datasets (e.g. National Landslide Inventory; regional land use and lithology data), associated to a high-resolution DTM capable to finely describe also terraced landscape, as the considered one. In this way, we want to provide a prompt methodology, easily applicable during emergency, to define landslide susceptibility distribution, and easily replicable in cases in which a new LiDAR survey become available, avoiding a time-consuming detailed field survey that can be performed at a later stage.

Additional validation of the Landslide Susceptibility map has been done applying the Relative Operating Characteristic (ROC) curve. The success rate is computed on the basis of a comparison between the landslide grid cells (Autumn 2014 rainfall events, Figure 2) and the rainfall-induced landslides susceptibility grid (Chung & Fabbir, 2003). We obtain a success rate of 75% (Figure 5).

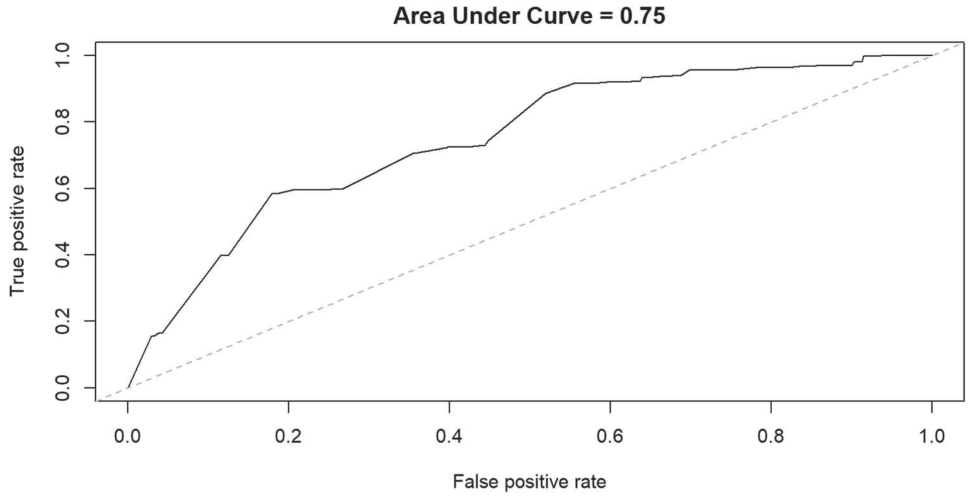

Figure 5. ROC curve computed on the basis of a comparison between landslide grid cells and landslides susceptibility grid.

5. Conclusion

The landslide susceptibility map assessment aimed at defining the potentially unstable areas, constitute a fundamental step for a more efficient land use planning and for hazard management. Various causes of landslides occurrence make the assessment of their natural and man-made predisposing factors a multidisciplinary procedure. This becomes even more evident when looking at territories extremely modified by human activity. On that basis, this study has been focused on a small coastal river basin, the Rupinaro catchment (eastern Liguria, Italy) characterized by a deeply human-influenced landscape, mainly represented by centuries-old agricultural anthropic terraces constitute by dry-stone walls. Remarkable interaction and mixing of natural and man-made factors, affecting slope instability, make this area a unique cultural and natural heritage.

The methodology proposed in this paper uses the AHP approach for shallow landslide susceptibility map generation. The causal factors definition is primarily based on field observation and in the light of experiences, strengthened by a frequency analysis computation based on the available dataset of the National Landslide Inventory. Moreover, we have exploited the available HR-DTM, acquired by helicopterborne LiDAR, to obtain a qualitative and quantitative data of morphological and man-made features like terraces. We developed a filtering procedure able to return a profile terrain without the geometric elements constituted by terraces. By this way, a robust morphometric parameters computation is ensured for the landslide susceptibility map definition.

The results display that most of the analyzed territory falls within very high and high classes of susceptibility (> 50%), predicting the 92% of the landslides exploited in the validation phase. Moreover, the application of ROC curve shows that the overall success rate of the shallow landslide susceptibility map is 75%. The obtained landslide susceptibility map can be a useful source for the management of high human-influenced territory, taking advantage of HR-DTM and its properly exploitation. Our procedure attempts to resolve the disturbing effect due to terraces, considered as a geometric element widespread throughout the whole territory, in order to clearly depict the pristine topographic pattern and define the most susceptible areas as realistic as possible. The proposed methodology, although provided encouraging results, will be improved in order to better represent critical areas such as very steep terraced study area.

Software

The shallow landslide susceptibility map was developed by the employment of several GIS tools, available in ArcGIS 10.2 (and following releases) and R 3.3 (and following releases).

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Disclosure statement

No potential conflict of interest was reported by the authors.

ORCID

Martina Cignetti http://orcid.org/0000-0002-4414-4386
Danilo Godone http://orcid.org/0000-0003-1455-6862
Daniele Giordan http://orcid.org/0000-0003-0136-2436

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A New Procedure for an Effective Management of Geo-Hydrological Risks across the "Sentiero Verde-Azzurro" Trail, Cinque Terre National Park, Liguria (North-Western Italy)

Daniele Giordan [1], Martina Cignetti [1,2,*], Danilo Godone [1], Silvia Peruccacci [3], Emanuele Raso [4], Giacomo Pepe [5], Domenico Calcaterra [4,6], Andrea Cevasco [5,6], Marco Firpo [5,6], Patrizio Scarpellini [7] and Marta Gnone [8]

1 Research Institute for Geo-Hydrological Protection (CNR-IRPI) Turin, National Research Council of Italy, 10135 Torino, Italy; daniele.giordan@irpi.cnr.it (D.G.); danilo.godone@irpi.cnr.it (D.G.)
2 Department of Earth Sciences, University of Pavia, 27100 Pavia, Italy
3 Research Institute for Geo-Hydrological Protection (CNR-IRPI) Perugia, National Research Council of Italy, 06128 Perugia, Italy; silvia.peruccacci@irpi.cnr.it
4 Department of Earth, Environment and Resources Sciences, Federico II University of Naples, 80126 Naples, Italy; emanuele.raso@unina.it (E.R.); domenico.calcaterra@unina.it (D.C.)
5 Department of Earth, Environmental and Life Sciences, University of Genova, 16132 Genova, Italy; giacomo.pepe@unige.it (G.P.); andrea.cevasco@unige.it (A.C.); firpo@dipteris.unige.it (M.F.)
6 Centro Studi Rischi Geologici of the National Park of the Cinque Terre, 19017 Riomaggiore, Italy
7 National Park of the Cinque Terre, 19017 Riomaggiore, Italy; patrizio.scarpellini@parconazionale5terre.it
8 Ministry of Cultural Heritage and Activities and Tourism, 16126 Genova, Italy; marta.gnone@beniculturali.it
* Correspondence: martina.cignetti@irpi.cnr.it

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Abstract: In recent years, Cinque Terre National Park, one of the most famous UNESCO sites in Italy, experienced a significant increase in tourist visits. This unique landscape is the result of the rough morphology of a small coastal basin with a very steep slope and a long-term human impact, mainly represented by anthropic terraces. This setting promotes the activation of numerous geo-hydrological instabilities, primarily related to heavy rainfall events that often affect this area. Currently, the main challenge for the administrators of Cinque Terre National Park is the correct maintenance of this environment along with the functional management of the hiking trail to ensure the safety of tourists. The definition of a methodology for effective management is mandatory for the sustainable administration of this unique site. We implement a new codified procedure based on the combined use of the Operative Monography and the Survey Form, focusing on the "*Sentiero Verde-Azzurro*" trail, for a proper description of the known landslides affecting the trail and the identification of damage and/or landslides activated by critical meteorological events. This guarantees effective geo-hydrological risk management, which is also applicable to other similar sites in a unique environmental and cultural heritage site such as Cinque Terre Park.

Keywords: geo-hydrological hazard; landslides; terraces; geoheritage; cinque terre national park; UNESCO; risk management

1. Introduction

Geo-hydrological instabilities, commonly associated with heavy or prolonged rainfall, often cause damage and casualties throughout the entire Italian territory [1,2]. These processes not only have a strong impact on urban areas but also cause severe damage to natural sites such as the Cinque Terre National Park, which was affected by a severe flood in 2011 [3].

In the international scene, the need for an effective administration through a sustainable development model of touristic places, featuring a great cultural and geo-heritage interest is increasingly evident [4–6]. The Cinque Terre National Park, established in 1999, is one of the most famous and visited parks in Italy. The name Cinque Terre refers to five medieval villages with economies previously based on agriculture and fishing, and today, these villages mainly depend on tourism. The villages, namely Monterosso al Mare, Vernazza, Corniglia, Manarola and Riomaggiore, are located along a jagged rocky coastline approximately 20 km in length in the easternmost sector of the Liguria Region (north-western Italy).

The Cinque Terre National Park area, covering approximately 38 km^2, despite the seaside location, displays a prevalently hilly mountainous environment with an altitude ranging from sea level to approximately 800 m a.s.l. This area is characterized by a series of southwest-facing small catchments with very steep slopes, limiting in some cases narrow coastal plains and often reaching directly to the shoreline, which is mainly shaped by rocky cliffs. This morphological setting promotes the activation of diverse geo-hydrological instabilities, especially during flash floods that frequently affect the area [7,8].

In 1997, the Cinque Terre area became a World Heritage Site, described as "a cultural landscape of great scenic and cultural value, with a layout and disposition of the small towns and the shaping of the surrounding landscape, overcoming the disadvantages of a steep, uneven terrain, encapsulating the continuous history of human settlement over the past millennium" [9]. In fact, this unique coastal landscape exhibits a long-term human land use history, mainly represented by agricultural terraces. Since 2018, agricultural terraces have been included in the Representative List of Intangible Cultural Heritage of Humanity [10]. The Cinque Terre landscape is almost completely occupied by agricultural terraces (approximately 60% of the entire park [11,12]) built since the Middle Ages and mainly consisting of dry-stone walls supporting a flat portion prevalently cultivated with vineyards and, to a lesser extent, with olive groves.

Starting from the first half of the last century, a progressive abandonment of agricultural activities, with a consequent lack of the maintenance of the dry-stone walls, led to widespread land degradation processes [3,13,14]. The effects of land degradation are forcefully exhibited in the case of heavy rainfalls and severe storms when shallow landslides and debris flows often occur. The presence of slope instabilities is a common feature not only of the Cinque Terre area but also of the whole territory of the Liguria region, where the effects of slope processing, climate changes, infrastructure and human modification are strictly related [15–23]. Recent studies focused on the Cinque Terre area noted the relationships between the degree of the abandonment of the terraces and the magnitude of rainfall-induced shallow landslides [24–28].

The Cinque Terre National Park is crossed by an extensive trail network, including both ridge trails and coastal hiking trails, walked by hundreds of thousands of tourists every year (e.g., 397,000 people were counted on the "Sentiero Verde Azzurro" (SVA) during 2016 [29]). Numerous landslides affect the territory of the Park [8,30,31], among which rainfall-induced landslides are the most widespread. Rock falls and degradation scarps are widespread along the eastern portion of the coastline, while large landslides with a complex style of activity are less abundant, e.g., the Guvano landslide, just below the San Bernardino hamlet, the Macereto area close to Vernazza, and the Rodalabia landslide located between the hamlets of Corniglia and Volastra [30,32].

In the literature, an in-depth analysis of the Vernazza catchment, the largest coastal basin within the Cinque Terre National Park, was performed after a flood event occurred on 25 October 2011 [15,24,33]. Starting from the first geographic analysis of the intersection between geo-hydrological phenomena and the Cinque Terre National Park trails [8], we noticed that a detailed analysis of the actual and potential impacts of slope instabilities on the trails was still missing.

In the Cinque Terre area, as well as in other tourist sites with strong cultural and natural elements of attraction, a comprehensive assessment of geo-hydrological instabilities becomes necessary for effective risk management to safeguard human life and to preserve these unique landscapes. In this paper, we present an interdisciplinary methodology based on the combined use of Operative Monographies (OMs) [34] and "Survey Forms" (SFs) to ensure safety along the most visited trails of the Cinque Terre National Park and thus reduce landslide risk. OMs are a useful tool for providing an overview of available data on certain areas or processes along the trails in a standard format that can be repeated and updated over time, ensuring a comprehensive knowledge of the investigated area. SFs, proposed by the Geological Risks Study Centre (GRSC) of the Cinque Terre National Park, provide during field survey campaigns a pre-defined format to identify and detect geo-hydrological instabilities triggered by severe meteorological events. The combined use of OMs and SFs is the basis of a methodology developed to define a codified procedure for the management of the Cinque Terre National Park trails network, which may be potentially affected by the activation/reactivation of slope instabilities in the cases of intense and/or prolonged rainfall events.

This procedure represents the first attempt at a national scale to define a standard approach that codifies actions, operators, and responsibilities for better management of the geo-hydrological risk assessment and the development of mitigation strategies along hiking trails or other human-related sites that are adaptable elsewhere in other natural and protected environments. The new methodology has been developed and tested on one of the most heavily visited trails of Cinque Terre: the "Sentiero Verde-Azzurro" (SVA). This trail connects Monterosso al Mare to Riomaggiore through a landscape characterized by vineyards, olive groves and woods, almost completely occupied by abandoned terraces, and along some tracts crossing some of the most relevant and well-known landslides of the National Park [35,36].

Currently, the SVA trail is developed within a fragile environment that suffers from severe slope degradation issues coming from widespread landslide phenomena and, in some cases, erosional processes. The choice of the SVA trail is not fortuitous because this trail every year records a high number of hikers (approximately 358,000 passages in 2017 and 363,000 in 2018), resulting in the most visited part of Cinque Terre and one of the most visited sites in Italy.

The main goals of this work are (i) the identification of the possible impact of recognized geo-hydrological processes on the SVA trail; (ii) the collection of existing bibliographical sources and the production of OMs; (iii) the development of a procedure for the identification of rainfall-induced geo-hydrological processes and damage based on the combined use of OMs and SFs; and (iv) the evaluation of the added value arising from the use of the proposed methodology for more effective management of the hiking trails.

A correct geo-hydrological risk management in such areas, due to its significant cultural and geological heritage, together with the high number of tourists and the high human impact, could represent a great challenge for the National Park authority to enhance a sustainable use of the territory, as well as being an interesting example for similar sites.

2. Study Area

This work concerns a section of the SVA trail, one of the most frequented and popular hiking paths of the Cinque Terre National Park. This park represents a renowned cultural and geological heritage known worldwide and visited by millions of tourists every year. The SVA trail extends for approximately 11.1 km along the seaside, from the hamlet of Monterosso al Mare to Riomaggiore (Figure 1), in the eastern Liguria Region of north-western Italy.

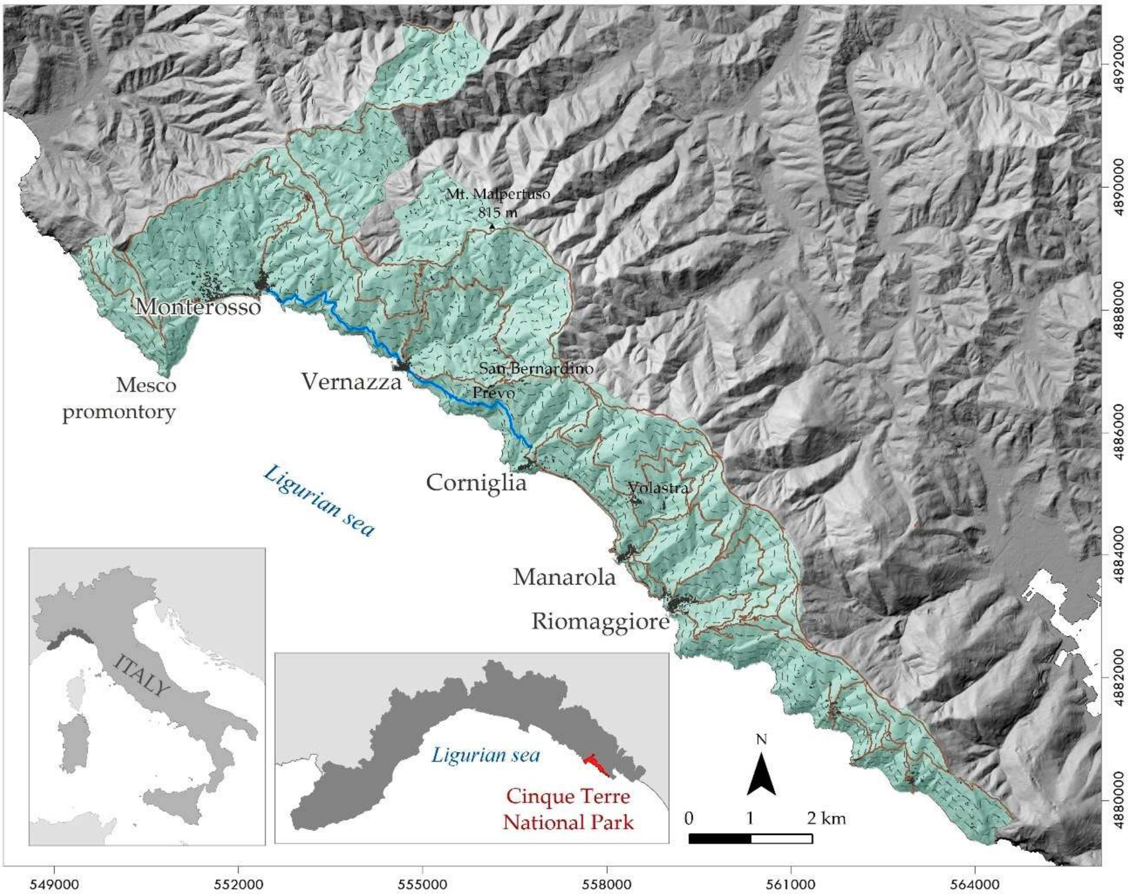


Figure 1. Map of the investigated portion of the "Sentiero Verde-Azzurro" trail (light blue line), located within the Cinque Terre National Park (teal polygon), Liguria Region, north-western Italy. The entire path network of the national park is indicated in light brown.

The SVA trail crosses several small coastal basins (Figure 2a), whose areas range from 3.75 to 573.6 hectares, generally impacted by erosional phenomena and characterized by high levels of geo-hydrological risk. The main geomorphic features of the territory are the closeness to the sea of the Cinque Terre/Vara valley watershed (highest elevation of 815 m a.s.l., Mt. Malpertuso), and the high steepness of the southwest-oriented (Figure 2b) slopes facing the Ligurian Sea, ranging from 35° to more than 45° (Figure 2c). Slopes are mainly covered by thin layers of eluvial-colluvial deposits [37].

From a geological point of view, the most widespread rock types are the Macigno Formation (upper Oligocene) and the Canetolo Unit, belonging to the Tuscan Nappe and the Sub-Ligurian Domain, respectively (Figure 2d) [38]. The Macigno Formation crops out along the entire coast and in the internal portion of the study area and consists mainly of sandstone and claystone flysch. Instead, the Canetolo Unit crops out in the central portion of the study sector and is represented by the Canetolo shale and limestone formations (claystone with limestones and silty sandstone turbidites of Paleocene age), which is associated with the Groppo del Vescovo limestone formation (marly limestone with claystone interlayers of early-middle Eocene age) and the Ponte Bratica sandstone formation (fine sandstone turbidites of upper Oligocene age). Localized outcroppings of the Marra Unit (silty marls and siltstones of the T. Pignone Formation of Oligocene age), part of the Sub-Ligurian Domain, are located in the middle of the study area.

The tectonic setting is characterized by a wide overturned antiform fold (La Spezia fold) characterized by southwestern Thyrrenian vergence and a series of main direct faults with the NW-SE, SW-verging antiform fold and by main NW-SE-oriented faults intersecting with perpendicular, NE-SW-oriented strike-slip faults, highly influencing the drainage pattern, as well as the coastline orientation [39].

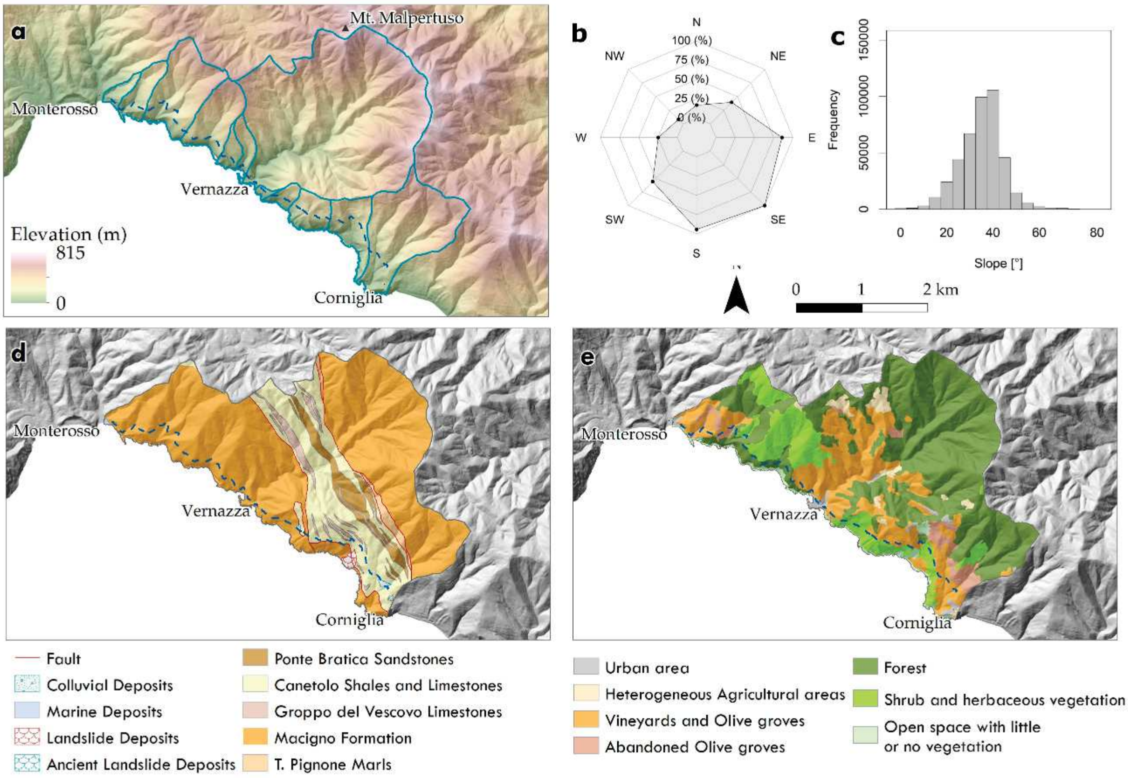


Figure 2. Map of the investigated portion of the "Sentiero Verde-Azzurro" trail (dotted blue line): a. number of catchments crossed by the trail, associated with the relief terrain map, b. aspect plot, c. slope bar diagram; d. lithological map, and e. land use map of the area of interest. All the vector data and the digital terrain model are available and downloadable in the Geoportal of the Liguria Region [40].

The land use setting of the study area exhibits a distinctive human-modified landscape characterized by agricultural terraces, mainly for vineyard and olive grove cultivation (Figure 2e). These land portions bounded by dry-stone walls occupy the majority of the study area, notably the Vernazza catchment, land of Cinque Terre DOC (a blend of Vermentino, Bosco and Albarola grapes) and "Sciacchetrà" renowned wine production. Despite the wide extension of terraced areas, the preservation and maintenance of these anthropic features is currently lacking or poor, thus giving a strong contribution to the onset geomorphological instabilities (e.g., the local collapse of dry-stone walls and small rotational slides involving the terraces). Additionally, the progressive abandonment of agricultural activities over the last sixty years enhanced a progressive recolonization by Mediterranean shrubs, herbaceous vegetation and forest tree species. The degree of dry-stone wall degradation, strongly related to the abandonment of agricultural practices along the terraces, is strictly correlated with rainfall-induced shallow landslide occurrence [25].

In addition, such coastal stretching is characterized by widespread rock falls and degradation scarps along the SVA trail. Some known large dormant or relict landslides cross the trail, such as (i) the Guvano landslide, a complex slide extended from the San Bernardino hamlet (350 m a.s.l.) to the seaside and currently monitored by a series of permanent GNSS stations [32,41]; (ii) the Macereto area, an extended area affected by widespread rock falls, in several sectors stabilized with different slope protection measures (e.g., rockfall barriers and gabionades) [30]; (iii) the Vernazza rock planar slide, stabilized with a set of hobnails [30].

3. Methods

In this paper, a new approach for investigating the instability proneness of the area of interest, with respect to both natural and anthropic causal factors, is employed. We analysed a stretch of the SVA trail to provide an effective procedure for managing the geo-hydrological risks along the trail. Figure 3 shows the overall methodology. Initially, the potential geo-hydrological hazards of the area of interest were identified, considering both natural and anthropogenic sources. A field survey was carried out along the SVA trail. Jointly, collection and organization of historical data has been performed. All obtained data converged in the Operative Monographies (OMs), a recent tool for data collection based on a standard structure [34]. When adverse weather conditions occur, the procedure provides for a field survey along the hiking path with the compilation of a predefined Survey Form (SF). By combining OMs and SFs, a specific procedure adaptable to different possible scenarios was implemented to ensure useful risk management.

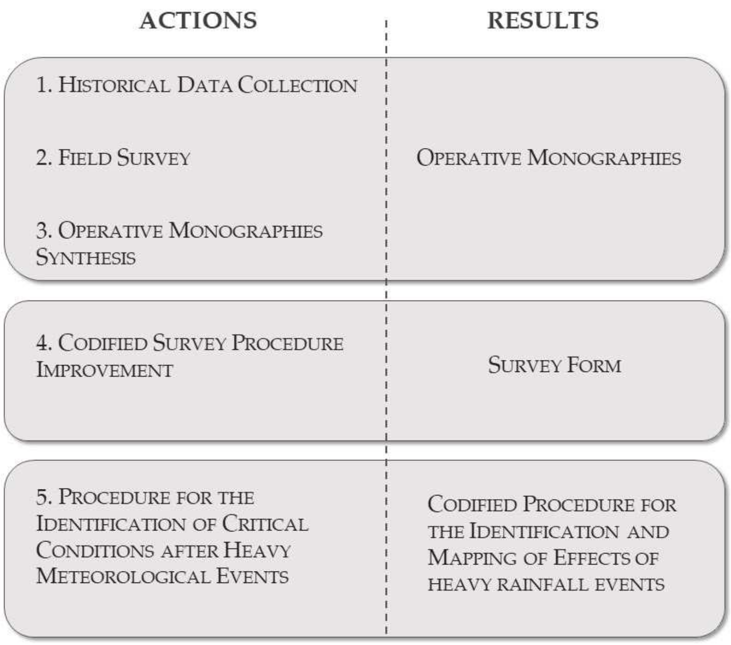


Figure 3. Methodology scheme.

3.1. Historical Data Collection

The collection and analysis of previous information available for the most dangerous landslides observed within the Cinque Terre National Park was carried out. By referring to a previous inventory, such as the National Landslide Inventory [42] and recent research [8], a landslide inventory of the area of interest was immediately available. This inventory was then compared with data acquired by a dedicated field survey. Focusing on the main recognized landslides, we carried out accurate scientific literature research, analysing all available data and information (e.g., geological and geomorphological maps and deformation measurements). In recent years, the GRSC of the Cinque Terre National Park progressively improved its internal archive by collecting previous scientific and technical studies.

3.2. Field Survey

A dedicated field survey was carried out by a group of expert geologists following the SVA path from Monterosso al Mare to Corniglia. The survey was completed by a detailed inspection of the studied area by boat. The waterborne survey was useful to acquire a comprehensive view of existing landslides, which are only partially visible along the trail. Furthermore, exposure to wave erosion represents one of the factors that can activate or increase slope instabilities. Natural and anthropic evidence interacting with the trail was inventoried. We considered all the potential geo-hydrological hazards noticeable in both the upstream and the downstream sides, including: (i) main landslides; (ii) rock fall-prone areas; (iii) headward erosion; (iv) degradation scarps; (v) local dry-stone wall collapses; and (vi) drainage network failures.

Taking advantage of a simple free app for tracking (i.e., "Trimble Outdoor"), we recorded and collected the points of interest associated with geocoded images taken directly from smartphones. Eleven critical points were identified, considering not only the main landslides affecting the trail but also the sectors of potential geo-hydrological hazards arising from the poor management of drainage networks, slope erosion, and degradation scarps. In addition, the partial or complete interruption of the path, mainly due to anthropic terrace collapses caused by lack or poor maintenance, was also taken into account. The acquired data were then quickly managed and organized in Operative Monographies.

3.3. Operative Monographies Synthesis

The Operative Monography is a document developed to provide guidance for the effective management of information on large and complex landslides [34]. This document is a useful tool for public security purposes, providing a brief, constantly updated overview of a single hazardous phenomenon located in a highly vulnerable area. The OM is a standardized and easily readable document that allows immediate access to historical data related to a specific area or a geo-hydrological phenomenon. OMs provide codified overviews that highlight key information as well as potential critical elements emerging from the analyses of the considered phenomena. The structured scheme, characterized by a standard format, is divided into different sections: (i) general information on the unstable area, (ii) the analysis and organization of available data, (iii) ground deformation time series analysis, and (iv) synthesis and possible proposals. The first section reports the basic information on the considered area or phenomenon (e.g., geographical location, type and state of activity). The second section contains an in-depth analysis of the existing historical information, focusing mainly on the geological, structural, geomorphological and hydrogeological aspects. The third section focuses on the analysis of ground deformation measurements derived from the monitoring network, if existing, for long-term evolution analysis. The last section provides a brief summary of the available data, highlighting the potential missing information and criticalities, and jointly providing several technical suggestions to overcome the identified issue.

This standardized approach ensures that future data will be organized with a consistent approach, limiting possible mismatch with previous studies. In addition, the standardized structure can be easily updated over time and, if necessary, modified for the analysis of diverse geo-hydrological processes and/or unstable areas.

In this work, we customized the OM structure by adding a section dedicated to the assessment of the degree of interference between the recognized geo-hydrological processes and the SVA trail. The adopted OM structure is as follows:

i. General information on the unstable area.
ii. Analysis and organization of previous data, divided into sub-sections:
    a. Photographic evidence;
    b. Geological and geomorphological aspects;
    c. Analysis of previous work.
iii. Analysis of potential interference between geo-hydrological processes and the SVA trail.
iv. Monitoring system analysis.
v. Summary and final proposal.

In this way, the revision of the OMs integrates the available material from the historical data collection with field survey observations. The OM facilitates the characterization of the SVA trail through the assessment of the geo-hydrological risks along the entire path and the definition of the state of knowledge of each recognized hazard. This document also represents a useful tool during emergencies when quick and effective access to the available historical data is fundamental for geo-hydrological risk management.

3.4. Codified Survey Procedure Improvement

The occurrence of numerous floods during the recent decades highlighted how disruptive these events could be, particularly for environmental and cultural heritage [43]. In the study area, one of the most recent and severe floods occurred on 25 October 2011 in response to extreme rainfall [3,27]. In the Mediterranean area, this event represents one of the most severe rainstorms in recent years, in terms of both rainfall intensities and cumulative rain quantities [44–47]. This rainstorm was responsible for intense erosive processes and triggered numerous shallow landslides that increased the sediment yield and the power of flow along streams, leading to severe flash floods of the hamlets of Monterosso al Mare [27] and Vernazza [3]. The amount of economic and structural damage was relevant both for villages and people. Moreover, many terraces were disrupted, and some stretches of the hiking trail were affected by landslides, causing the closure of part of the trail network. After such a disastrous event, according to the land management strategies adopted by some local municipalities, numerous remedial works were planned to stabilize the most unstable slopes and the most problematic stream segments [33,48]. On slopes, several types of solutions have been adopted to reduce rain-wash effects and to consolidate the areas affected by shallow landslides. Moreover, reinforcements of dry-stone walls were also performed. On the other hand, along streams, most of the interventions were carried out with the aim of improving flows and restoring the former flow sections. Geo-hydrological risk mitigation measures allowed the restoration of hiking paths and related facilities to give tourists the opportunity to visit this beautiful and unique environment. In recent years, the GRSC has promoted multidisciplinary studies and activities aimed at examining the state of the conservation, efficiency and damage of both geo-hydrological risk mitigation measures and hiking paths after the occurrence of severe rainstorms. A survey form (SF) has been implemented to properly support the work of surveyors after severe hydro-meteorological events. The adopted SF allows an effective and fast inventory of damage and rainfall-induced hydro-geomorphological effects along the hiking trail. This procedure is expected to provide a useful contribution in terms of civil protection measures by decreasing the exposure of trail users to geo-hydrological risk.

3.5. Procedure for the Identification of Critical Conditions after Heavy Meteorological Events

In areas with a very high number of tourists, such as the Cinque Terre National Park, when particularly adverse weather conditions occur, it becomes necessary to verify the accessibility of the path network. In addition, the identification of any critical issue along the trails requires the planning and execution of remedial activities that can provide adequate safety conditions.

Commonly, after heavy rainfall occurs, e.g., 25 October 2011, the closure of the entire path network becomes necessary. At this stage, survey operations are carried out by the so-called "Presidianti", i.e., adequately trained and skilled geologists, entrusted with the identification of the occurrence of geo-hydrological processes and damage. "Presidianti" are also trained in the use of OMs that provide a ready-to-use document able to supply a reasoned summary of the overall framework of this peculiar territory, focusing on the main geo-hydrological hazards and criticalities already present (and known) along the trail path. The identification of something that could hamper the reopening of the trail is supported by the use of SFs, which support the "Presidianti" in the data collection, using a homogeneous approach. Starting from the development of the procedure, we also defined several possible scenarios and the sequence of activities to be carried out before the reopening of the trail.

4. Results

4.1. Operative Monographies

Based on the historical data collection and field survey observations along the analysed SVA trail, eleven Operative Monographies have been compiled. These documents focus on the diverse critical issues recognized along the path related to geo-hydrological instabilities and their impact on the SVA trail (Table 1). Moreover, to obtain a comprehensive view of this peculiar landscape, all potential punctual criticalities along the track have also been considered. Therefore, local dry-stone wall collapses threatening path safety were also included (Figure 4d).

Moving on from Corniglia to Vernazza, the main landslides that intersect the SVA trail are: (i) the Guvano landslide, (ii) the Macereto area, and (iii) the Vernazza rockslide. The Guvano landslide is a complex landslide extending from San Bernardino hamlet (approximately 350 m a.s.l.) to the seaside (Figure 4a). The source area evolves into rock falls and topples, threatening the main road positioned just above the SVA track. This complex landslide then evolved into an earth flow, generating a large accumulation whose toe is exposed to the erosional activity of the sea waves and that in the past was stabilized by different protection measures. This landslide is monitored by a permanent network of GNSS stations and instrumented with five inclinometers derived from a past geotechnical investigation performed in 2003–2004 [32,41].

Table 1. Geo-hydrological instabilities and critical issues analysed in the OMs and their locations with respect to the "Sentiero Verde-Azzurro" trail.

OM title	GPS location	Critical issues	Location with Respect to the Sentiero Verde-Azzurro Trail
Costa Lunga	44.12422–9.70790	Runoff	Upstream and Downstream
Guvano Beach	44.12506–9.70590	Degradation scarp	Downstream
Guvano Landslide	44.12943–9.69940	Active Complex Landslide	Upstream and Downstream
Massolina	44.128838–9.701558	Engraved channel associated with debris cone	Downstream
Prevo	44.12943–9.69940	Degradation scarp	Downstream
Macereto	44.13087–9.69266	Widespread rock fall area	Upstream and Downstream
Gerai	44.13244–9.68971	Engraved channel	Upstream and Downstream
Vernazza	44.133636–9.68971	Rockslide	Upstream and Downstream
Costa Messopano	44.14008–9.67714	Rock falls	Upstream
Valle Crovarla	44.140286–9.676803	Dry-stone wall collapse	Upstream
Scoglio del Frate	44.14054–9.67513	Degradation scarp	Downstream

Figure 4. Main landslides and critical issues recognized along the "Sentiero Verde-Azzurro" trail: (**a**) Guvano landslide; (**b**) Macereto area; (**c**) rock sea cliff equipped with falling rock protections, Crovarla Valley; (**d**) local dry-stone wall collapse along the path; (**e**) visible dry-stone wall deformation along the SVA trail between Vernazza and Corniglia; (**f**) degradation scarp in correspondence of the Guvano beach, close to Corniglia; (**g**) rockslide close to Vernazza; and (**h**) local rock falls corresponding to the bedrock outcropping along the "Sentiero Verde-Azzurro" trail. White arrows indicate the path location.

The Macereto area corresponds to a wide slope sector with widespread rock falls and other geo-hydrological instabilities, mainly due to drainage network failure (Figure 4b). Almost the entire area is equipped with massive rock fall defences and barriers along the path. In the western portion, defined as the "Gerai area", an important engraved channel threatens the dry-stone wall built upstream of the trail to protect it (Figure 4e). The Vernazza rockslide took place in the upstream portion of the trail, actually equipped by rivets, while the landslide body, made up of large rock blocks, extends up to the shoreline (Figure 4g). Numerous rock falls, degradation scarps and engraved channels associated with debris cones are observed along the entire path, both in the upstream and downstream sectors (Figure 4c,h). The impressive degradation scarps, which are mainly located just downstream of the trail and threaten the road, correspond to the "Prevo area", a small hamlet between Corniglia and Vernazza, defined as the "Massolina area" on the right side of the Guvano landslide, as well as in correspondence of the Guvano beach area (Figure 4f).

OMs allow a rapid evaluation of the state-of-the-art by providing an overall picture of the geological-geomorphological setting of the study area, identifying the main geo-hydrological instabilities and critical issues that can threaten the trail network.

For each document, a brief form has been reported to identify a distinct phenomenon or critical issue, indicating the general information about the geographic location, type of phenomenon, and state of activity. Then, an analysis of previous data, including scientific papers, technical reports and eventual map annexes, has been carried out, dividing the collected information into three sub-sections: i. photographic evidence, ii. geological and geomorphological settings and iii. available data analysis. Significant importance has been given to the degree of interference between the recognized geo-hydrological instabilities and the SVA trail. By reference to the eleven critical issues recognized and analysed in the OMs, the SVA trail has been divided on the basis of the degree of potential risk, considering high, medium and low interferences between the geo-hydrological instability and the path (Figure 5).

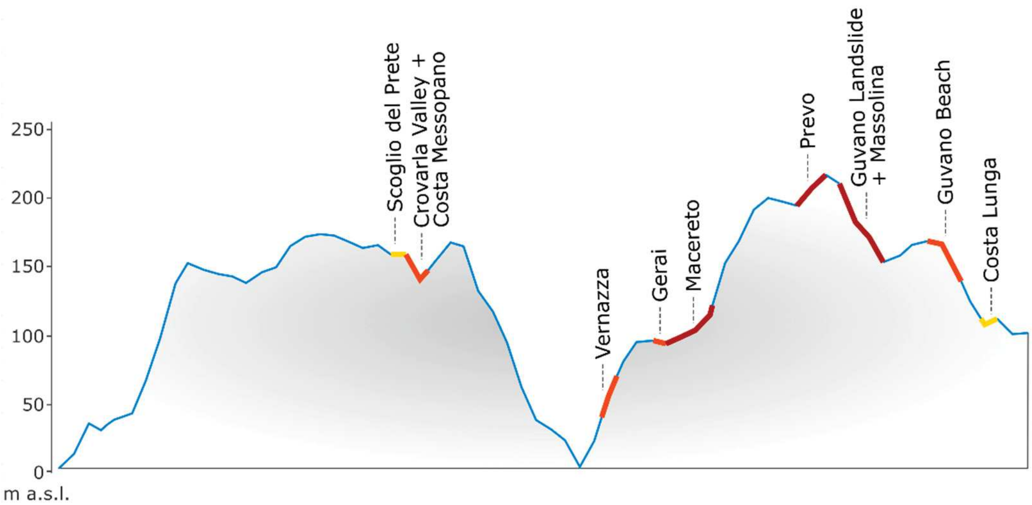


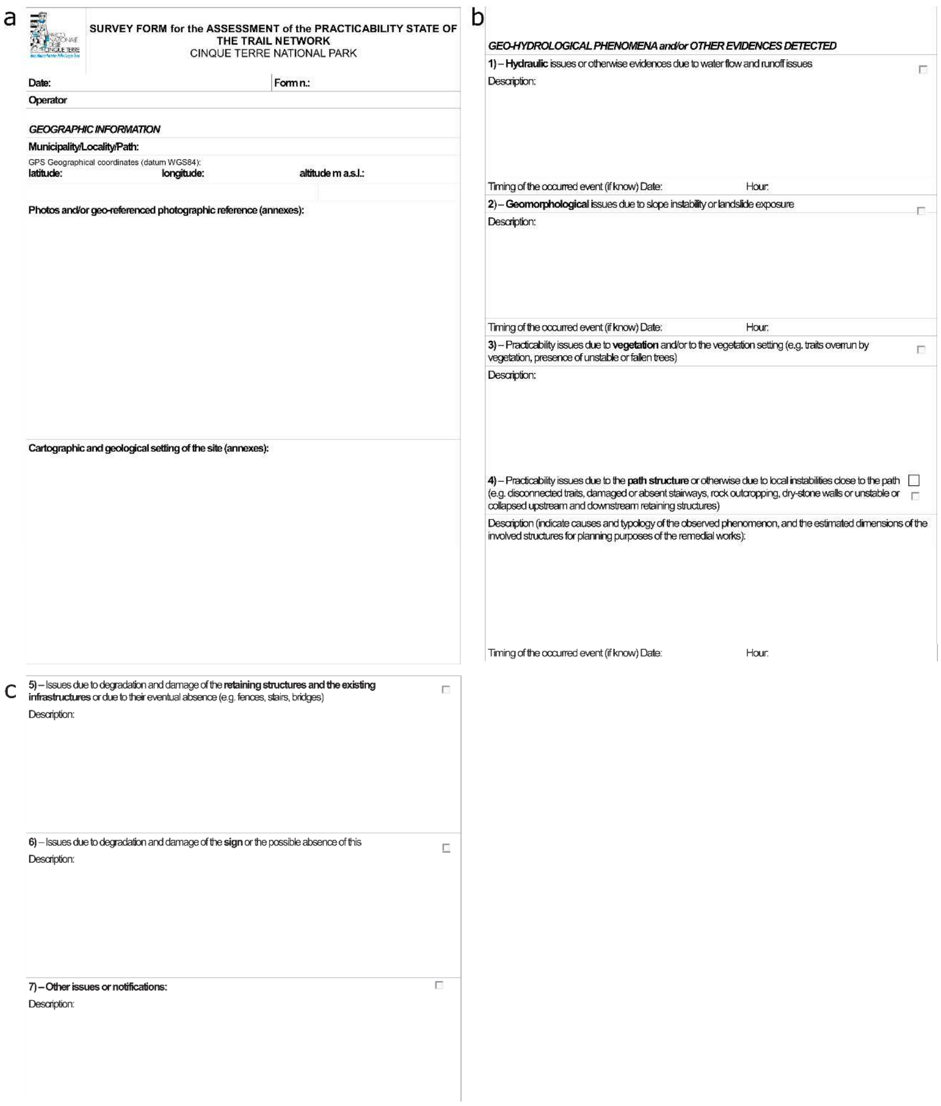
Figure 5. Sketch of the "Sentiero Verde-Azzurro" trail profile characterized on the basis of the degree of hazard with respect to the recognized geo-hydrological instabilities described in the OMs: high interference in red, medium degree in orange, and low degree in yellow.

OMs have been developed to support "Presidianti" in the recognition of new phenomena and in the identification of possible changes in known phenomena, giving a full description of what we already know. A brief summary, as comprehensive as possible, of the available data is provided. In association, technical and remedial solutions aimed at effective risk management can be proposed.

4.2. Survey Form

The survey sheet has been developed to be used by geologists hired by the National Park in the case of some slope instabilities affecting a trail, or when a severe weather alert leads the Park authority to close the trail network. Under these circumstances, such geologists are in charge of performing a detailed Cinque Terre trail survey to identify potentially dangerous situations or ground effects that could hamper the reopening of the trail.

The survey sheet is composed of two main sections: i. general overview and ii. geo-hydrological phenomena and/or other detected evidence. The first section (Figure 6a) principally includes geographic information, useful for the localization of the documented phenomenon, completed with eventual photos, geological and geomorphological sketch and other eventual annexes. The second section focuses on damages and the occurred process (Figure 6b,c), including: i. damage or processes related to water runoff; ii. damage or processes related to slope instabilities; iii. damage or processes occurring to roads, trail sectors and other infrastructure; iv. eventual problem and description of damage occurring to the National Park signposting; and v. other potential problems. Every recognized phenomenon or damage is scheduled, reporting a brief description, the date of the event (if known), and the hour.



a

SURVEY FORM for the ASSESSMENT of the PRACTICABILITY STATE OF THE TRAIL NETWORK
CINQUE TERRE NATIONAL PARK

Date: **Form n.:**
Operator

GEOGRAPHIC INFORMATION
Municipality/Locality/Path:
GPS Geographical coordinates (datum WGS84):
latitude: **longitude:** **altitude m a.s.l.:**

Photos and/or geo-referenced photographic reference (annexes):

Cartographic and geological setting of the site (annexes):

b

GEO-HYDROLOGICAL PHENOMENA and/or OTHER EVIDENCES DETECTED
1) – **Hydraulic** issues or otherwise evidences due to water flow and runoff issues
Description:
Timing of the occurred event (if know) Date: Hour:
2) – **Geomorphological** issues due to slope instability or landslide exposure
Description:
Timing of the occurred event (if know) Date: Hour:
3) – Practicability issues due to **vegetation** and/or to the vegetation setting (e.g. traits overrun by vegetation, presence of unstable or fallen trees)
Description:
4) – Practicability issues due to the **path structure** or otherwise due to local instabilities close to the path (e.g. disconnected traits, damaged or absent stairways, rock outcropping, dry-stone walls or unstable or collapsed upstream and downstream retaining structures)
Description (indicate causes and typology of the observed phenomenon, and the estimated dimensions of the involved structures for planning purposes of the remedial works):
Timing of the occurred event (if know) Date: Hour:

c

5) – Issues due to degradation and damage of the **retaining structures and the existing infrastructures** or due to their eventual absence (e.g. fences, stairs, bridges)
Description:
6) – Issues due to degradation and damage of the **sign** or the possible absence of this
Description:
7) – **Other issues or notifications:**
Description:

Figure 6. Survey sheet structure: (**a**) general overview section, (**b**,**c**) geo-hydrological phenomena and/or detected evidence section.

4.3. Codified Procedure for the Identification and Mapping of the Effects of Heavy Rainfall Events

Starting from the experience of past events (e.g., 25 October 2011), when adverse weather conditions obliged the closure of the Cinque Terre National Park trails, we designed a procedure aimed at the identification of possible effects that can reduce the safety of trails.

Through the establishment of a repeatable and effective protocol aimed at a "multi-user" exploitation during the occurrence of an emergency, this procedure addresses the needs of the Cinque Terre National Park for useful geo-hydrological risk management.

Figure 7 shows the structure of the proposed codified procedure. The weather alert follows the meteorological and hydrological forecasting and warning procedures adopted by the Liguria Region [49], based on the 27 February 2004 Directive of the Italian President of the Council of Ministers of "Guidelines for the organizational and functional management of national and regional warning system for hydraulic and geo-hydrological risks for Civil Protection purposes". At the regional scale, five alert zones defined on the basis of physiographic aspects, both topological (i.e., catchment extent) and meteorological criteria were established by the Italian National Civil Protection Department with respect to the level of hazard in terms of floods and landslides. A total of four alert levels have been defined, following a "traffic-light" code. In a meteorological and hydrological "state of alert" when "orange" or "red" alert levels are being issued, the SVA path closure is planned.

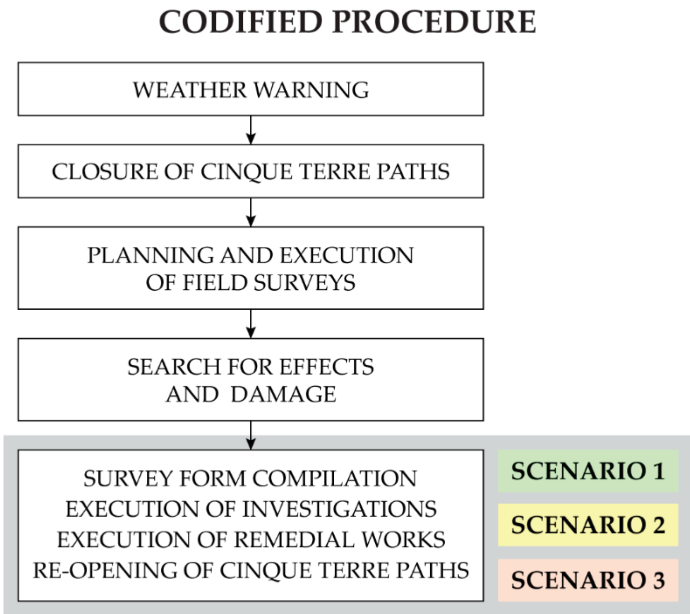


Figure 7. Codified procedure proposed for the Cinque Terre National Park administration after a weather warning occurrence.

In the path network closure and activation of the "Presidianti" phase, geologists selected within the National Association of Geologists and coming from diverse regions of Italy are designated by the Cinque Terre Park authority to carry out field surveys along the entire SVA trail. Beforehand, the selected "Presidianti" are adequately trained with dedicated formation courses aimed at providing an overall geological and geomorphological knowledge of this characteristic landscape. It should be noted that in this phase, OMs supply the "Presidianti" with a global interpretation and explanation of the state of the art about the geo-hydrological hazards previously recognized along the path.

In the possible effects and damage identification by the "Presidianti" phase, the "Presidianti" carry out the dedicated field survey along the path to identify all the new and/or reactivated geo-hydrological instabilities that occurred after a relevant meteorological event. In the Survey Form compilation process and communication by the "Presidianti" to the Cinque Terre Park phase, SFs supply a pre-defined form to collect and inventory all information on geo-hydrological hazards threatening the path through the compilation of a series of alphanumeric fields. After, the field surveys and SF drafting, the "Presidianti" transmit these documents to the Cinque Terre Park authority.

At the final step of our procedure, i.e., possible remediation activities coordinated by Cinque Terre Park and re-opening of the Network path, specific and dedicated interventions along the trail are predisposed by the Park authority, assisted by external consultants, if necessary, aimed at the re-opening of the path to tourists.

Starting from the path closure up to the SF compilation and transmission to the Park authority, three possible scenarios may occur, on the basis of the level of damage and effects that occurred after the weather alert. Figure 7 shows the first scenario, which arises when no damage or effects occur. After the "Presidianti" involvement by the Park authority, the field survey supported by the OMs is planned. Scenario 1 (Figure 8) is applied when no difference with respect to the previous setting takes place, and any new or reactivated geo-hydrological instabilities occur. In this scenario, the "Presidianti" state the absence of critical issues to the Cinque Terre Park administrators, hence the absence of SF drafting, by concluding their survey.

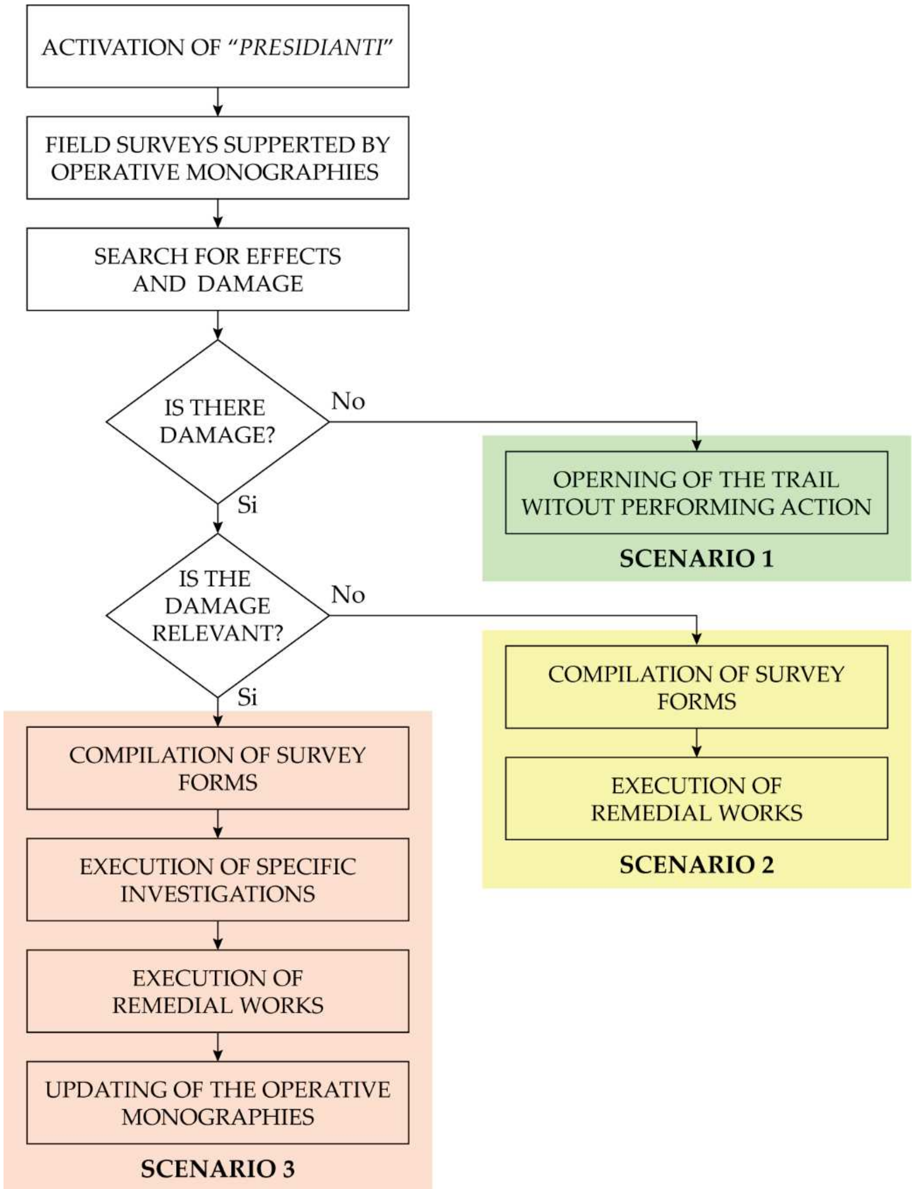


Figure 8. Structure of the codified procedure for different Scenarios.

Scenario 2 (Figure 8) is planned in cases of limited damage, and effects are observed during field surveys. For instance, a minor damage condition can be represented, for example, by trees falling down or by small stones located along the path (Figure 9a–c). In those cases, an SF is filled in for each critical issue observed. Subsequently, all the compiled SFs are transferred to the Cinque Terre Park authority and commensurate remedial works are planned and executed before the reopening of the trail.

Figure 9. Examples of damage and/or rainfall-induced effects recorded using survey forms after a weather alert: (**a**) trees fall down; (**b**,**c**) small dry-stone wall collapses; and (**d**) dry-stone wall failure causing a local path interruption.

Scenario 3 (Figure 8) considers the possibility that the meteorological event could cause relevant damage. Rainfall-induced landslides, runoff and erosion processes are the most common effects that could occur. In this case, the "Presidiante" fills in an SF for each geo-hydrological instability identified, considering both first activated or re-activated instabilities, that partially or totally involve the surface path. A focus has also been dedicated to local damage to the dry-stone walls that could collapse involving the path surface (Figure 9d). Even in this case, the first identification of the critical condition is based on the completion of the SFs and a consequent report to the Cinque Terre Park authority that will activate the procedure for the implementation of remedial works. It should be noted that if the geo-hydrological phenomenon, already described in the OM in this area, is reactivated during the most recent meteorological event, at the end of the procedure, the update of the dedicated OM is mandatory to guarantee a correct description of known geo-hydrological instabilities. Moreover, if a new and relevant geo-hydrological phenomenon has been identified during the dedicated field survey, a new OM can be drafted to constantly update a standardized document and the overall state-of-the art of the study area.

5. Discussion and Conclusions

The increased awareness of local and national administrators in preventing damage to geological and cultural heritage is constantly growing. Planning for the assessment of both pre-existing and future effects of geo-hydrological instabilities becomes an essential aspect for managing popular tourist landscapes and therefore, limiting further degradation, ensuring long-term sustainability, and assuring the safety of conditions along trails.

The sites of geological and cultural interest, in both nature conservation and tourist sectors, are often threatened by geo-hydrological hazards, which could put the accessibility of the heritage sites themselves in danger [50]. Similarly, the local agricultural policies on the rural landscape, with consequent abandonment in farming, may lead to an increase in slope instabilities [51–55]. Some efforts have been made to highlight that the knowledge of past and current geological and geomorphological processes can help to increase the awareness and perception of geo-hydrological risks [43,56–58]. In Italy, slope instabilities threaten 25% of the UNESCO sites, flooding threatens 54% of the sites and earthquakes threaten 82% [59].

A proper assessment of the potential geo-hydrological hazards and possible damage to geological and cultural heritage sites is the key element for effective risk management and prevention. In fact, the availability of specific procedures able to provide management strategies to preserve these unique landscapes and based on the interoperability of geoscientists, practitioners and cultural heritage managers are limited or missing.

In this work, we proposed a new codified procedure for the management of the "Sentiero Verde-Azzurro" trail, one of the main popular paths of the Cinque Terre National Park. This UNESCO site is historically closely linked to the anthropic modification of the environment, mainly represented by agricultural terraces bounded by dry-stone walls. Agricultural terraces record at least one thousand years of human fingerprint necessary to modify and adapt a natural and tough environment for cultivation purposes. This unique site, visited by people from all over the world, shows a complex equilibrium between the geomorphological environment fully integrated with human interventions, and the usability of the path network by hundreds of thousands of tourists every year. The combination of gravity and runoff processes, characterizing the steep slopes of the terraced coastal basins, coupled with marine erosion along the coastline, promotes the occurrence of geo-hydrological instabilities, especially in the case of heavy rainfall events. In addition, the effects of such geohazards are favoured by the extensive abandonment of the agricultural terraces.

A procedure aimed at addressing the needs of the Cinque Terre National Park for useful geo-hydrological risk management was implemented. The main goal was to establish a repeatable and effective procedure to be applied after relevant meteorological events affecting the Park territory. This requirement was born from previous experiences [34] in which we realized that the lack of a standard way to collect and organize data and information about geo-hydrological phenomena and related damage could be a crucial problem in landslide risk assessment and management. For several years, the use of defined methodologies and specific protocols has been considered quite usual and well-established in some specific fields for emergency management [60,61]. For example, for the International Civil Aviation Organization (ICAO), in the medical framework or in industrial risk management, the adoption of standard protocols is mandatory to define the specific actions that competent institutions and stakeholders should execute. This led us to find a proper solution in geo-hydrological risk management in this unique landscape through the definition of a predefined protocol to adopt in the case of severe meteorological events. However, it is important to note that, with respect to, for example, an industrial accident, in the case of geo-hydrological risk, this codification is difficult to achieve due to the high variability in data and involved entities. Diverse scenarios could take place, mainly on the basis of typology and the characteristics of the occurred phenomena and related damage. This large range of possibilities overcomplicates the drafting of the procedure. Therefore, we defined a methodology that is based on two instruments (the OMs and the SFs) and on the definition of three possible scenarios.

Based on the available information and experiences gained during previous adverse meteorological events, a codified methodology was proposed. The foreground has been primarily acquired by investigating the effects of severe floods in recent years in the Liguria Region, among which is the flood of 2011 [3,21,24], and considering other events such as those in November 2014 [17,21], and November 2016 [22]. This procedure is aimed at developing an approach that is standardized as much as possible for field survey operations to be carried out after relevant rainstorms and is useful for "multi-user" exploitation during the occurrence of emergencies.

The importance of the correct management of the impact of slope instabilities on Cinque Terre trails is particularly evident in Raso et al. [8], who made an inventory of landslides that have an interaction with trails. Starting from this published inventory, it is possible to identify that 66 landslides have a direct impact on the trails. In particular, from the methodological point of view, we focused on a stretch of the SVA trail (1.1 km on a total length of the 149 km trail network in the entire park) that is the most visited path by tourists and one of the most affected by slope instabilities of different typologies.

The overall geo-hydrological instabilities interacting with the SVA trail have been identified and analysed using OMs. This standardized procedure represents a useful tool for obtaining a focus on the main geo-hydrological instabilities affecting the area of interest and their degree of impact on the usability of the path. The OMs also constitute a useful tool for the "Presidianti", the first actors in the implemented procedure activated upon the occurrence of severe meteorological events. It should be noted that these expert geologists are selected at a national level and potentially do not have a specific awareness of the investigated area of interest, which can be filled using the OMs.

The combined use of OMs and SFs by the "Presidianti" guarantees constant updating on the potential interferences between the identified geo-hydrological instabilities and the SVA trail. Moreover, the SF data structure has been implemented to allow a simple and functional construction composed of cartographic information and alphanumeric fields so that it can be easily converted into a digital data management system for completion. In this context, the proposed methodology represents, from now, an easy instrument to make comparative analysis over the time of all the produced documents by any "Presidiante", thanks to their standard structure, and make an overall evaluation of the geo-hydrological phenomena effects on the Cinque Terre National Park.

The codified process may constitute the basis for an extended analysis of the interaction between landslides and the entire hiking network of the National Park. Therefore, the standardised procedure should provide a practical response to the needs for the National Park authority to enhance a sustainable administration of the territory and schedule the appropriate management measures, to guarantee the safeguard of both heritage and tourists safety from geo-hydrological risks. Our strategy allows the effective management of geo-hydrological risks in a highly geological and cultural heritage site, where the high influx of tourists and human pressure require a well-defined procedure, especially with the occurrence of weather alerts. The implemented methodology constitutes a useful approach for a sustainable use of the territory, which is also applicable in similar UNESCO sites.

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5

Rockfalls

Rockfall events mainly occur as detachment, fall, rolling and bouncing of rock fragments, usually of limited volume, occurring abruptly singly or in a cluster (Hungr et al., 2014). These events are very common in mountain areas and their unpredictable occurrence, with high energy and long-runout, often cause victims and damage, particularly along with the road network (Guzzetti et al., 2004; Michoud et al., 2012; Pantelidis, 2011).

National and regional landslide inventories represent a significant source of data, specifically in term of the spatial and temporal distribution of a specific area. This provides the basic data for better awareness of the potential impact of rockfall events on the urbanized territory, with a specific focus on viability network.

By exploiting a territory highly affected by rockfalls like Aosta Valley Region (northwestern Italy), by leveraging on the existing regional landslide inventory (*i.e. Catasto Dissesti*, Centro Funzionale Regione Autonoma Valle d'Aosta, 2019), in Phase I (Figure 5.1), the spatial and temporal distribution analysis of rockfall events has been investigated. This led to obtaining suitable information to define the main variables influencing rockfalls occurrence and to assess the more susceptible areas. In Phase II, a susceptibility map along the road network of the Aosta Valley region has been generated, taking advantage of the Analytic Hierarchy Processes of Saaty (1977) approach. All the obtained results are presented in the *Paper VIII*, actually accepted to Journal of Maps (Accepted 9 November 2020, DOI: 10.1080/17445647.2020.1850534).

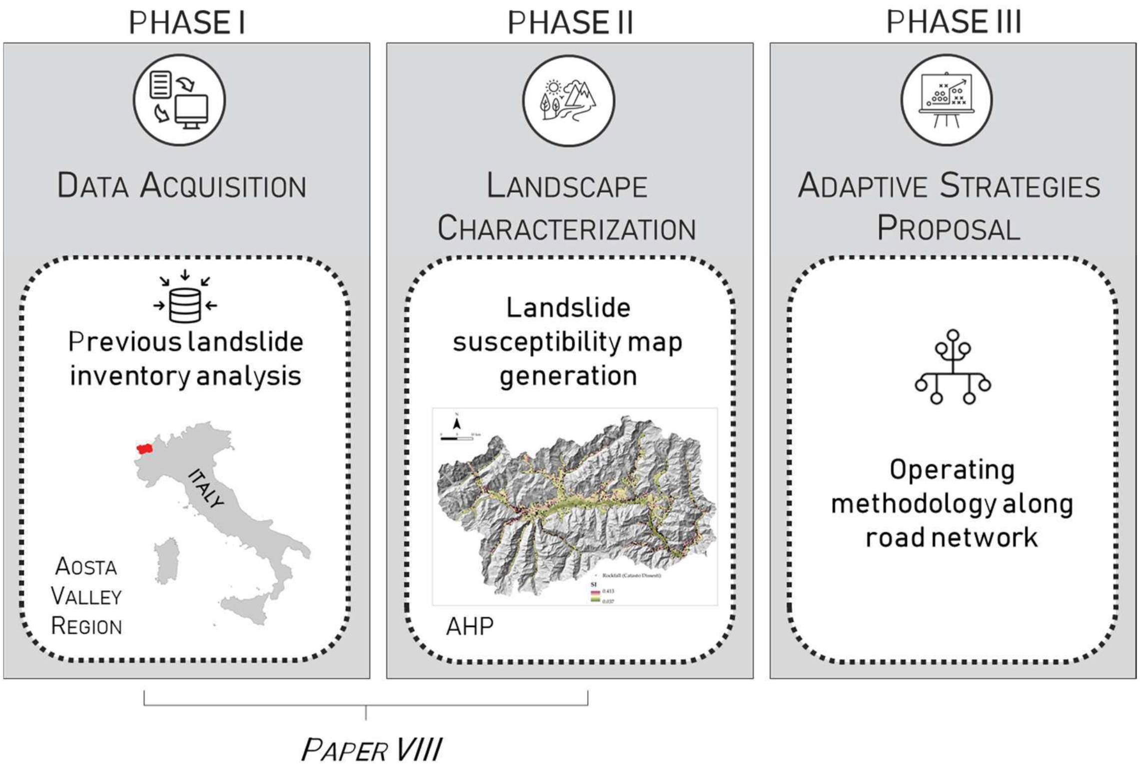

Figure 5.1 - Reiterated structured proposed for the rockfall typology.

A preliminary landscape characterization, through the definition of the area more susceptible to rockfall events, should represent the primary step for landslide risk assessment and management. Moreover, rockfall susceptibility map computation allows recognizing those areas to place under observation, representing a preliminary step in the definition of an intervention methodology to set the activities to be carried out, with a focus on the phases between the collapse and the planning of permanent interventions to reduce risk.
The Phase III, looking at the codified procedure developed for the UNESCO site of the Cinque Terre National Park (Paper VII), with some modification and arrangements proper for rockfall typology, is currently being implemented in the forecast of future research developments. The fulfilment of safety requirements in rockfalls occurrence requires a composed design process involving public technicians and administrators, aimed to define proper scheduling of priorities, choices and activities in an appropriate timeline.

The full version of the scientific paper, accepted 9 November 2020, is available below in the Proof version.

Paper VIII: Cignetti M., Godone D., Giordan D., Bertolo D., Thuegaz P., Paganone M. (2020) *Rockfall susceptibility along the regional road network of Aosta Valley Region (northwestern Italy)*. Journal of maps. DOI: 10.1080/17445647.2020.1859534

Note

Rockfall susceptibility along the regional road network of Aosta Valley Region (northwestern Italy)

Cignetti, M.[1,2], Godone, D.[1,*], Bertolo, D.[3], M. Paganone[3], Thuegaz, P.[3], Giordan D.[1]

[1] National Research Council of Italy, Research Institute for Geo-Hydrological Protection (CNR IRPI), Torino 10135, Italy; martina.cignett@irpi.cnr.it (M.C.); danilo.godone@irpi.cnr.it (D.G.a); daniele.giordan@irpi.cnr.it (D.G.b)

[2] Department of Earth and Environmental Sciences, University of Pavia, 27100, Italy;

[3] Strutture Attività Geologiche, Regione Autonoma Valle d'Aosta, Quart 11020, Italy; d.bertolo@regione.vda.it (D.B.); m.paganone@regione.vda.it (D.B.), p.thuegaz@regione.vda.it (P.T.).

* Correspondence: danilo.godone@irpi.cnr.it (D.G.a)

Abstract

Rockfalls are a major hazard in mountain areas. They can endanger human settlements and infrastructures, and every year they cause multiple damage and victims. An investigation and delineation of those areas more susceptible to rockfall represents a key approach to improve the analysis and management of rockfall impact and its consequences. The proposed procedure involves the study of occurred rockfall databases and thematic map layer to compute a susceptibility map, by the employment of Analytical Hierarchic Process. The computation is focused on the road network of Aosta Valley Region (northwestern Italy) and its proximity. The results of the model highlight the importance of morphometric factors on the investigated phenomena. The outcomes of the analysis were also validated by comparing the rockfall databases with the receiver operating characteristic curve, in order to confirm their reliability. The results of the procedure are a starting point for a detailed planning actions in order to manage the hazard related to these phenomena.

Keyword

Rockfall hazard; Analytic Hierarchy Process; landslide inventory; alpine region.

1. Introduction

In mountain territories rockfall events are extremely common along the road networks, often causing casualties, damage to vehicles or to the roads (e.g. pavements, retaining walls), with consequent economic losses (Budetta, 2004; Guzzetti, 2000; Guzzetti, Reichenbach, & Ghigi, 2004; Palma, Parise, Reichenbach, & Guzzetti, 2012). Rockfalls are unpredictable phenomena usually involving small volumes, the areas involved are very small and often punctual, with high energy and long runout distances (P. Frattini, Crosta, & Agliardi, 2012). The relating hazard characterization and forecast is still a challenge, depending on various factors for any single investigated area (Mineo, 2020; Mineo & Pappalardo, 2019). Great importance is given to the characterization of the rockfall spatial distribution, their frequency and intensity, which are often assessed by landslide inventories (Hungr, Evans, & Hazzard, 1999; Volkwein et al., 2011).

The Alpine region is widely anthropized and characterized by diffuse environmental and cultural heritage and represents a territory highly susceptible to the rockfall occurrence. Therefore, the rockfall hazard assessment become essential in the Alpine areas, with the aim to implement countermeasures and to adopt an adequate land use planning.

Rockfall hazard has been defined by Jaboyedoff, Baillifard, Hantz, Heindenreich, & Mazzocolla, (2001) as the probability that a specific location is reached by a rockfall of given intensity. The definition of magnitude-frequency relationship can be obtained by estimating the annual frequency of rockfall events in specified volume classes (Hungr et al., 1999). Some limitations can occur because of the information availability for a specific area of interest, specifically in term of spatial and temporal heterogeneity. Without an accurate assessment of the annual frequency of the rockfall events of a given magnitude, the hazard computation is not possible. In these cases, the risk assessment should meaningfully be supported by the susceptibility computation. By this way, it is possible to provide a general overview of areas more affected by potentially collapses, based on specific environmental characteristics. This process plays a fundamental role for obtaining an overview of the potentially endangered areas, before proceeding to the risk assessment (Jaboyedoff et al., 2012).

Focusing on the Aosta Valley Region (AVR), a small alpine region in the northwestern Italy, widely affected by many different slope instabilities like Deep-seated Gravitational Slope Deformation (Cignetti, Godone, Zucca, Bertolo, & Giordan, 2020; Martinotti, Giordan, Giardino, & Ratto, 2011), large rockslides (Crosta et al., 2015; M Giardino, Giordan, & Ambrogio, 2004), and rockfalls (Trigila, Iadanza, & Spizzichino, 2008), this study aims to assess the rockfall susceptibility across the regional road network, highly threated by this type of slope instability. This small mountainous Region (about 3200 km^2) shows a dense road network that branches off along the main valley and the secondary ones. By applying a semi-quantitative index-based method, capable to organize and analyze multi-criteria decision, i.e. Analytic Hierarchy Process (AHP) (Saaty,

1980) we drafted a prompt and rapid approach to define the areas more susceptible to rockfalls at regional scale. Starting from the available landslide inventories and catalogues (Centro Funzionale Regione Autonoma Valle d'Aosta, 2019; ISPRA Ambiente, 2007), we defined the main variables to consider in the susceptibility computation process. Finally, the obtained susceptibility map was validated by the receiver operating characteristic curve, or ROC curve.

The definition of the more susceptible areas should represent a useful tool for the regional authorities and municipalities, and represents an initial step for subsequent in-depth analysis, in order to define effective risk and emergency management strategies. For instance, the aforementioned map will constitute one of the layers employed in the ARTEMIS (Advanced Regional Terrain Motion InSAR Screening system) procedure, an automated method elaborated by the Aosta Valley Regional Geological Survey. Concerning slope instabilities affecting this mountainous region (ISPRA Ambiente, 2007), this procedure will be used to identify the sites to be primarily investigated, by leveraging on a GIS-based filtering process for the operative field management of the Permanent Scatterers (PS) monitoring anomalies regime.

2. Material and methods

The developed methodology is structured in two main phases: (i) definition of the current knowledge framework on the occurred rockfall events; (ii) application of the Analytic Hierarchy Process (AHP).

We focused on the area close to regional road network, which extends over 2600 km approximately, exploiting the "*Catasto Strade*", *i.e.* regional roads inventory (Aosta Valley Region - Cartographic office, 2016), applying a buffer of 250 m along the network, which includes a portion of territory that is relevant for the scopes of the analysis. In addition, a 25 m buffer around the main settlements (SCT Geo Portal, 2005), merging them with the road network area, was operated. The area of interest (AOI) obtained, with an area of 475 km^2, corresponds to the 17% of the entire regional territory (Figure 1).

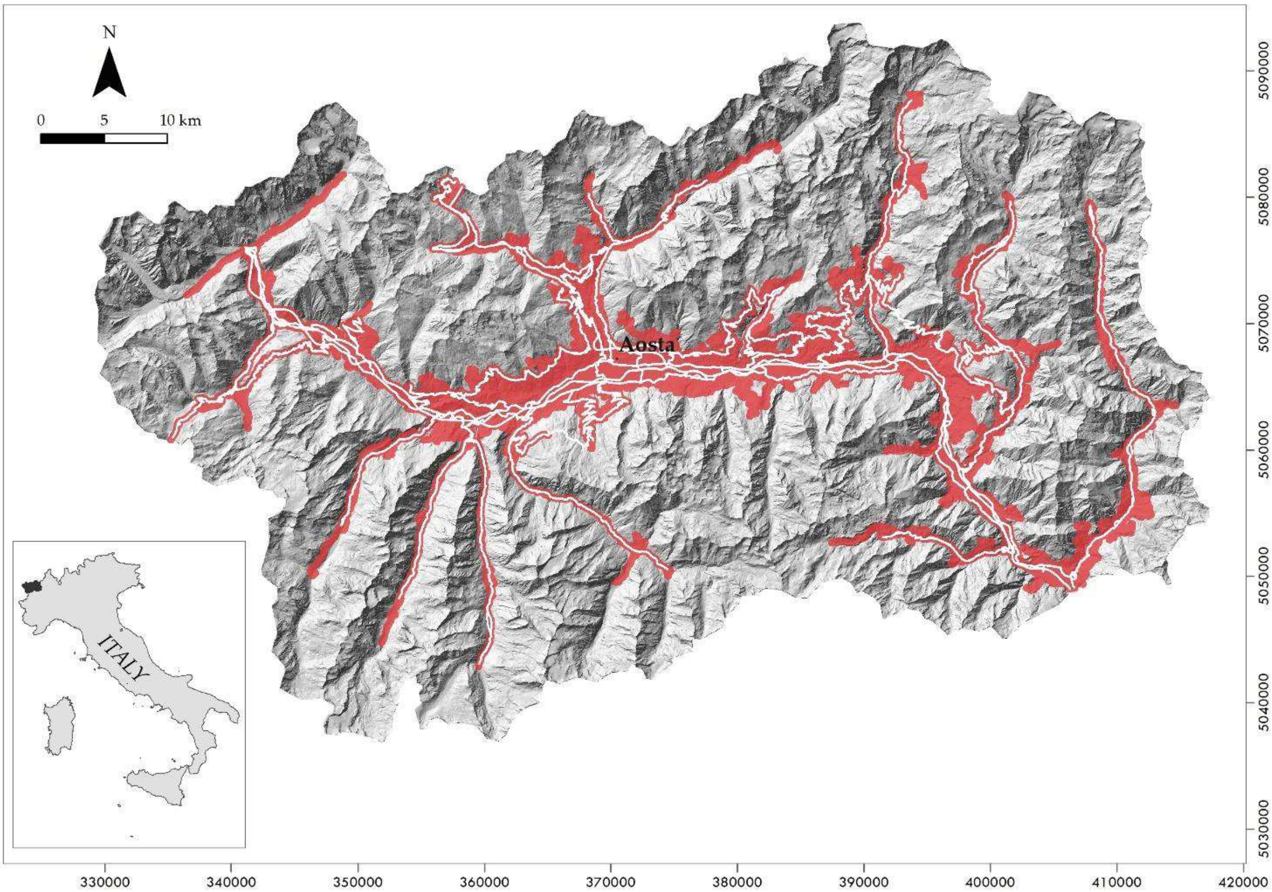

Figure 1 – Aosta Valley Region elevation map. The AOI corresponds to the red area, white lines correspond to the regional road network.

Taking advantage of the landslide inventories actually available for the AVR territory (*i.e.* Italian Landslide Inventory (IFFI) (ISPRA Ambiente, 2007), and of the "*Catasto Dissesti*", an on-line landslide catalogue at regional scale (Centro Funzionale Regione Autonoma Valle d'Aosta, 2019), the spatial and temporal distribution of the occurred rockfalls was analysed. By this way, useful information, suitable to define the variables influencing rockfall events and to identify and assess the more susceptible areas, were obtained. Subsequently, operating in a GIS-environment, the identified variables, commonly referred to the rockfalls occurrence, were derived. Successively these variables were combined to generate the Susceptibility Index (SI) of the area of interest (AOI) applying the AHP. The workflow of the implemented methodology is exposed in Figure 2.

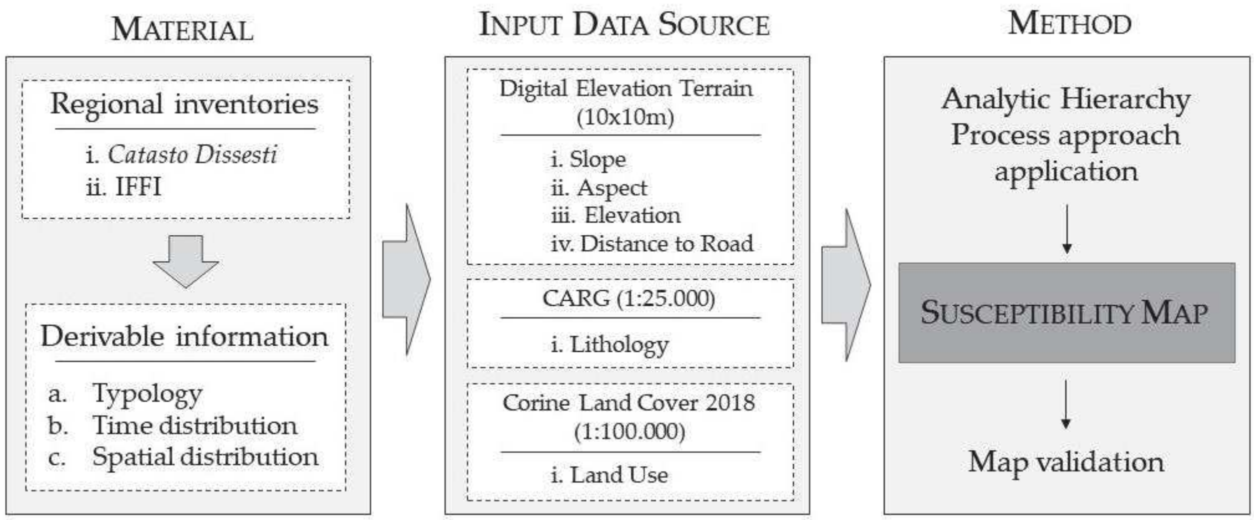

Figure 2 – Scheme of the adopted methodology.

3. Rockfalls regional inventories analysis

The availability of landslide inventories is crucial to gather useful information, particularly in terms of morphological, geological and land use characterization, aimed at the rockfalls occurrence definition at regional scale. Thanks to the large amount of available data, referring to the "*Catasto Dissesti*", the occurred landslides in terms of spatial and temporal distribution were analyzed, with the goal to characterize the regional territory relatively to the rockfall events occurrence.

Operating with several tools in a GIS environment, the main morphometric parameters of each inventoried phenomenon were extracted. Taking advantage of the regional Digital Terrain Model (DTM) (10x10 m cell size), several derivative products were obtained: (i) slope; (ii) aspect; (iii) elevation. Jointly, land use and lithological data were derived respectively from the Corine Land Cover (Copernicus & Land Monitoring Service, 2018) updated to 2018, at 1:100.000 scale, and from the Geo-tectonic Map of the Aosta Valley Region (De Giusti, Dal Piaz, Massironi, & Schiavo, 2003). Both for land use and lithology, we operated a merging in homogeneous classes, in order to standardize the datasets, and a conversion to the raster format, with the aim of combining them with DTM related products.

Figure 3 shows the distribution of the inventoried rockfall events for each considered factor at regional scale. It should be noted that the majority of the inventoried phenomena occurred in correspondence of sectors with South-Southeast-Southwest exposure, and high relief, ranging from 25° to 45° (*i.e.* 27% for "25°-35°", 26% for "35°-45" and 23% for ">45°").

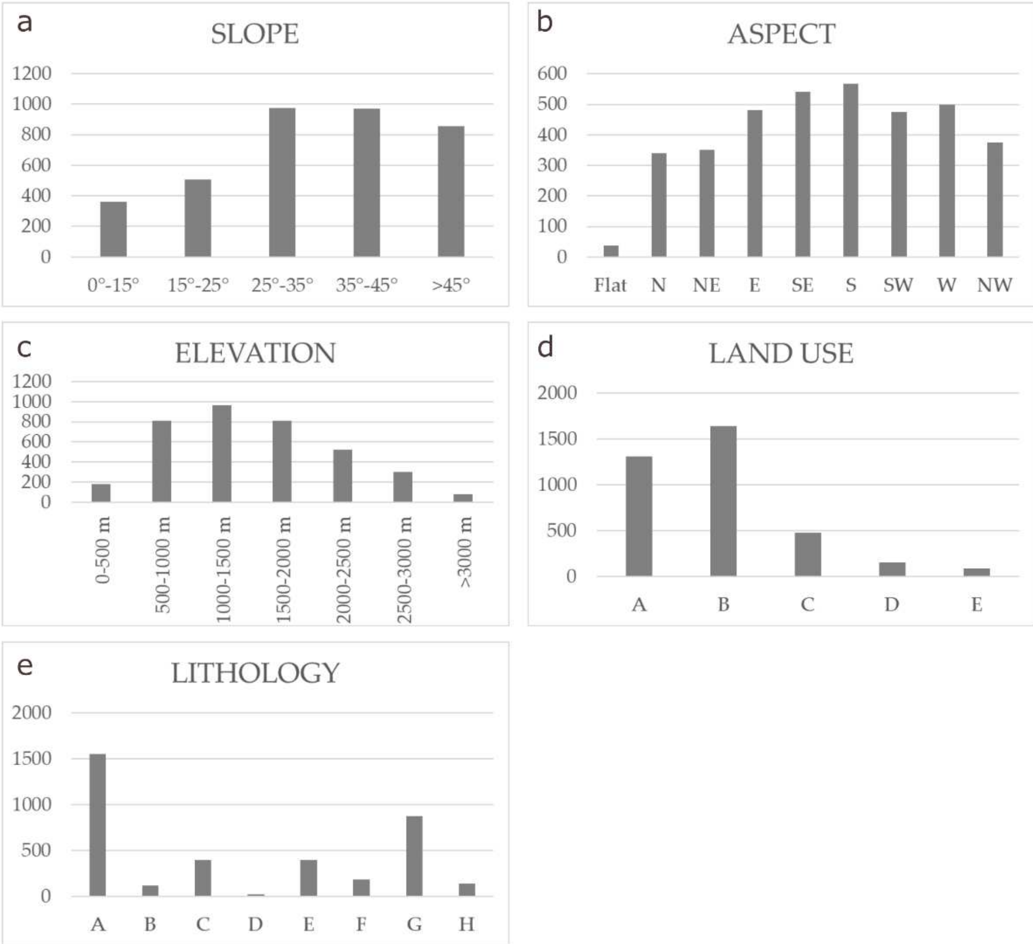

Figure 3 – Rockfall events distribution at regional scale, referring to the "*Catasto Dissesti*" inventory, respect to the considered factors: a) Slope; b) Aspect; c) Elevation; d) Land Use (A = Forest; B = Zones characterized by shrub and/or herbaceous vegetation; C = Open space with little or no vegetation; D = Zones mainly occupied by agricultural areas; E = Urban areas); e) Lithology (A = Calcschists and Serpentinites; B = Conglomerates; C = Quaternary deposits; D = Gypsum, Dolomite; E= Gneiss; G = Micaschists; H= Black Schists).

Referring to the elevation, the medium-high portions of the slopes reveal the highest frequency in rockfalls occurrence, with the 16% of cases in correspondence of the "1000-1500 m" class, and the 22% for the "1500-2000 m" one. The distribution in correspondence of the highest portions (i.e. 8% in the "2500-3000 m" class, and 2% for the ">3000 m" class) is poor.

Considering the land use factors, the 45% of rockfalls occurred in areas characterized by shrub and/or herbaceous vegetation, and the 36% in correspondence of woodlands. Considering the lithology, the 42% of the rockfalls occurred in the lithological units belonging to the so-called "Piedmont Zone". This domain includes rocks deriving from the Piemonte-Liguria Ocean crust, *i.e.* “green stones” (serpentinites and various grade metabasites), and from the Mesozoic sediments of coverage, *i.e.* calcschists, mainly schistose rock.

By analysing the inventoried rockfalls in terms of temporal distribution, we evaluated a timeseries ranging from the 1180 A.D. and the 2020 A.D., for a total time span of 840 years. Figure 4a shows the overall distribution of the available data, with an evident peak in correspondence of the October 2000 (Figure 4b), during which one of the most catastrophic flood event hit the Aosta Valley Region (Marco Giardino et al., 2013). In general, the most part of inventoried phenomena is recorded in the last forty years (1980-2020). In fact, during the last decades, the need to characterize the territory for risk management and prevention purposes, certainly led to a more complete and accurate data collection, as reflected by the available data abundancy.

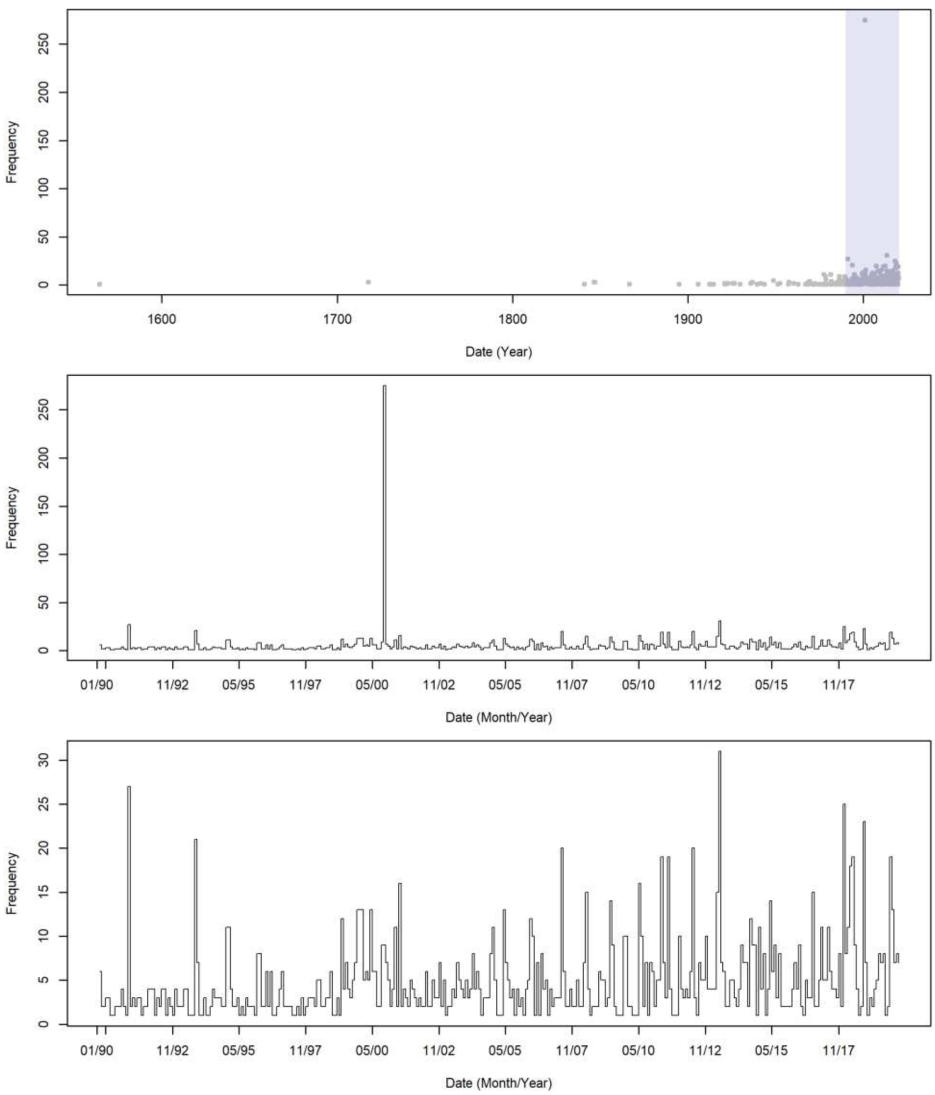

Figure 4 – Monthly distribution of the inventoried rockfalls at regional scale, referring to the "*Catasto Dissesti*" inventory, a) for the overall period, b) for the period from the last decade of the twentieth century (1990-2000); c) for the same period but excluding the October 2000 flood.

Observing the distribution in the last decades' distribution, without consider the October 2000 event (Figure 4c), we can notice that the highest peaks are recorded in spring seasons (e.g. 1991, 2013), while minor peaks occurred during the autumn seasons (e.g. 1993, 2007 and 2018). It is interesting to observe the peak of January 2018 in correspondence of a particularly warm winter season (Centro Funzionale, 2018), which almost certainly influenced the rockfall occurrence due to the anomalous inflow of groundwater in the slopes due to the cyclical melting of the snow cover during January and February and freeze thaw cycles.
Performing the analysis of the rockfall monthly distribution, it can be observed that, at regional scale, these phenomena are more frequent in the spring season (months from March to May, 37%), and in the autumn season (months from September to November, 25%), with peaks respectively in May (16%) and October (9%). It should be considered that 47% of the analysed phenomena do not report information relating to the month of occurrence.

4. Considered variables for rockfall susceptibility estimation

Usually, there are not general guidelines for the selection of the variables useful to generate susceptibility maps. Commonly, rockfalls triggering is due to the combination of several factors, including topographic features, earthquakes, vegetation conditions, rock mass conditions, pore pressure increases, mainly related to rainfall infiltration and/or freeze/thaw cycles, and other climatic variables (Lan, Martin, Zhou, & Lim, 2010). By carrying out a regional analysis, decision was made to exploit previous open-data available in order to provide a quick and ready-to-use methodology that supplies a preliminary zonation of the area of interest. For this reason, detailed characteristics about rock mass fracturing, local geological and tectonic setting, were not considered at this stage. We considered six variables: (i) slope; (ii) aspect; (iii) elevation, (iv) lithology; (v) land use; (vi) distance to road. From the previously mentioned DTM, we therefore extracted the morphometric parameters relative to the AOI across the regional road network. For the land use, we cropped the Corine Land Use at regional scale on the AOI, while for lithology, we considered the Geological Map of the CARG project

(ISPRA Ambiente, 2012), made available by the Aosta valley regional administration. By these means, we obtained a more detailed information at the 1:25.000 scale.

4.1 Morphometric parameters

Topographic information are among the most common intrinsic factors adopted to create a susceptibility map (Ayalew, Yamagishi, Marui, & Kanno, 2005; Paolo Frattini, Crosta, Carrara, & Agliardi, 2008; Othman, Gloaguen, Andreani, & Rahnama, 2018). The slope degree is directly related to landslides occurrence and rock falling trajectory. Therefore, this parameter is one of the most used in landslides susceptibility computation (Moreiras, 2005). This factor has been divided in five classes: (i) less than 15°; (ii) 15°-25°; (iii) 25°-35°; (iv) 35°-45°; (v) more than 45°.

The slope exposition is another relevant aspect, mainly in relations to exposure to weather events, for instance rainfall events, solar radiation, and freeze-thaw cycles (Gruber, Hoelzle, & Haeberli, 2004; Hall, 2004). This factor is divided in four classes, by grouping the conventional aspect class in: (i) flat; (ii) South-Southwest-Southeast; (iii) East-West; (iv) North-Northwest-Northeast.

Finally, the topographic elevation, strictly related to the land cover typology (Demir, Aytekin, Akgün, İkizler, & Tatar, 2013), in general, a high elevation is associated with a land cover mainly represented by bare rock and/or poorly vegetated areas, whilst the lower altitudes are characterized by moderate slope, corresponding to areas with lower rockfall susceptibility. This factor, limited to the AOI elevations, is divided in seven classes: (i) less than 500 m; (ii) 500-1000 m; (iii) 1000-1500; (iv) 1500-2000; (v) 2000-2500; (vi) 2500-3000; (vii) more than 3000m.

4.2 Lithology

Lithology plays a relevant role in slope instability. The AVR displays a complex geological setting showing a complete sequence of the Western Alps structural domains (Dal Piaz, Bistacchi, & Massironi, 2003), with a wide range of lithologies as well as a great local variety of structural settings, due to the multiple deformative stages of the alpine orogenetic process. Starting from the Geological maps of the CARG project, available at the 1:10.000 on the 85% of the regional territory, the various lithologies have been grouped on the basis of their litho-technical properties (Palomba, Giardino, Ratto, & Pogliotti, 2015). We operated merging in macro-typologies, firstly distinguishing between deposits and rocks type, and subsequently on the type of deposits or rocks, on the basis of their degree of mobilization. This arrangement reflects the original affiliation to the main alpine tectonic units; the classes have been grouped, depending on the litho-technical properties of the rock, in seven main classes: (i) shale rocks; (ii) massive igneous and metamorphic rocks; (iii) marbles, limestones and dolomites; (iv) tectonized and contact rocks; (v) gravitational deposits; (vi) colluvial and glacial deposits; (vii) alluvial deposits.

4.3 Land Use

Land use and vegetation cover can variably condition the rockfall occurrence, playing a relevant role in slope stability. Starting from the detailed classification of land use done in Corine Land Cover project (ISPRA Ambiente, 2018), five different classes are generated: (i) urban areas; (ii) agricultural areas; (iii) forests; (iv) sparsely vegetated natural areas; (v) natural areas not or poorly vegetated. Urban areas include all the anthropic areas occupied by residential and industrial buildings, and/or other infrastructures (*e.g.* airports, quarries, landfills and dumping areas). Pastures, vineyard, fruit trees and other plantations, permanently irrigated arable lands, are gathered in the agricultural areas class. With regard to the forest class, according to the literature, the woodlands have been considered as a protective factor against rockfalls (Fuhr, Bourrier, & Cordonnier, 2015). Instead, natural areas sparsely vegetated and natural areas not or poorly vegetated could represent important source areas in rockfalls occurrence.

4.4 Distance to roads

The distance to roads is a key parameter in term of rockfall susceptibility computation. Changes in topography due to road construction, as well as the related local decrease in rock-mass load due to excavations, may influence the bedrock fracturing. Considering also the rockfall risk and the associated damage and casualties, the areas highly close to the road network have been considered the more susceptible. Five classes, obtained applying a dedicated tool in GIS environment, are created along the main regional road network: (i) 0-50 m; (ii) 50-100 m; (iii) 100-150 m; (vi) 150-200; (v) 200-250 m.

5. Analytic Hierarchy Process

The Analytic Hierarchy Process is a multi-criteria decision-making method, developed by Saaty, 1977. This approach is suitable for complex decisions, which involves a multi-object comparison, enabling the user to define a scale of preference from a set of alternatives. To apply the AHP, the initial complex problem needs to be disassembled into its component factors, organizing them in a hierarchic structure. Once the structure is defined, the user operates through the construction of a pair-wise comparison matrix; each factor, or class of factor, is classified against every other one of the matrix, by assigning a numerical value (see Table 1). The numerical value assignment follows subjective, expert based, judgments on the relative importance of each factor (Saaty & Vargas, 2012). Finally, the pair-wise comparison matrix is normalized, and the weighted average rating for each decision alternative is computed.

Table 1 – Scale of preference between two parameter i and j in the AHP approach (Saaty & Vargas, 2012).

Value a_{ij}	Degree of preference
1	i and j have equal importance
3	i is moderately more important than j
5	i is strongly more important than j
7	i very strongly more important than j
9	i is extremely more important than j
2, 4, 6, 8	Values for intermediate comparison

In our study, operating with the above-mentioned causal factors, the AHP has been applied assigning weights to both causative factors and to the classes defined for each factor (Table 2).

Table 2 – Pair-wise comparison matrix and relative weights for rockfall causative factors and relative classes. All the pair-wise comparison matrices are structured ranking the established items with respect to their impact on rockfall occurrence. The meaning of values displayed in the "Pair-wise comparison matrix" are explained in Table 1.

Causative factors and factor classes	**Pair-wise comparison matrix**							**Weights**
	[1]	[2]	[3]	[4]	[5]	[6]	[7]	
Causative Factors								
[1] Slope	1	4	4	3	5	7		0.41
[2] Aspect		1	2	1/3	1/2	5		0.11
[3] Elevation			1	1/3	1/2	5		0.09
[4] Lithology				1	4	6		0.24
[5] Land Use					1	4		0.12
[6] Distance to road						1		0.03
Slope								
[1] 0°-15°	1	1/2	1/5	1/9	1/7			0.04
[2] 15°-25°		1	1/4	1/7	1/5			0.06
[3] 25-35°			1	1/2	1/3			0.18
[4] 35°-45°				1	1/2			0.32
[5] >45°					1			0.4
Aspect								
[1] Flat	1	1/6	1/7	1/9				0.04
[2] North-Northeast-Northwest		1	1/2	1/4				0.16
[3] East-West			1	1/3				0.25
[4] South-Southeast-Southwest				1				0.55
Elevation								
[1] <500m	1	1/6	1/8	1/6	1/3	1/2	1	0.03
[2] 500-1000m		1	1/3	1	2	5	7	0.19
[3] 1000-1500m			1	3	5	7	9	0.4
[4] 1500-2000m				1	2	5	7	0.19

[5] 2000-2500m					1	1	5	0.09
[6] 2500-3000m						1	4	0.07
[7] >3000m							1	0.03
Lithology								
[1] Shale rocks	1	7	9	9	3	3	8	0.41
[2] Massive igneous and metamorphic rocks		1	7	7	2	2	7	0,2
[3] Marbles, limestones, dolomites			1	1	1/7	1/7	1	0.03
[4] Tectonized and contact rocks				1	1/7	1/7	1	0.03
[5] Gravitational deposits					1	1	5	0.15
[6] Colluvial and glacial deposits						1	5	0.15
[7] Alluvial deposits							1	0.03
Land use								
[1] Urban areas	1	1/3	1/4	1/7	1/9			0.04
[2] Agricultural areas		1	1/3	1/6	1/8			0.06
[3] Forest			1	1/5	1/7			0.11
[4] Natural areas sparsely vegetated				1	1/2			0.31
[5] Natural areas not or poorly vegetated					1			0.49
Distance to road								
[1] 0-50m	1	4	5	5	7			0.5
[2] 50-100m		1	3	4	6			0.25
[3] 100-150m			1	2	4			0.13
[4] 150-200m				1	2			0.08
[5] 200-250m					1			0.05

The consistency of the judgments is verified through the Consistency Ratio (CR) computation (Saaty, 2000), which is obtained by the ratio between the Consistency Index (CI) and the Random Consistency Index (RI)

$$CR = \frac{CI}{RI} x 100\% \quad (1)$$

When the CR is larger than 10%, the subjective judgment is inconsistent and needs a revision.

The computation of the susceptibility is performed in a statistical open source environment (R Development Core Team, 2011), by reclassifying and rasterizing the thematic layers of the six considered causal factors.

More in detail, we applied the procedure based the weighted linear sum (WLS) to define the landslide susceptibility index (LSI)

$$LSI = \sum_{j=1}^{N} W_j w_{ji} \quad (2)$$

The performance of the model was the evaluated by comparing it with occurred rockfall database and by computing ROC (Chung & Fabbri, 2003).

6. Rockfall Susceptibility map and validation

By exploiting spatial and temporal information of the occurred rockfalls of previous inventories, together with the application of the AHP, we obtained the Rockfalls Susceptibility Map (Main map ref) of the study area, i.e. the road network of the AVR and the main settlements in its proximity. The pair-wise comparison matrix was based on six main variables, divided in sub-classes, and ranked in term of their impact on slope instability. Through the comparison matrix application, we obtained the normalized principal eigenvector, both for the main variables and the classes of each one (Table 2). The slope factor provided the highest weight of 0.41, resulting the most relevant variable, followed by lithology with a weight of 0.24. Focusing on each factor classes, the most relevant variables correspond to the slope interval “35°-45°”, aspect “Southeast-South-Southwest”, lithology “Shale rocks”, land use featuring “Natural areas not or poorly vegetated” and distance to road “50-1000 m” interval. In order to verify the consistency of the obtained weights and rating of each considered causative factors, we computed the Consistency Ration (CR), based on the relative value of Consistency Index (CI) and Random Consistency Index (RI) (Table 3).

Table 3 – Consistency values of the considered factors

	All factors	slope	aspect	elevation	lithology	land use	Distance to roads
CI	0.09	0.05	0.05	0.05	0.07	0.08	0.06
RI	1.24	1.12	0.90	1.32	1.32	1.12	1.12
CR	0.08	0.04	0.05	0.03	0.06	0.07	0.06

The obtained Rockfall Susceptibility Map (Main map) shows SI values ranging from 0.037 and 0.413. By applying the “Natural breaks” classification of Jenks (Ayalew & Yamagishi, 2005), available in GIS environment, the SI values are classified in four classes: (i) low; (ii) medium; (iii) high; (iv) very high.

Considering the AOI, close to the regional road network, on a total of 475 km^2, the 'very high' and 'high' classes cover respectively 28.05% and 11.63% of the analyzed area (Figure 5). The computation of these values is carried out on a filtered AOI surface where flat (i.e. aspect value of -1) or gently sloping (i.e. slope lower than 5°) sectors are removed. This selection was performed to exclude the main valley bottom, which is negligible in terms of hazard characterization and whose inclusion in the analysis might lead to an underestimation of the susceptibility classes distribution.

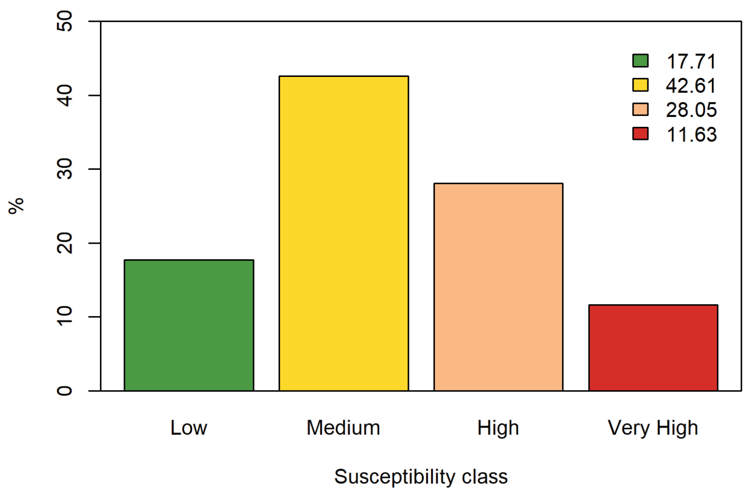

Figure 5 – Surface distribution (% of the filtered AOI) of the susceptibility classes

Analysing the distribution of the inventoried rockfalls of the regional catalogue within the AOI (Figure 6), a first validation of the obtained result has been performed. This result shows that about 70% of the inventoried phenomena are located in areas with high or very high susceptibility. The obtained susceptibility map consistently matches the previous inventoried rockfalls, showing that, as predicted by the model, these events mainly fall in "high" (35%) and in "very high" (33%) classes.

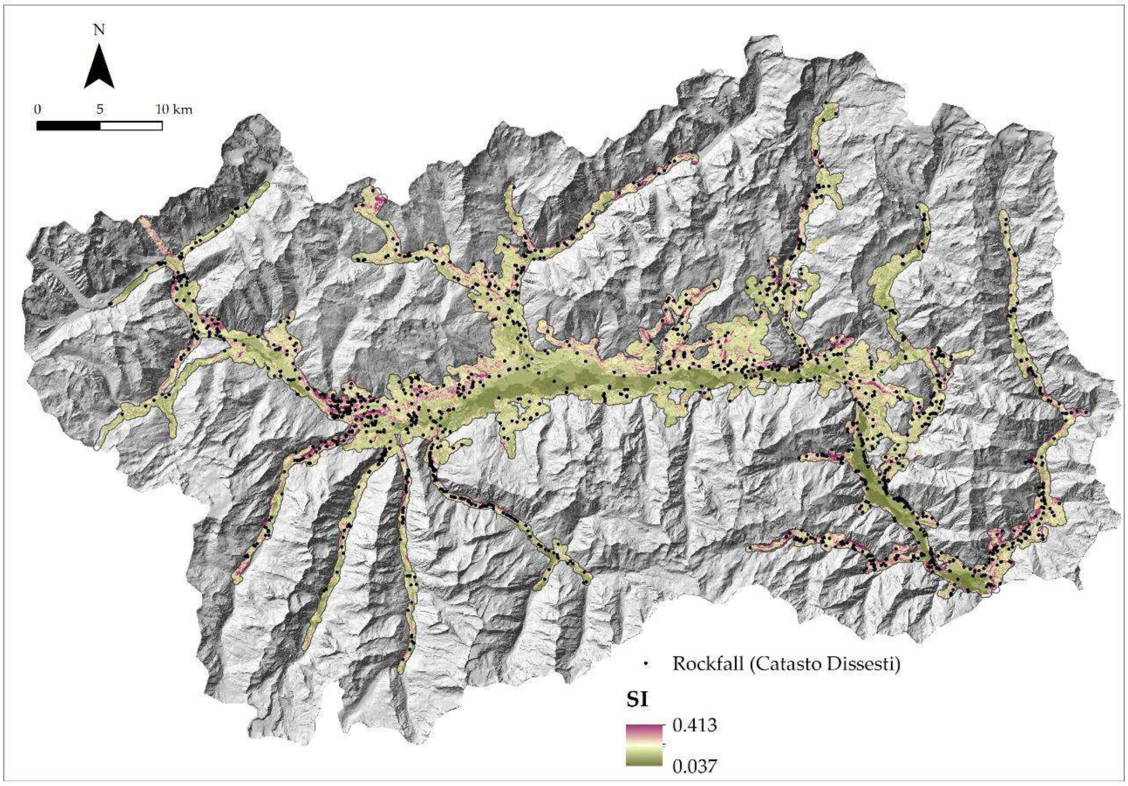

Figure 6 – Susceptibility map of the road network of the AVR; black dots correspond to the rockfall events collected in the "*Catasto Dissesti*" regional inventory within the AOI.

The most part of phenomena occurred in sectors with high to very high relief (e.g. class "25°-35° 27%, class "35°-45°" 24%), with a South-Southeast-Southwest exposition. Considering the elevation factor, about 70% of the occurred phenomena are located from 500 to 1500 meters a.s.l., as also highlighted by the results obtained. Lithologically, the majority of the events involved "Shale rocks" lithologies (18%), while considering quaternary deposits, the most part occurred in gravitative deposits or in colluvial/glacial deposits (respectively 35% and 27%). Considering land use factor, the rockfalls are mainly distributed in correspondence of "Natural areas not or poorly vegetated" (47%). It should be noted that more than about 60% of rockfalls within the AOI, occurred at a distance of fewer than 50 m from the road network. Excluding the morphometric and the lithology factors, the only modifiable factors to reduce rockfall susceptibility are the "Land use" and "Distance to Roads". However, even though increasing the distance of the road from the rock cliff should reduce the susceptibility, the implementation of this measure is hardly feasible in a very compartmentalized territory marked by narrow valleys. Analysing the available information about the recorded damage, although most of inventoried phenomena do not report information, we observed that about a hundred of the occurred phenomena indicate damage to roads, comprehensive of vehicles damage, and a few tens to buildings, mainly private, and other facilities. In the last years, the availability of web services led to a more accurate collection and management of the ancillary data related to each event, standardizing the format of the data gathering. Therefore, the recent reports include key information as rockfall volume, damage, occurrence date. Future improvements should be carried out, based on this increasingly collected and updated information, specifically, in term of relationship between rockfalls occurrence and their impact. Moreover, the role of forested areas should be investigated, in order to exploit their protective function (Moos, Fehlmann, Trappmann, Stoffel, & Dorren, 2018).

Additional validation of the obtained map has been done applying the Receiver Operating Characteristic (ROC) curve, obtaining a success rate of up to 75% (Figure 7) and confirming the reliability of the proposed modelling.

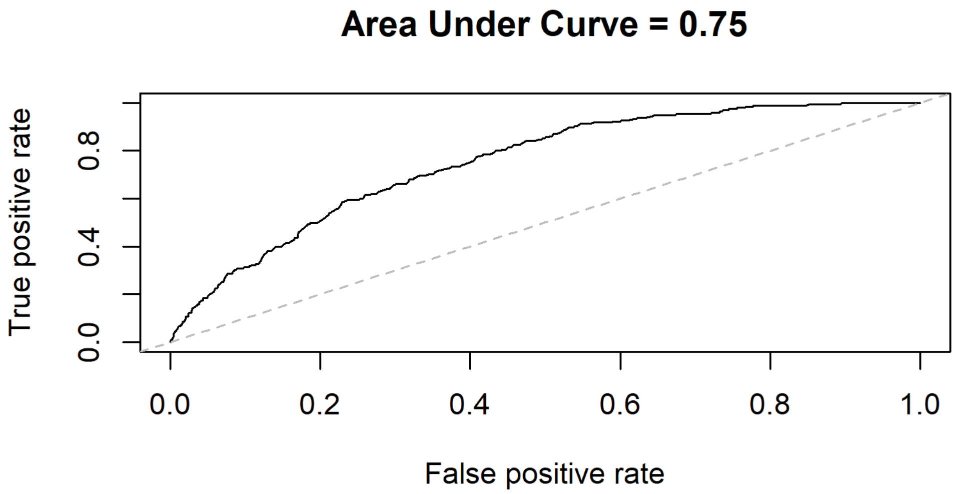

Figure 7 – ROC curve computed on the basis of the comparison between rockfall grid cells and rockfall susceptibility grid.

7. Conclusion

Rockfall hazard is a threat for human settlements and infrastructures in mountain areas. Its characterization deserves a dedicated methodology in order to better manage its impact and consequences. The proposed procedure takes in account several morphometric and thematic parameters in order to map rockfall susceptibility focusing on road network of the AVR by the use of AHP. Additionally, with the aim of improving the analysis set up, a detailed investigation of the recorded events, in the last 40 years, was carried out pointing out seasonality and other relevant data. The outcome of the AHP was then validated by the comparison with a national database of rockfall events resulting in a satisfactory result thus confirming the validity of the proposed approach. The proposed methodology, provides a quick procedure for a preliminary zonation of the areas more susceptible to rockfalls at regional scale, representing a first step in rockfall risks assessment. This preliminary step allowed to identify those areas to be targeted for an in-depth risk analysis, with the support of field observations and measurements collection for following local aspects characterization (e.g. local geological and tectonic setting, rock mass condition). Jointly, this procedure becomes functional to the definition of the actions for the risk management and the implementation of regulation infrastructural works for risk reduction, useful for regional authorities of mountainous territories.

Software

The rockfall susceptibility map was developed by the employment of several GIS tools, available in ArcGIS 10.5.1 (and following releases) and R 3.3 (and following releases).

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6

Conclusions and future perspectives

The main topic addressed in this PhD research project concerned the definition and implementation of adaptive strategies, able to provide innovative approaches for the mitigation of slope instabilities impacts on the urbanized area and anthropic activities. The thesis proposed diverse solutions and tools in this sense, adaptable to the varieties of slope instabilities observed, their features, particularly in term of state of activity and evolution over time, by merging all the available *a-priori* knowledge too. Therefore, this research tried to answer some of the main, still open issues, in the framework of landslide risk mitigation strategies: (i) establishment of the potential impacts of diverse typologies of landslides; (ii) definition of correct management of a large amount of data in the field of monitoring; (iii) development of dedicated methodologies and codified procedures for the diverse phases of an emergency.

The countless slope instabilities affecting mountainous and hilly regions all over the World can vary in type and size, as well as in processes rates. Specifically, the landslide velocity can vary from very-slow, slow (few mm/year) to extremely rapid (more than 5 m/s) (Cruden and Varnes, 1996). In general, the largest number of casualties and losses are due to rapid and extremely rapid landslides. In contrast, minor damage to urbanized areas and anthropic elements can be expected from slow to very-slow phenomena. It is important to note that mountain territory as the north-western Italian one, largely affected by slope instabilities of various type, represents one of the most anthropized mountain areas in the World, with, in addition, significant environmental and cultural heritage. This mountain landscape is the result of centuries, to not say millennium, of human presence and modification through social, cultural and economic footprint, constituting a strategic and economic hinge between North and South of Europe. All these aspects make this territory highly susceptible to landslides and ensure an ideal site for the analysis and the implementation of adaptive strategies for landslide risk management and mitigation. In this scenario, close to the mainstream risk mitigation strategies, *i.e.* engineering solutions, monitoring networks and land utilization regulations, an incoming approach represented by non-structural measures are taking on a relevant role in landslide risk management and mitigation. This new approach is mainly devoted to reduce risk and define novel adaptation measures to safe landscape and guarantee environmental sustainability. It aims to represent an effective response to policy-makers, national and or regional authorities and other stakeholders, in landslide risk management and mitigation, as well as for land use planning purposes.

The research activities performed have allowed the implementation of devoted approaches and methodologies for slope instabilities management and regulation, as well as for the assessment of their impacts on urban areas and anthropic activities. Referring to the considered type of slope instabilities (*i.e.* DsGSDs, complex landslide, shallow landslides, and rockfalls), the multiple results obtained, presented in the published scientific publications, on the whole aim to satisfy some fundamental requirements. In particular, they aim to provide repeatable and effective procedures for a more effective slope instabilities management and mitigation. Moreover, great attention has been drawn to the diverse observation scales, from slope-scale, for single phenomena investigation, to national or regional scale, for several slope instabilities analysis. These requirements, closely related to each other, follow the pillars of the Open Government concepts, for responding to the current trend towards openness and sharing to the policy-makers, national and regional administrations, citizens and other stakeholders of data and information:

1. *STANDARDIZATION*: in order to have a properly functioning organization of the know-how, updatable over time, as well as to guarantee prompt access to data and information, specifically in the emergency phases. Moreover, standardization also in term of appropriate management measures and actions definition and structuration, for a proper landslide risk management and mitigation.

2. *RAISE AWARENESS*: in order to raise the perception of the various slope instabilities risk and their impacts on anthropic activities, specifically for policy-makers, national and regional administrations and the other stakeholders. The awareness is requested to urgently direct attention toward the necessity of landslide risk reduction and management, through multi-source and multi-sensor knowledge acquisition and organization, also according to the previous concept of “standardization”, and for the implementation of sustainable practices.

3. *VERIFIED INFORMATION AND DATA*: in order to answer to the exponential growing production in the last years of multi-source and multi-sensors data and information about slope instabilities characterization and management, following the principles of the Open Data. The use of the Open Data guarantees data and information with good

provenance, regulated by internationally recognized standards about services, software and protocols, by ensuring an efficient organization, managing and sharing of both data and metadata.

4. *TRANSPARENCY*: in order to have efficient protocols and well-defined actions for a more effective slope instability risk reduction and mitigation, able to regulate the interoperability of geoscientists, practitioners, policy-makers and other stakeholders. Transparency provides for a synergic collaboration of all the stakeholders, by ensuring, following the open data principles too, the access to data and their reuse in other similar contexts.

In agreement with these principles, different scale and landslide-type dependent methodologies, have been tested and employed in this research, from the traditional field survey one to the more recent remote sensing techniques, to achieve a proper landscape characterization through a well-reasoned data and information acquisition and organization.
The first step, basilar for proper analysis and characterization of each specific slope instability typology considered, is based on data acquisition, drawing on both historical data and new data acquisition. By this way, the systematic acquisition of the already known or new knowledge about the considered type of slope instability has been carried out for a slope instability characterization as more comprehensive as possible. This stage allowed to the optimization of the existing data, functional to a proper reorganization and integration of the diverse information and data collected over time, for both site-specific phenomena and slope instabilities distributed over wide areas.
By exploiting previous and historical data, mainly obtainable from national and regional institutional sources (*e.g.* national and regional landslides inventories, catalogues, Geo-Portals), the usage of validated data and information and transparency were intrinsically respected. In particular, taking advantage of regional institutional sources, as in the case of DsGSDs and of rockfalls, an overall framework of distribution, geomorphological characteristics and state of activity have been retrieved. The analysis of the available data and their interlinking constituted the basis for DsGSDs characterization and the definition of the impact of these huge phenomena on anthropic elements, actually still poorly or often overlooked in the scientific community, as presented in *Paper II*. Always using data from institutional sources, the in-depth analysis in term of the spatial and temporal distribution of rockfall event catalogued in the Aosta Valley Region landslide inventory (*i.e.* "*Catasto Dissesti*"), has been performed, as presented in *Paper VIII*. For complex landslides, exploiting the Aosta Valley Region landslide cases, previous data correspond to a large amount of internal technical reports, scientific papers and ground deformation measurements directly derived from the regional monitoring network, made available by the regional authorities.
On the other hand, novel data acquisition has been performed for shallow landslide typology investigation, in the Liguria territory, by leveraging on a very-high-resolution digital elevation model acquired by LiDAR survey, carried out in collaboration with the GMG of the CNR IRPI. Based on this previous study presented in (Giordan et al., 2017b), a specific focus on the relationships between shallow landslides occurrence and a human-made environment as the

Liguria one, precisely in terms of agricultural terraces (*i.e.*, anthropic elements that have profoundly modified the Ligurian landscape over time), has been available.
However, the wide availability of multi-source and multi-sensor data and information about the diverse type of slope instabilities considered in the thesis highlighted the still existing problem of proper management and organization of this large amount of data. This issue has been discussed in *Paper III* for site-specific phenomena, and in the *Paper V* for diverse slope instabilities distribute over wide areas. A proper data collection and organization constituted the basis for an in-depth landscape characterization, for each considered type of slope instability and their effects on anthropic activities. With this purpose, diverse methodologies and techniques scale-dependent and landslide-type dependent have been implemented and or applied, all of which meet low cost and easy repeatability requirements. In the cases of shallow landslide and rockfall types, the Analytic Hierarchy Process has been used to generate dedicated landslides susceptibility maps. In order to consider the single peculiarities of the type of slope instability analysed, as well as of the landscape in which they occurred, specific causal factors have been separately considered for shallow landslides and rockfall cases (*Paper VI* and *Paper VIII* respectively). Moreover, in the case of the shallow landslides occurred in a part of the Liguria Region, specific customization of this method has been made, to verify the role of anthropic agricultural terraces in shallow landslides occurrence, as presented in the *Paper VI*.
Jointly, for complex landslide type, the Structure from Motion technique has been applied, by leveraging on multi-source images from aerial photos one to high-resolution images acquired by UAV. By this way, the geomorphological characterization and definition of the Champlas du Col landslide evolution (Piemonte Region) at the slope scale, has been carried out in an easily repeatable and low-cost way, as presented in the *Paper IV*.
Only in the case of DsGSDs typology, the characterization of several phenomena affecting strategic anthropic infrastructures located in the Aosta Valley Region has been carried out by exploiting previously acquired field data, internal to the CNR IRPI Institute, with a dedicated revision leveraging on high-resolution digital elevation model and orthophotos. Moreover, the characterization of the state of activities and the definition of morpho-structural domains of these huge phenomena has been performed by A-DInSAR techniques application. The SAR data have been mainly processed with a free tool, *i.e.* G-POD of the ESA, partially produced in the framework of this thesis and partially available from previous projects of the CNR IRPI Institute (Cignetti et al., 2016; Giordan et al., 2017a). An in-depth geomorphological characterization of several DsGSDs has been carried out, combining on-site observation and A-DInSAR techniques, realizing four detailed geomorphological maps, presented in the *Paper I*.
The core of this research is dedicated to the implementation and testing of dedicated procedure designed for each considered slope instability typology, *i.e.* DsGSDs, complex landslides, shallow landslides, and rockfalls. During the PhD research, it was possible to develop the useful knowledge to establish an operating methodology and dedicated and innovative non-structural mitigation strategies, in synergy with the previous stages devoted to the data acquisition and landscape characterization. By this way, the research outlined the need of the national and regional authorities, policy-makers and other stakeholders to have a

comprehensive and contextualized response for any specific type of slope instability. Moreover, the research focused on the related landslide risk and impacts on human activities, which goes beyond the more common mitigation strategies (*i.e.* engineering solutions, monitoring network, land use regulation). In response to this need, this research provided real tools and non-structural measures, following the abovementioned cornerstones of standardization, awareness, use of validated data and information and transparency.

A dedicated procedure to define the DsGSDs impacts on anthropic activities have been realized to fill a still existing gap both in scientific research and in the current regulatory framework. The methodology has been tested in the Western Italian Alps territory, highly affected by these huge phenomena. The results have displayed the impact on anthropic elements of such phenomena, highlighting the need for a comprehensive assessment of their effects and degree of impact, as presented in the *Paper II*. These findings revealed the need of a functional review of the current regulatory framework, for including modern tools for the effective and safe management of the territories affected by these slow gravity-induced phenomena into the urban planning legislation, filling a still existing gap.

Specific tools and dedicated measures, able to guarantee a proper slope instability characterization and related risk assessment, through a comprehensive and contextualized collection, organization and reusing of the available data, have been implemented. Among these tools and dedicated measures, in this research have been proposed two distinct solutions, one for single phenomena at the slope scale, and one for numerous slope instabilities analysis over wide areas. In the first case, the Operative Monographies (OM in the following) have been implemented, to provide a useful tool able to offer an easily readable standardized document referred to a specific case study. The OM tried to respond to the need of the diverse regulators in landslide risk management and mitigation. This document provides a standardized guidance help for the management of all the numerous available data, collected over time, about a single phenomenon, in order to avoid possible misunderstanding, and jointly suggesting reasoned intervention and the actions to be adopted. This tool resulted particularly suitable for complex landslides investigation, referring to the active complex landslide included in the regional monitoring network of the Aosta Valley Region, a theme highlighted in the *Paper III*. With minor variation and amendments, the OM could also be easily applied for all the type of slope instabilities and in other contexts.

When numerous phenomena, distributed over wide areas, are investigated, for instance, in case of national or European projects, data and information may increase exponentially. A dedicated spatial data infrastructure, implemented through the open-source software GeoNetwork, has been proposed. This service, which has recognized standard about services and protocols, provides a practical tool in slope instability risk management and mitigation, as described in *Paper V*. By this way, a platform aimed to organize, manage and share multi-source and multi-sensor data and metadata, following recognized policies and transparency principle (*e.g.* validated data and information, the possibility to re-use data), has been guaranteed to both scientific community and policy-makers.

This framework has made it possible to take a further step in the PhD research. In particular, the OMs have been included in a dedicated codified procedure designed for efficient management of the impacts of slope instabilities, during the occurrence of adverse weather

conditions. This procedure, tested in the UNESCO site of the Cinque Terre National Park (Liguria Region), and exposed in the *Paper VII*, has been designed for mainly slope instabilities affecting this strategic site from a cultural and geo-heritage point of view. Its main aim is to establish a repeatable and effective protocol aimed at a “multi-user” exploitation, during the occurrence of an emergency and addressed to a more effective slope instabilities management. This codified procedure represents a valid non-structural measure that group the key elements as management and organization of previous data and information about diverse slope instabilities, the manner of collect information about new or reactivated landslides and related damage through a standard form, and the assessment of their potential impact on anthropic activities, following all together with the principles of the standardization, awareness, use of validated data and information, and transparency. This allowed to provide a practical response to national and regional authorities to enhance a sustainable administration of the territory and schedule the appropriate management measures to guarantee the safeguard.
This model paved the way for similar procedures aimed at managing the diverse phases of an emergency during the occurrence of slope instability. For instance, in the case of rockfalls occurrence, a dedicated procedure specific for the definition of the interventions and activities taking place between the rockfall and the installation of permanent risk reduction works, was evident, as preliminary highlighted by the *Paper VIII*. In fact, one of the primary activities of the public technicians and administrators is the evaluation of the danger along the viability to define the correct priorities and choices in an appropriate schedule. At this stage of the thesis a preliminary study for the implementation of a dedicated non-structural measure for the rockfalls occurrence along with road network of the Aosta Valley Region, similar to that experienced in the UNESCO site, is in an experimental phase, representing a future development of this research.

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Part II

Appendixes

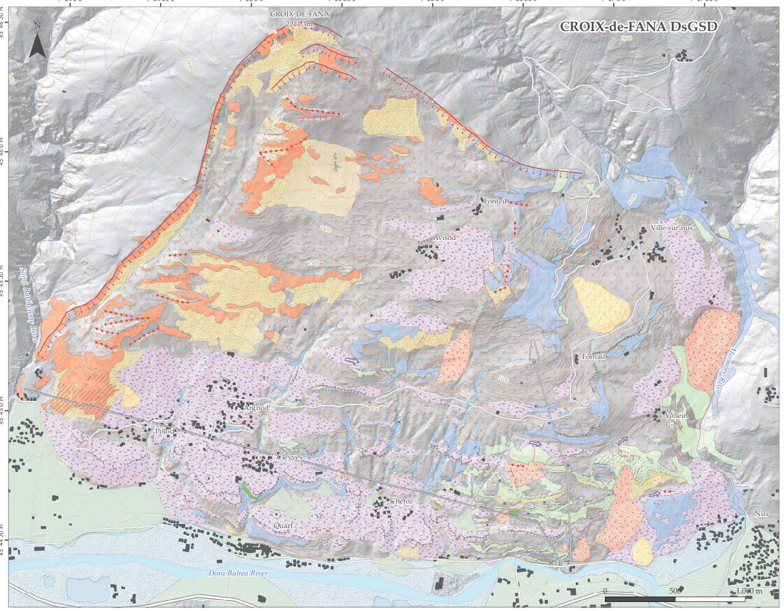
Appendix A – PhD Publications Appendixes and Supplementary Material

Appendix I - Main Map of the Paper I

Paper I: *Geomorphological map of the main Deep-seated Gravitational Slope Deformations of the Aosta Valley Region (NW Italy).*

GEOMORPHOLOGICAL MAP of the MAIN DEEP-SEATED GRAVITATIONAL SLOPE DEFORMATIONS of the AOSTA VALLEY REGION (Northwestern Italy)

D. Giordan[1], M. Cignetti[1 2 *]



QUATERNARY DEPOSITS
- Alluvial deposit with sand and gravel
- Alluvial fan with sand and gravel
- Active talus
- Vegetated inactive talus

ROCK BASAMENT
Piedmond Nappes Domain
- Calcshists with intercalation of mica marbles
- Prasinites with (a) local intercalation of metagabbro

Austroalpine Domain
Dent Blache Nappe
Mont Mary Unit
- Metapelite, granodioritic and leucocratic gneiss

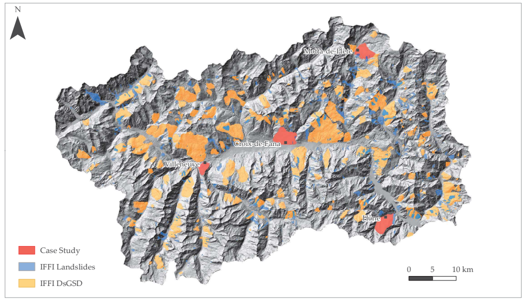
STRUCTURAL LINEMENTS
- Fault
- Low-angle shear plane

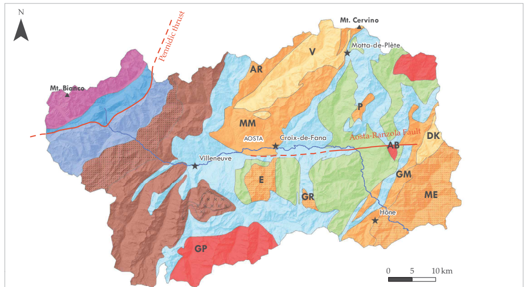
GRAVITY-INDUCED SLOPE LANDFORMS
- Landslide deposit - rock fall deposit; angular caotic blocks deposit with fine matrix. a) active, b) inactive
- Main scarp with downhill step
- Scarp
- Erosional scarp
- Trench
- Elongated depression
- Closed depression
- Local rock dissolution
- Deep-seated Gravitational Slope Deformation

GLACIAL DEPOSITS and LANDFORMS
- Undifferentiated glacial deposit
- Spill-ways
- Sheep-back
- Erratic boulder

ROCK MASSES FRACTURING
- Highly fractured rock
- Very blocky, disarticulated rock
- Poorly interlocked, heavily broken rock

ANTHROPIC ELEMENTS
- Hydroelectric plant
- Cave and backfill





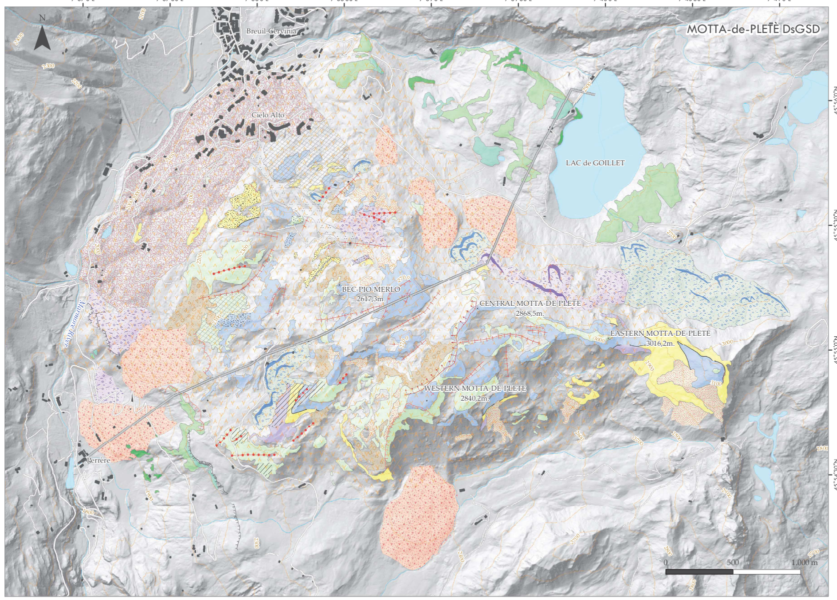
AUSTROALPINE DOMAIN
- GRANULITIC ZONE
Sesia-Lanzo Zone: II dioritic-kinzigitic zone (DK)
Dent Blanche Nappe: Valpelline serie (V)
- GREENSCHISTS ZONE
Sesia-Lanzo Zone: Gneiss Minuti Complex (GM)
Dent Blanche Nappe: Arolla Unit (AR), Mont Mary (MM), Pillonet (P)
- ECLOGITE ZONE
Sesia-Lanzo Zone: Eclogitic Micascist Complex
Dent Blanche Nappe: Emilius (E); Glacier-Refrays (GR)

PIEDMONT NAPPE DOMAIN
- Metasedimentary Cover Unit
- Oceanic Unit

PENNIDIC DOMAIN
- Upper Pennine Unit: Monte Rosa (MR), Gran Paradiso (GP) massifs; Arcesa-Brusson window (AB)
- Middle Pennine Unit (Gran San Bernardo) Axial Permo-Carbonifer Zone (Houillere Zone)
- Ruitor Polimetamorphic Basement and Brianzonese Metasedimentary Cover a: Gran Nomenon Granodioritic Pluton
- External Penninic Unit

ULTRAHELVETIC DOMAIN
- Decollement Nappe

HELVETIC DOMAIN
- Mt. Blanc Massif



QUATERNAY DEPOSITS
- Talus
- Talus with large rock blocky

ROCK BASAMENT
PIEDMONT NAPPE SYSTEM
Combin Unit - Tsatè nappe
Upper Ofiolitic Unit
- Prasinites
- Calcshists

Pancherot - Cime Bianche Unit
Non Ophiolitic Unit
- Calcareous marbles
- Dolomitic marbles
- Quarzites and quarzitic schists

Zermatt Saas Unit
Lower Ofiolitic Unit
- Calcshists s.l. undifferentiated
- Albitic Amphibolites
- Serpentinites

GRAVITY-INDUCED SLOPE LANDFORMS
- Landslide deposit - rock fall deposit; angular caotic blocks deposit with fine matrix
- Chaotic accumulation of angular blocks
- Main scarp with downhill step
- Scarp
- Erosional scarp
- Counter scarp
- Elongated depression
- Trench

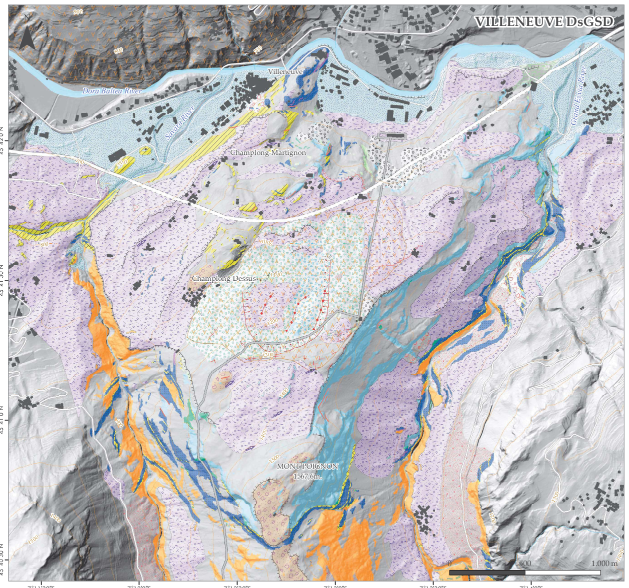
GLACIAL DEPOSITS and LANDFORMS
- Undifferentiated glacial deposit
- Moraine
- Rock Glacier

STRUCTURAL LINEMENTS
- Tectonic limit
- Fault

- Deep-seated Gravitational Slope Deformation

ROCK MASSES FRACTURING
- Highly fractured rock
- Very blocky, disarticulated rock
- Poorly interlocked, heavily broken rock

ANTHROPIC ELEMENTS
- Hydroelectric plant
- Cave and backfill



QUATERNARY DEPOSITS
- Alluvial deposit with sand and gravel
- Lacustrine deposits
- Colluvial deposit
- Major surficial accumulation of rubble
- Talus
- Talus with large rock blocky

ROCK BASAMENT
Piedmont Nappe Domain
- Calcshists with local level of grey schistose marbles
- Prasinites with albite, clorite, epidoto
- Serpentinites

Mid Penninic Gran San Bernard-Briançonnaise System - Gran Nomenon Unit
- Carbonatic micaschists with local albistic micaschists and marbles
- Metrical level of prasinites with albite
- Marbles massif and schistose with Crinoids
- White and yellow marbles, from massive to foliated with muscovite
- Carnioles
- Micaschists and albitic gneisses
- Quartzites massive and micaceous
- Amphibolites massive and foliated, with local garnet

GRAVITY-INDUCED SLOPE LANDFORMS
- Gravitational accumulation with large boulders of prasinites
- Gravitational accumulation with large boulders of calcshists
- Gravitational accumulation with large boulders of prasinites and calcshists
- Deep-seated Gravitational Slope Deformation
- Main scarp with downhill step
- Scarp
- Erosional scarp
- Elongated depression
- Trench
- Closed depression

GLACIAL DEPOSITS and LANDFORMS
- Undifferentiated glacial deposit
- Glacial deposits - skeletal morain
- Spill-ways
- Sheep-back

STRUCTURAL LINEMENTS
- Tectonic limit
- Main fault
- Minor fault
- Main fault

ANTHROPIC ELEMENTS
- Hydroelectric plant
- Cave and backfill

QUATERNAY DEPOSITS
- Alluvial fan with sand and gravel
- Talus
- Debris flow fan
- Mixed fan (alluvial, debris flow, avalanche)
- Lacustrine deposits
- Spring

ROCK BASAMENT
Sesia Lanzo Zone
- Cataclasites and ultracataclasites
- Micaschists and gneiss
- Micaschists albitic-cloritic-epidotic and Gneisses Minuti indistinc
- Paragneisses with garnet porphyroblast

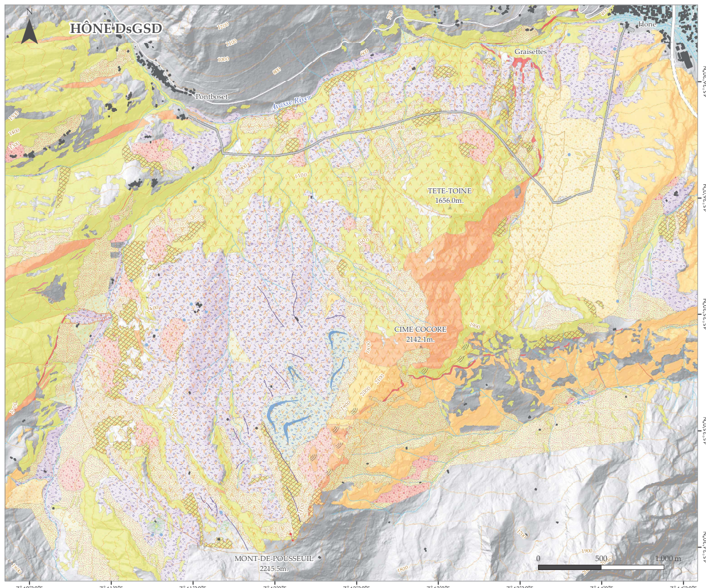
GRAVITY-INDUCED SLOPE LANDFORMS
- Landslide deposit - rock fall deposit; angular caotic blocks deposit with fine matrix. a) active, b) inactive
- Elongated depression
- Scarp
- Double ridge
- Trench
- Deep-seated Gravitational Slope Deformation

GLACIAL DEPOSITS and LANDFORMS
- Undifferentiated glacial deposit
- Moraine
- Rock glacier

STRUCTURAL LINEMENTS
- Fault

ROCK MASSES FRACTURING
- Highly fractured rock
- Very blocky, disarticulated rock
- Poorly interlocked, heavily broken rock
- Very blocky, disarticulated rock

ANTHROPIC ELEMENTS
- Hydroelectric plant
- Slope affected by diffused anthropic remodelling



Croix-de-Fana: Giardino M., Martinotti G., Giordan D.
Villeneuve: Martinotti G., Carraro F.
Motta-de-Pleté: Bertolo D., Martinotti G., Giordan D.
Hône: Martinotti G., Delle Piane L.

Coordinate System:
European Datum 1950
Universal Transverse Mercator, Zone 32N

Base map:
© OpenStreetMap contributors, CC BY-SA
Contour lines interval: 100 m
Digital Terrain Model: Aosta Valley region 2 m cellsize

Affiliation:
[1] National Research Council, Research Institute for Geo-Hydrological Protection, Strada delle Cacce 73, Torino (Italy)
[2] Università degli Studi di Torino, Dipartimento di Scienze della Terra (Ret.), Via Valperga Caluso 35, Torino (Italy)
* Corresponding author: martina.cignetti@irpi.cnr.it

Appendix II – Supplementary material of the Paper II

Paper II: *Impact of Deep-seated Gravitational Slope Deformations on urban areas and large infrastructures in the Italian Western Alps*.

Supporting Information for

Impact of Deep-seated Gravitational Slope Deformation on urban areas and large infrastructures in the Italian Western Alps.

Cignetti, M.[1,2], Godone, D.*[1], Zucca, F.[2], Bertolo, D.[3], Giordan, D.[1]

[1] National Research Council of Italy, Research Institute for Geo-Hydrological Protection (CNR IRPI), Torino 10135, Italy; martina.cignetti@irpi.cnr.it (M.C.); daniele.giordan@irpi.cnr.it (D.Gi.)

[2] Department of Earth and Environmental Sciences, University of Pavia, Pavia 27100, Italy; francesco.zucca@unipv.it

[3] Strutture Attività Geologiche, Regione Autonoma Valle d'Aosta, Quart 11020, Italy; davide.bertolo@regione.vda.it (D.B.).

[*] Correspondence: danilo.godone@irpi.cnr.it (D.Go.)

Contents of this file

Supplementary material

In order to define the impact of DsGSDs on the main anthropic elements of the Italian Western Alps, drawing on the information stored in national and/or regional inventories, or described in both scientific literature and technical report, mainly ordered by regional authorities over time, we could list the notable and know damage due to DsGSDs evolution within the AOI. Table S1 shows the recorded damage, by providing a brief description of DsGSDs characteristics and type of injuries occurred. The source of each information is also reported, associated to the "Supplementary references" section.

Table S1 – List of the documented damage to anthropic elements, caused by DsGSDs long-lasting evolution over time in the Italian Wester Alps area of interest.

Name	Description	Type of Damage	Source
		PIEMONTE AREA (PR)	
Rosone, Locana (TO)	Active DsGSD evolving in a complex landslide	Penstock and reservoir	Amatruda et al., 2004; Delle Piane et al., 2010
Sauze d'Oulx, (TO)	Active DsGSD highly evolved through "rock flow" mechanism.	Groups of buildings/urban areas damage	Fioraso, 2017
		Road pavement damage	
Cima del Vallone, Exilles (TO)	Active DsGSD with high relief energy, and numerous secondary landslides associated (e.g. rockfall)	Road damage	Fontan and Dematteis, 2002; Giardino et al., 2004; Giardino and Ambrosio, 2002
		Rockfalls close to the Cels hamlet	

Cima del Bosco, Cesana Torinese (TO)	Active DsGSD with distinct kinematic domains	Groups of buildings/urban areas, with evident injuries to the outer walls of the Thures, Rif.o la Chenal, Thures Gorlier and Champ Quartier buildings. Abnormal inclinations of slabs, walls, columns and flues are also recorded	Alberto et al., 2008a
		Road damage	
		Damage to the water regulation infrastructural works of the Thuras river	
Grange Sises, Sauze di Cesana (TO)	Active DsGSD, known since the 1970s, associate to numerous secondary landslides.	Groups of buildings/urban areas damage	Angelino et al., 2004; Ansaldi et al., 1979; Barla et al., 1983; Grasso, 1979
		Road damage	
Champlas du Col, Sestriere (TO)	Active DsGSD associated to numerous secondary landslides	Road damage, repeated over time. Paroxysmal event occurred during spring 2018, with the interruption of the SP 23 road to Sestriere.	Cignetti et al., 2019
Rocca Sella, Rubiana (TO)	Active DsGSD with distinct kinematic domains, associated to secondary landslides	Road damage, with retaining wall collapse at the 3 km of the SP 197, and downstream slide of gabionades.	Mortara, 1997, 1994
Torre delle Giavine, Boccioleto (VB)	Active DsGSD associated to numerous secondary landslides.	Damage along the road network and retaining walls injuries. Interruption of the SP for the Sermenza Valley, close to Torre delle Giavine hamlet.	Amici et al., 2003
Agrò, Trasquera (VB)	Active DsGSD with distinct kinematic domains	Groups of buildings/urban areas – some cracking of the Schiaffo hamlet buildings	ARPA Piemonte, 2011

Delpizzen, Traversella (TO)	Active DsGSD associated to secondary landslides	Road deformation in the middle and low portion of the DsGSD, with road pavement damage and lowering Building damage (2002-2016 surveys)	Perrone and Troisi, 2004; Prinzi and Troisi, 2002
Oira, Nobio (VB)	Dormant DsGSD. Last activation in November 1951 and November 1968	Lowering of the front part of a building, with consequent evacuation	Crosta and Berto, 1996; Perrone and Troisi, 2001
		AOSTA VALLEY AREA (AVR)	
Saint Nicolas	Active DsGSD	Groups of buildings/urban areas damage Road damage	Centro Funzionale Regione Autonoma Valle d'Aosta, 2019
Moriond, Valgrisenche	Active DsGSD with distinct kinematic domains	Anomalous stresses and deformations in the dam structure, with consequent demolition of this structure	Barla, 2018; Marcello and Meda, 2013
Croix de Fana, Quart	Active DsGSD with distinct kinematic domains	Damaging of the concrete lining of a hydroelectric bypass tunnel Road damages Triggering of a large rockslide with river damming scenario (Vollein)	Centro Funzionale Regione Autonoma Valle d'Aosta, 2019; Martinotti et al., 2011
Gabinet, Gressoney La Trinitè	Active DsGSD with distinct kinematic domains	Penstock damages and replacing of the older one with a new penstock on a new layout	Aosta Valley Region, Geological Survey
Rondias, Donnas	Active DsGSD	Damages to secondary roads	Aosta Valley Region, Geological Survey
Motta de Pléte, Breuil-Cervinia		Strong damages at the buildings of Cielo Alto locality	Martinotti et al., 2011

	Active DsGSD with distinct kinematic domains	Injuries to the penstock of the hydroelectric plant	
Valtournenche	Active DsGSD with distinct kinematic domains, associated to secondary landslides	Several active kinematic domains, distributed damages to buildings and secondary roads.	Aosta Valley Region, Geological Survey
Becca d'Aver, Verrayes-Chambave	Active DsGSD with distinct kinematic domains, associated to secondary landslides	Damages to a tunnel of the Turin-Aosta railway in the XX century led to the building of a new layout.	Aosta Valley Region, Geological Survey
Pleyney-Predumaz, Saint-Rhemy-en-Bosses	Active DsGSD with distinct kinematic domains, associated to secondary landslides	Several damages to the Grand Saint Bernard International Highway E27. Several refurbishments during the last decades.	Aosta Valley Region, Geological Survey
Verrogne, Rhemes-Saint-Georges	DsGSD	Damages to buildings and secondary roads. A collateral active and faster-evolving landslide is triggered (Parriod).	Aosta Valley Region, Geological Survey
Mont de la Saxe, Courmayeur	Inactive DsGSD	Large collateral rockslide threatening the A5 international Highway, the Skyway ropeway and touristic location.	Aosta Valley Region, Geological Survey
Verrand, Courmayeur	DsGSD	Several ancient buildings damaged and the medieval church in the town center.	Aosta Valley Region, Geological Survey
Punta Lavassey, Rhemes Notre Dame	Active DsGSD	Groups of buildings/urban areas damage	Centro Funzionale Regione Autonoma Valle d'Aosta, 2019

Cleyva, Champorcher	DsGSD	Groups of buildings/urban areas damage	Centro Funzionale Regione Autonoma Valle d'Aosta, 2019
Nayon, Torgnon	DsGSD	Groups of buildings/urban areas damage	Centro Funzionale Regione Autonoma Valle d'Aosta, 2019
Villeneuve	DsGSD	Modification of the Villeneuve hydroelectric plant projection, due to a collapsed zone in the central portion of the DsGSD	Martinotti et al., 2011
Hône, Pontboset	DsGSD	Modification of the Hône hydroelectric plant projection, due to a reactivation of the shear plane of the DsGSD	Martinotti et al., 2011

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Appendix III - Main Map of the Paper III

Paper III: *Operative Monographies: Development of a new tool foe effective management of landslide risk*

BOSMATTO

Municipality: Gressoney Saint Jean, locality Bosmatto

Type of landslide: Complex landslide, evolved into a debris flow.

Height min/max.: 1460 – 2150 m a.s.l.

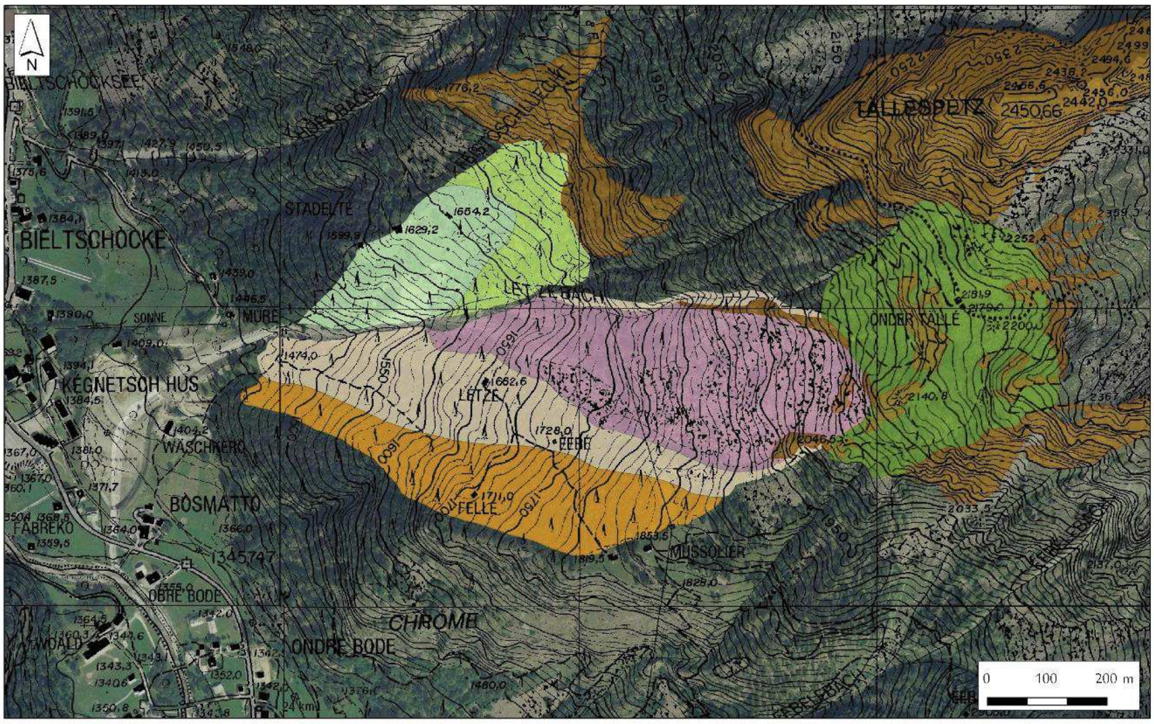
Land use: Open spaces with little or no vegetation, bare rock or deposits; localized urban areas associated to pastures.

Geology: Austroalpine Domain, divided in two principal units: i) Sesia-Lanzo Zone, composed by the Eclogitic Micaschists Complex, the Gneiss Minuti Complex, and the Second Dioritic kinzigitic Zone; ii) Dent Blanche *s.l*. nappe.

Geomorphology: Letzé catchment divided in: i) an upper sector characterized by extended scree material, with local rock fall deposits sometime associated to glacial deposits; ii) a lower sector characterized by a glacial step with a lateral-end moraine. Processes of river capture in correspondence of the basin watershed.

The October 2000 flood event: the Bosmatto landslide evolved into a debris flow, affecting the alluvial fan of the Letzé River, by modifying the morphometric aspects. Subsequently activation of the landslide located on the right side of the Letzé River.

The 2002 flood event: Stadelte landslide activation, involving the moraine deposits.



Landslides subdivision (modified from the technical report edit by Geodes S.r.l. (may 2010)).

Stadelte Landslide - no vegetated
Stadelte Landslide - vegetated
Bosmatto (or Letzé) Landslide - no vegetated
Bosmatto (or Letzé) Landslide - vegetated
Mussolier Landslide - vegetated
Area characterized by unstable bedrock
Bare rock

1 PREVIOUS WORKS ANALYSIS

The previous data analysis revealed a large number of technical and scientific studies, associated to thematic maps and technical annexes, drafted by diverse private agencies over time (from March 2002 to September 2012). All the collected data are summarized in the table below, separated in eight categories. In general, the existence of two separate phenomena, the Bosmatto landslide and the Stadelte landslide, was observed. In the first row is specified when the report speaking of Bosmatto, or Stadelte landslide, or both.

BOSMATTO LANDSLIDE

	Bosmatto		Stadelte	Bosmatto + Stadelte	
Category	Agency 1 Mar. 2002	Agency 1 Apr. 2002	Agency 2 Nov. 2006	Agency 3 May 2010	Agency 4 Jun 2011
Geological-Geomorphological survey	X	-	X	X	-
Geological Map	X	-	-	X	-
Geomorphological Map	X	-	-	X	-
Structural survey map	X	-	-	X	-
Geological Profile	X	-	-	X	-
Hydrologial/Hydrogeological survey	X	-	X	X	-
Risk scenarios/Spatial prediction model	-	X	-	X	X
Monitoring network analysis	-	-	X	X	-

The collected data also included ancillary data, including technical test results and specific surveys, reported in the table below.

Technical test/survey	Society	Month/Year
Snow water equivalent assessment	Agency 4	Aug. 2010 Nov. 2011 Sept. 2012
Geophysical survey	Agency 5	Jun. 2006
Borehole thecnical specification	Agency 3	Oct. 2007

1.1 Geological, Geomorphological, Structural and Hydrogeological aspects

The previous data analysis show an exhaustive framework from a geological, geomorphological, structural and hydrogeological point of view. From March 2002 to September 2012 various technical and scientific studies have been carried out for the Letzé catchment, drafted by three distinct private agencies: 1) Agency 1 (2002); Agency 2 (2006); Agency 3 (2010).

Agency 1 (March 2002)

Definition of two old landslides, named "**Paleofrana 1**" and "**Paleofrana 2**", located on the left side of the Letzé River. The technical report sets out a **complete geological study**, comprehensive of geological setting definition, geomorphological survey, lithological survey, structural survey, aimed at the establishment of the landslide activation during **the October 2000** flood event, **focusing on the effect of the landslide activation on the Letzé torrent alluvial fan**. A technical annex is reported in figure below.

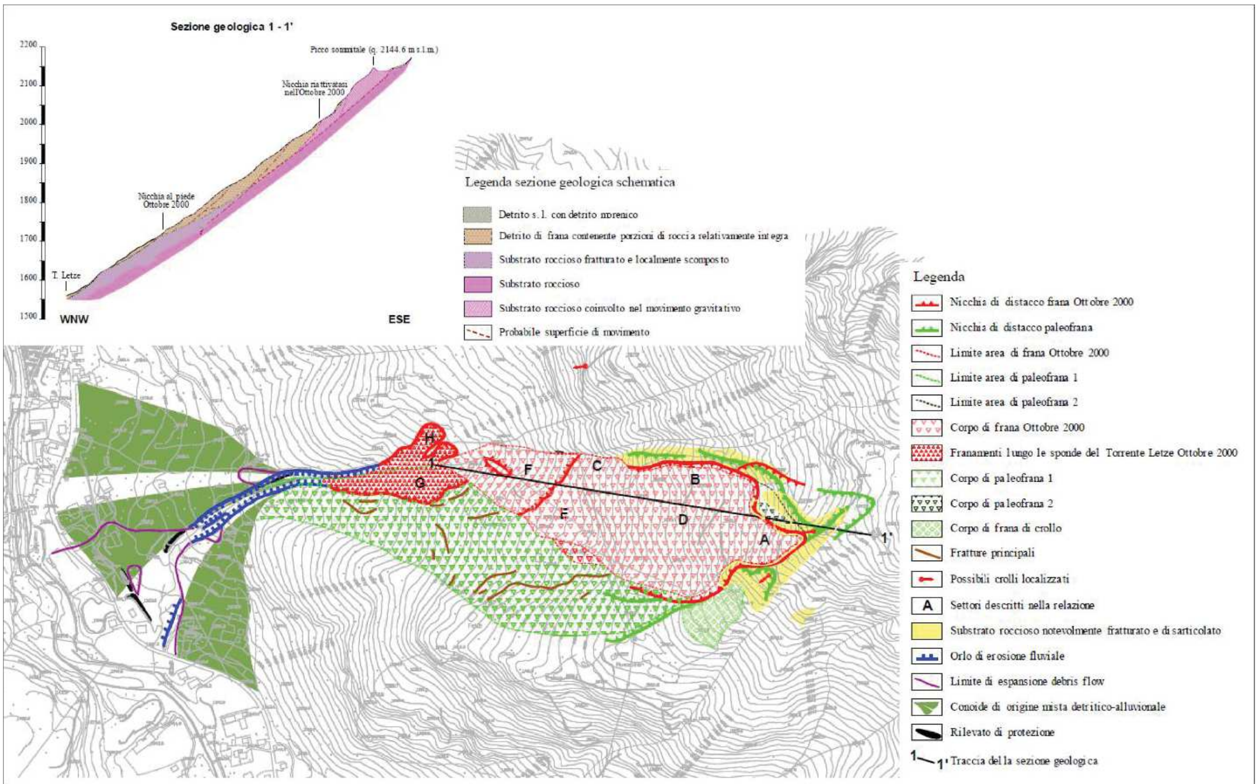


Figure 1 – Technical annex of the geomorphological map of the Paleofrana 1 and Paleofrana 2, relative to the October 2000 flood event (from Agency 1 2002).

Agency 2 (November 2006)

Definition of the **hydrogeological aspect of the Letzé catchment**, comprehensive of a geological setting definition, a detailed geomorphological field survey, and ground deformation measurement acquisition from the **GPS monitoring network**, active from the August 2004.

Specifically, this technical report analyzes the **Stadelte landslide**, located in the right side of the Letzé River, activated during the summer of 2002. Ancillary data are available, with several **seismic sections** along and across the landslide body, revealing a landslide body with a variable thickness from 5 to 20 m. From the GSP measurements analysis, a cross-correlation from snowmelt and seasonal reactivation (in May-June) has been assumed.

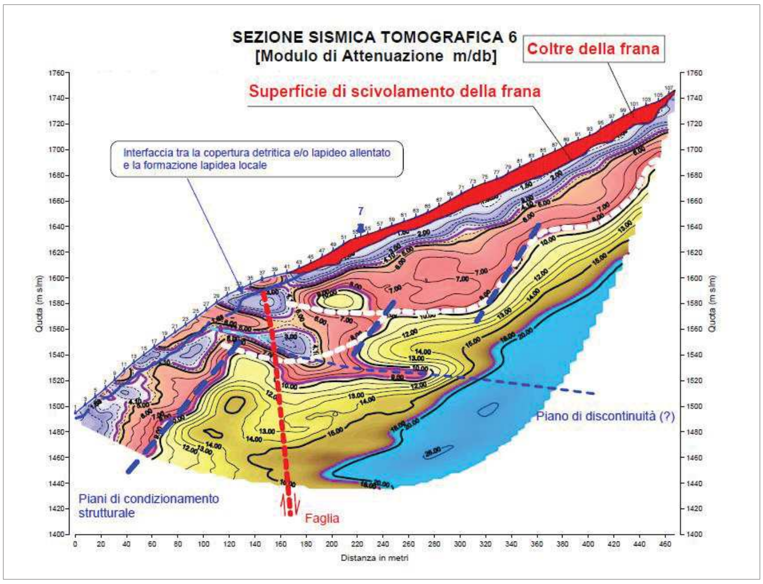


Figure 2 – Tomographic profile (from Agency 5 in Agency 2' report, 2006). The blue line corresponds to the Stadelte landslide surface.

Agency 3 (May 2010)

Revision of the state of knowledge of the **Bosmatto landslide**, in the left side of the Letzé River, and the **Stadelte landslide**, on the right side. By exploiting the previous knowledge (Agency 1, 2002, Agency 2, 2006), integrated with a photo-interpretation of the basin, field survey, hydrogeological survey, monitoring network data analysis, and new seismic survey, the definition of the landslides occurred within the Letzè basin is provided. This technical report is a good example of an **in-depth characterization of the landslides evolution** over time, **integrating previous data** in a complete geological study.

For the **Stadelte landslide**, a superficial movement involving residual soil (thickness from 12-18 m to 18-20 m), with a landslide surface corresponding to the soil-rock interface is proposed. The landslide behavior is highly related to the rain and snow precipitation, with late-spring reactivation.

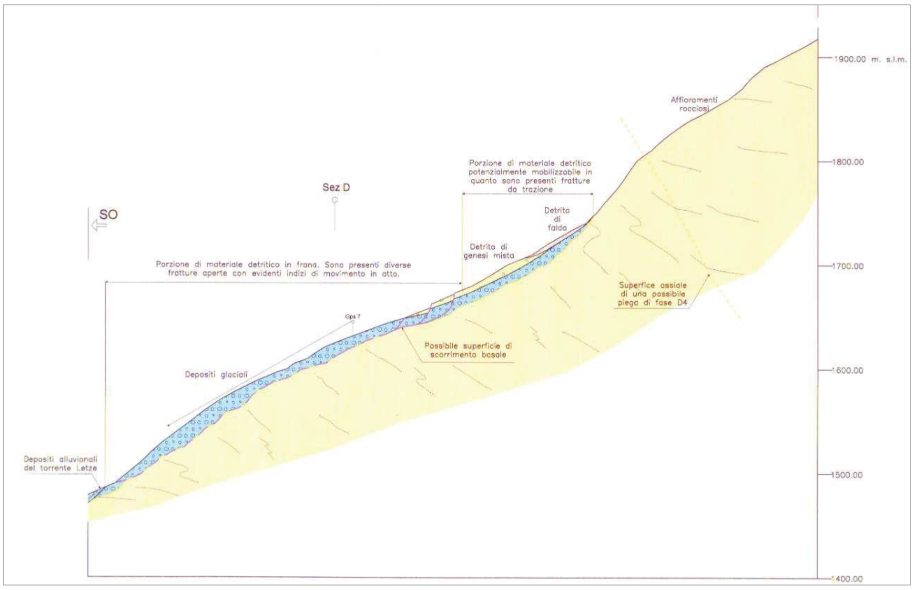


Figure 3 – Geological profile of the Stadelte landslide (from Agency 3, May 2010).

For the **Bosmatto landslide**, a deeper landslide involving the bedrock, with surface variable from 25 to 60 m in depth, and surmounted by two smaller superficial landslides, is proposed. The landslide behavior results independent from the rain and snow regime.

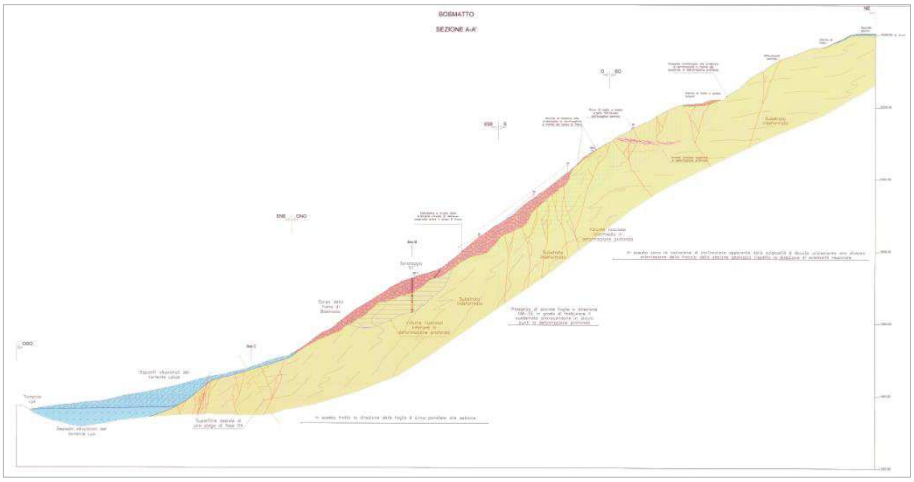


Figure 4 – Geological profile of the Bosmatto landslide (Agency 3, May 2010).

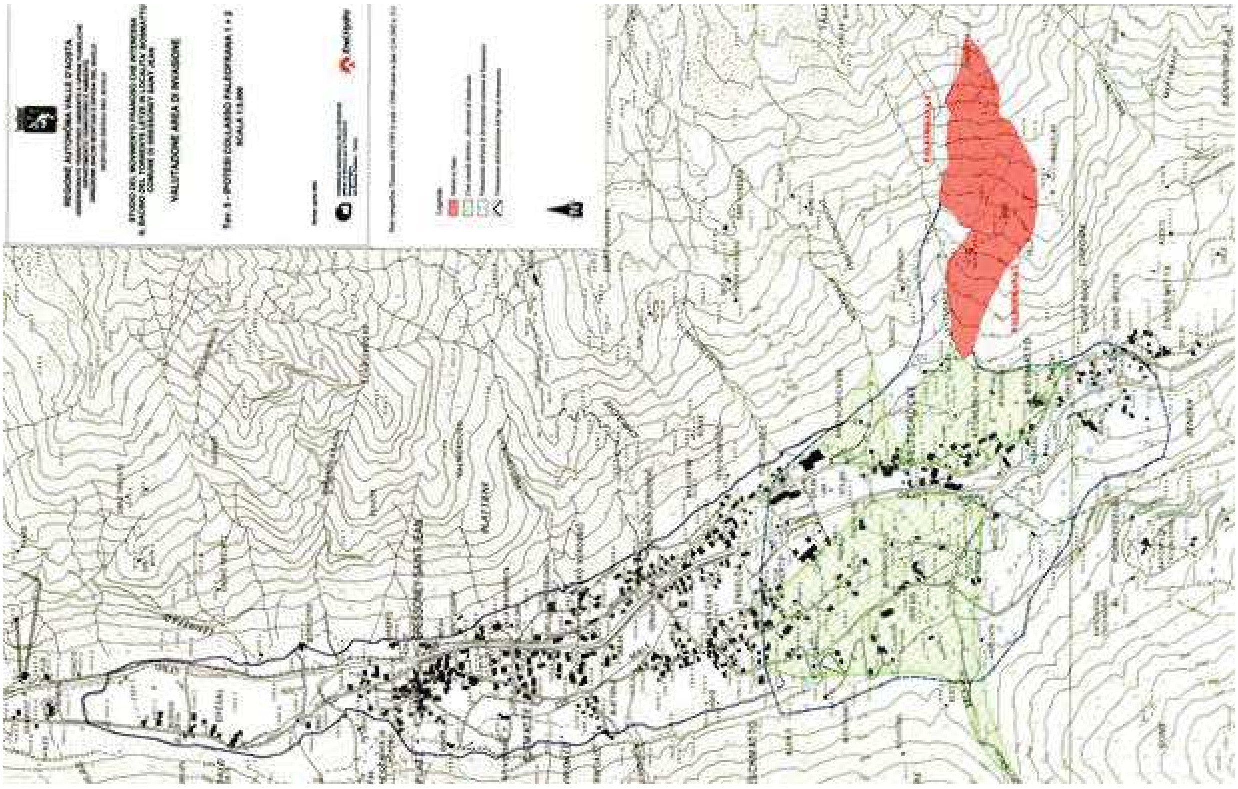
1.2 Risk scenarios and spatial prediction model

Relative to the risk scenarios and the spatial prediction model, three private agencies (Agency 1, Agency 2, Agency 4) drafted technical report from April 2002 and June 2011.

Agency 1 (April 2002)

Definition of the prediction model by computing:

- Evaluation of maximum rate of the flow and its lateral expansion
- Accumulation and/or invasion area of the Bosmatto landslide
- Accumulation and/or invasion area of debris flow associated

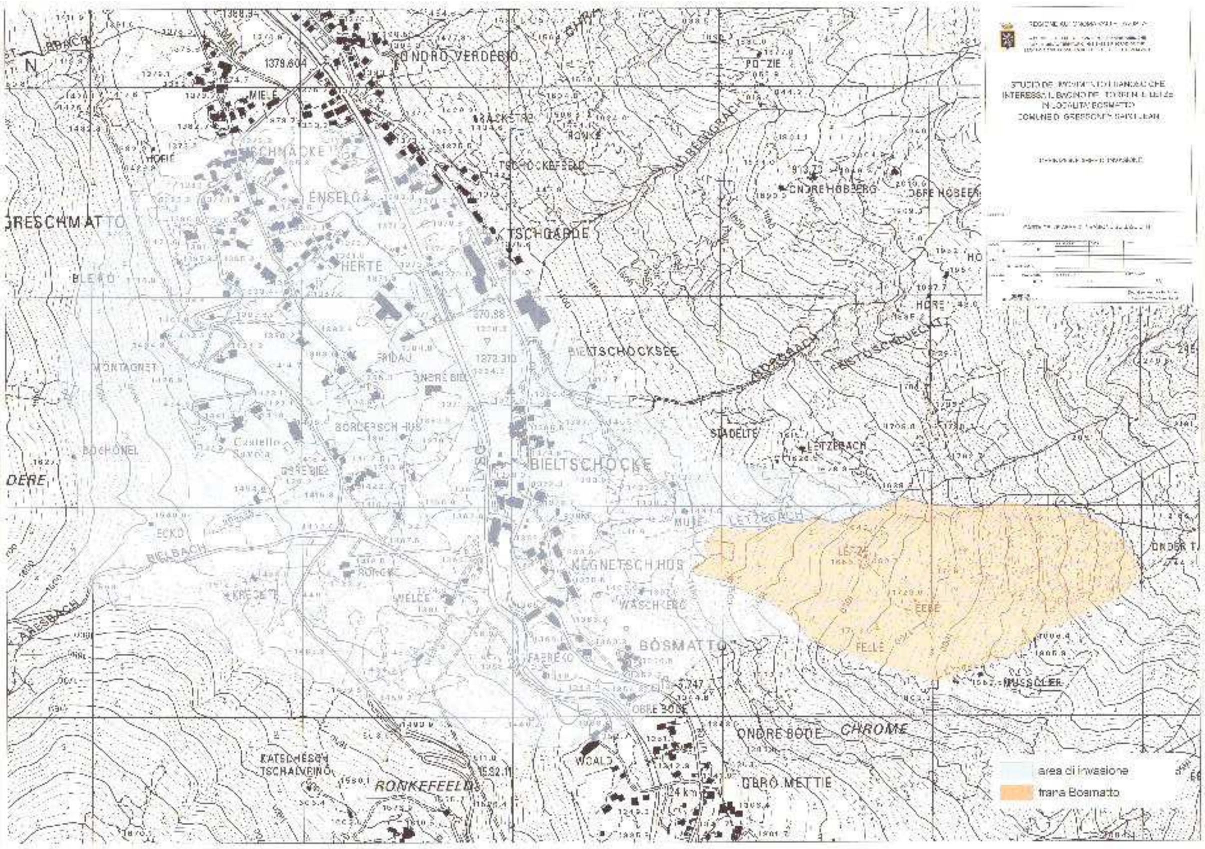


Bosmatto landslide accumulation and/or invasion area (from Agency 1, Apr 2002).

Agency 2 (May 2010)

Definition of:

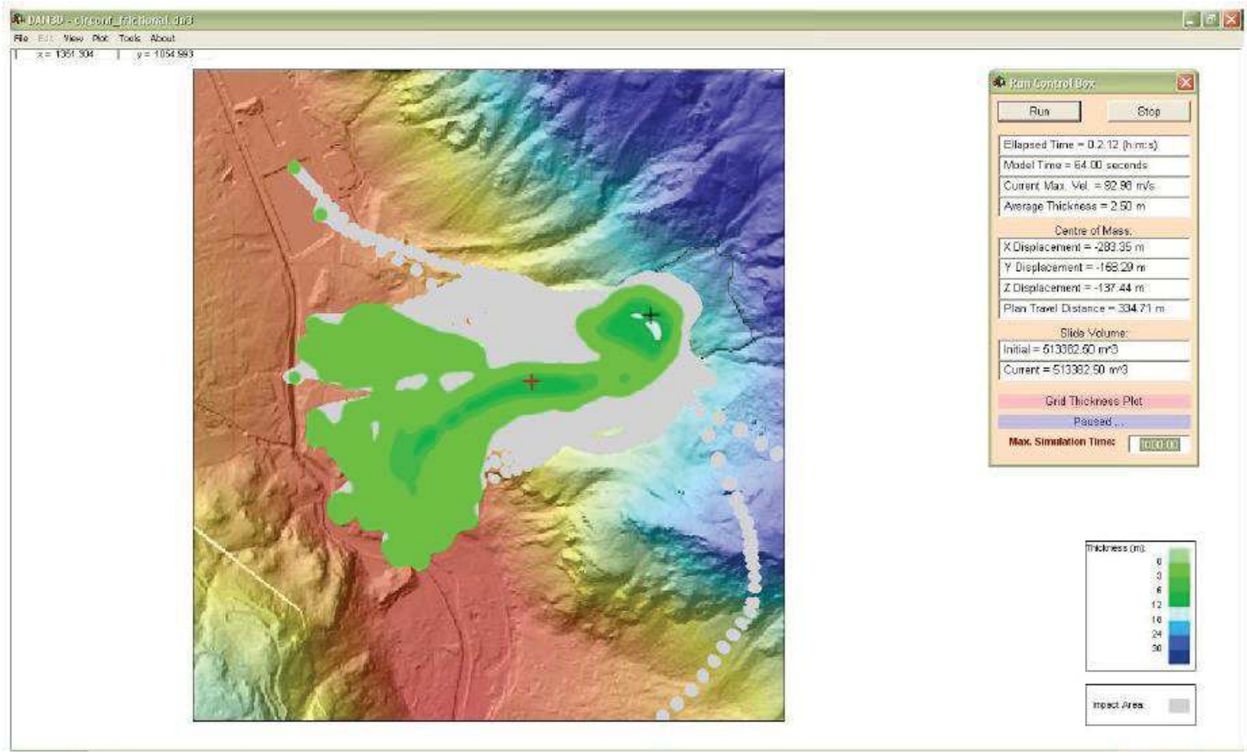
- Computation of the trigger model and of the Bosmatto and Stadelte landslides evolution
- Prediction model with definition of axial speed and lateral expansion
- Accumulation and/or invasion areas delimitation
- Prediction model with definition of pre-alert and alert thresholds



Bosmatto landslide accumulation and/or invasion area (from Agency 2, May 2010).

Agency 4 (June 2011)

Definition of accumulation and/or invasion areas with the computation of the run out of the Stadelte landslide by DAN3D.



Example of runout computation with DAN3D for the Stadelte landslide (Agency 4, June 2011).

The table below summarize the principal data and results collected by the three private agencies.

Author	Landslide	Type of movement	Volume (m^3)	Risk scenario
Agency 1 (April 2002)	PALEOFRANA 1	Rock and debris avalanche	3.270.000	Straight propagation along the Letzè river, up to the valley floor.
	PALEOFRANA 2	Rock/debris slide	1.700.000	Propagazione rettilinea NO-SE, con impatto sul versante destro del T. Letzé, scavalcandolo nel tratto terminale, sino ad invadere il fondovalle principale
Agency 2 (May 2010)	Bosmatto landslide		4.946.928	
	Mussolier landslide		1.141.928	
	Stadelte landslide, active portion		328.525	

	Stadelte landslide dormant portion		373.485	
Agency 4 (June 2011)	Hypothesis 1 (Paleofrana 1)	Planar surface	380.000	Landslide with basal surface corresponding to the rock/deposit interface, based on seismic data
	Hypothesis 2	Rotational surface	510.000	Most probable scenario based on geotecnical data

1.3 Monitoring network data

The monitoring network data acquisition and analysis is carried out by three diverse private agencies, in different period over time (table below). Generally a discrepancy in data representation has been observed.

	First acquisition	Last acquisition
Agency 2 **November 2006**	August 2004	July 2006
Agency 3 **May 2010**	2000	2008
RAVdA **Internal annual reports**	2010	2014

From the previous data analysis the distinction between the Bosmatto and Stadelte monitoring network has been delineated.

The Stadelte monitoring network consists of:

- Four extensometers
- One automated GPS

The Bosmatto monitoring network consists of:

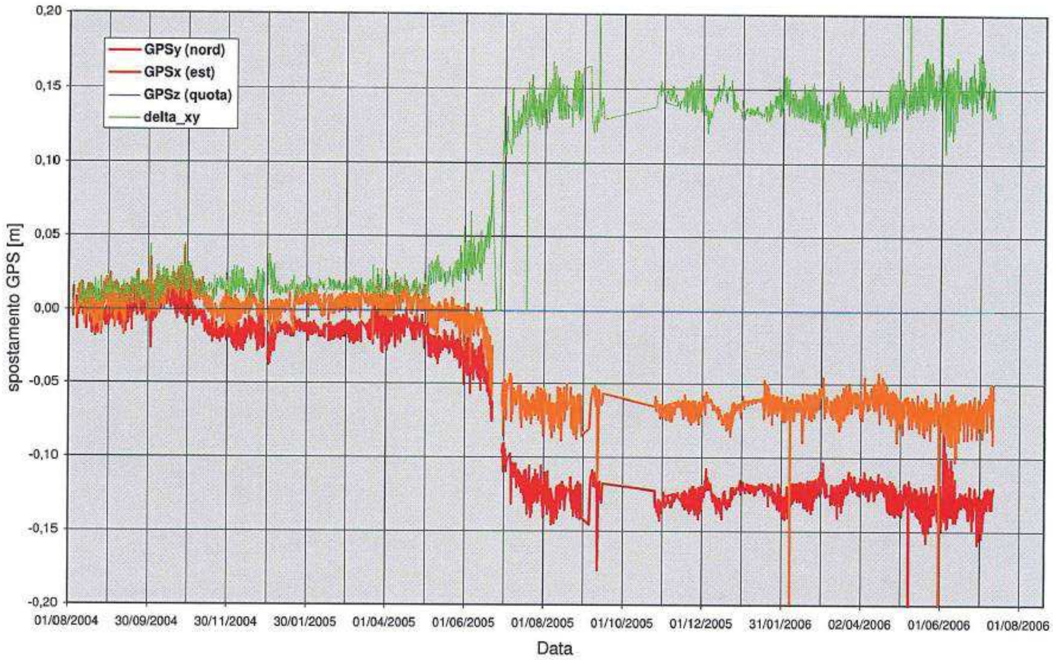
- Four extensometers (removed in 2010);
- Two automated GPS and one reference point;
- Seven GPS benchmarks (manual);
- One piezometer;
- Three Webcam;
- A meteorological station.

	Monitoring network	Acquisition range	First acquisition	N° of elements	Note
Stadelte landslide	Extensometers (Stadelte)	Hourly	1 Jun. 2007 (E1) 2 May. 2010 (E2, E3) Dec 2011 (E4)	3 + 1	Late spring and autumn acquisitions. The instruments do not guarantee a proper functioning.
	Automated GPS	4 sessions/day	Aug. 2004	1	
Frana di Bosmatto	Extensometers (Bosmatto)		Aug. 2006	4	Active only during the late spring and autumn. Instruments removed in 2010.
	Automated GPSi	4 sessions/day	2002	2+1 REF	Short break in data acquisition in 2005. GPS7 recorded the landslide reactivation in 2005 and from 2010 to 2014.
	Manual GPS	yearly	Jul. 1997	7+1 REF	
	Piezometer	Hourly	Summer 2009	1	

Table 5 – List of the instruments constituting the Stadelte and Bosmatto monitoring networks.

Agency 2 (November 2006)

Monitoring network data acquisition and elaboration of the Stadelte landslide from 2004 to 2006. In specific, the ground surface deformation time series of the automated GPS7 are generated and compared with the available meteorological parameters. In the late spring of 2005 a reactivation (15-20 cm) was recorded, as a result of the snowmelt. The time series show separately the East, North and altimetric components, for each year in the period of acquisition.

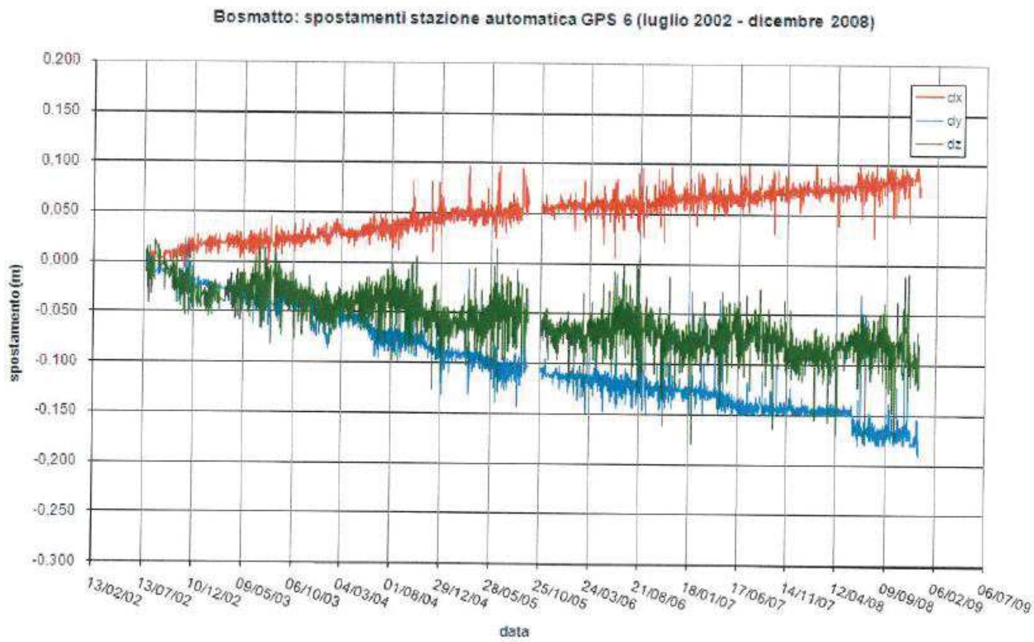


Example of ground deformation time series presentation, relative to an automated GPS (Agency 2, November 2006). The graph report the East, North, planimetric and altimetric time series of the Stadelte GPS from August 2004 to July 2006

Agency 3 (May 2010)

Monitoring network data acquisition and elaboration of the Stadelte and Bosmatto landslides from 1992 to 2008. The period is very extensive due to the PS data availability, processed by the PSInSAR technique, relative to the period from 1992 to 2000 (table below).

	First acquisition	Last acquisition
Extensometers	2006	2008
Manual GPS	2002	2008
Automated GPS	2002	2008
Permanent Scatterers	1992	2000



Example of ground deformation time series presentation, relative to an automated GPS (Agency 3, May 2010). The graph report the three displacement components East, North and altitude from July 2002 to August 2008.

For the **Bosmatto landslide**, the monitoring network consists of four extensometers, two automated GPS, and eight manual GPS are measured. The extensometer are measured only from the late spring to autumn, due to the snow cover. Agency 3 establishes these instruments unusable and disagree with the other instruments.

The **manual GPSs** are measured once a year, and the ground deformation time series report the planimetric and altimetric displacement, with planimetric displacements variable from 3 cm/year to 14 cm/year, with ESE-WNW direction, and altimetric displacements variable from 1 and 7 cm/year.

The **automated GPS** network are measured four times a day, and the ground deformation time series report the three component East, North and altimetric with variable displacement from 1.5 to 3.5 cm/year.

The **PS data** analysis point out the October 2000 event activation, with LOS displacement of about 28 mm/year. From 2005 a general reduction in rate has been recorded.

For the **Stadelte landslide**, the monitoring network consists of one automated GPS and one extensometer, while in 2010 and 2011 three other extensometers are installed.

The automated GPS recorded a displacement of about 4 m, until 2008, with an acceleration during the 2007 spring. A good agreement with the extensometer measurements has been recognized.

RAVdA INTERNAL REPORTS (from 2009)

From 2009, internal reports drafted by the Aosta Valley authority are available. The ground deformation time series report variably the singular component of the displacement (e.g. East, North, altitude) and /or the planimetric and 3D displacement, without a standardized format. In the table below are reported the annual displacement recorded from each monitoring network and the associated time series reported.

	Monitoring network	Type of acquisition	2009	2010	2011	2012	2013	2014
Stadelte Landslide	GPS 7	Planimetric and Altimetric displacement	5.08 m	1 m	35 cm	15 cm	80 cm	32-35 cm
	E1	Displacement	4 m	80 cm	25-30 cm	10-12 cm	Operational problems	21 cm
	E2	Displacement		80 cm		No data	Instrument removal	-
	E3	Displacement		65 cm	25-30 cm	10-12 cm	80 cm	30 cm
	E4	Displacement				7 cm	60 cm	33 cm
Frana di Bosmatto	E1 E2 E3 E4	Displacement form 2006 to 2009		Instruments removal				
	GPS 5	3D displacement	0,012 m	0.0048 m	0.001 m	0.013 m	0.007 m	0.013 m
	GPS 6	3D displacement	0,08 m (Jun-Dec)	0.0262 m	0.026 m	0.021 m	0.02 m	0.031 m
	B2	3D displacement	0.009 m	0.009 m	0.002 m	0.008 m	0.09 m	0.098 m
	B3	3D displacement	0.314 m	0.218 m	0.121 m	0.215 m	0.147 m	0.104 m
	B4	3D displacement	0.166 m	0.009 m	0.007 m	0.015 m	0.013 m	0.006 m
	B5	3D displacement	0.092 m	0.052 m	0.034 m	0.04 m	0.065 m	0.039 m
	B6	3D displacement	0.113	0.035	0.025	0.04	0.038	0,019
	B7	3D displacement	0.044 m	0.025 m	0.018 m	0.029 m	0.023 m	0.017 m
	B8	3D displacement	0.102 m	0.064 m	0.045 m	0.062 m	0.06 m	0.039 m

Table 7 – Extensometers and GPS displacement measurements relative to the RAVdA.

2 GROUND DEFORMATION TIME SERIES ANALYSIS

The analyses of the monitoring systems of Bosmatto and Stadelte landslides resulted in a large amount of data covering approximately two decades (see Table 8).

MONITORING SYSTEM	BEGINNING OF ACQUISTION	LAST AVAILABLE DATA
GPS manual	July 1997	October 2014
GPS automatic	July 2002	December 2015
Extensometer	June 2007	December 2015

Table 8 – Periods of data availability for Bosmatto landslide.

The collection and revision of the bibliographic material showed a certain variability in the presentation of ground deformation series from various monitoring networks. Furthermore, there is no a clear distinction between the presented data of the two landslide bodies (Stadelte and Bosmatto). Moreover, different choices were made by different companies to perform data elaboration, both for the type of data representation (e.g. graphs, vectors) and for the parameters to be represented (e.g. planimetric, three-dimensional displacement).

In order to standardize the monitoring data sets received from the Department of public works, soils conservation and public housing, the data were first analyzed and reprocessed in Matlab environment, creating the most complete and continuous historical time series. Specifically, time series without interruptions were obtained for the GPS 5 and 7. In the case of GPS 6, the continuity of data was interrupted in 2009 by an avalanche, and in consequence, two separate time series are reported (pre and post avalanche).

For automatic GPS 5 and 6 of Bosmatto landslide, the following plots were generated:

- time series of planimetric displacement for entire period
- time series of altimetric displacement for entire period

A smoothing function based on a moving average was applied to the raw data of GPS 5 and 6. Figures 8 and 9 show the evolution of planimetric and altimetric displacement of GPS 5 and 6.

It should be noted that during 2009 an avalanche affected the GPS6, and for this reason only data from June to December were considered. The measures acquired in that year showed a significant variation in altimetric direction, with movements not comparable with previous years. After all, in 2010, it was found that this problem was related to the repositioning of the pylon on which GPS benchmark was located.

It should be noted that the extensometers installed within the Bosmatto landslide were acquiring the data from 2006 to 2010. These instruments were removed in summer 2010, as the measures were non-representative of the evolution of the landslide body. It should be noted that, in accordance to the present convention, the raw data from four extensometers installed within Bosmatto landslide were not included in the material delivered by the RAVdA. For data related to the manual GPS, please refer to the annual internal reports of RAVdA. These data are not available in this document.

The following plots were generated, for automatic GPS 7 of Stadelte landslide:

- time series of planimetric displacement for entire period
- time series of altimetric displacement for entire period
- comparative representation of planimetric displacement on one year time window
- comparative representation of altimetric displacement on one year time window

As for the other GPS, a smoothing function based on a moving average was applied. Figures 10, 11 and 12 show the elaborated plots for the GPS 7, where the reactivations are noticeable.

Figures 10 and 11 highlight the highly seasonal trend of this landslide, which is certainly affected by the melting effect of the snowpack.

For the extensometric network, the available data were revised in order to create the most continuous possible time series (Figures 13, 14, 15 and 16). No time intervals have been defined with limits set a priori, but data are presented when available and reliable. The presented data are shown separately for each year. However, the analysis showed a strong heterogeneity of the data, as shown in Table 9, in which the level of reliability of the extensometric series, based on the comparative analysis of the data, is presented.

FIGURE 8: AUTOMATIC GPS 5 FOR THE PERIOD 2002 – 2015

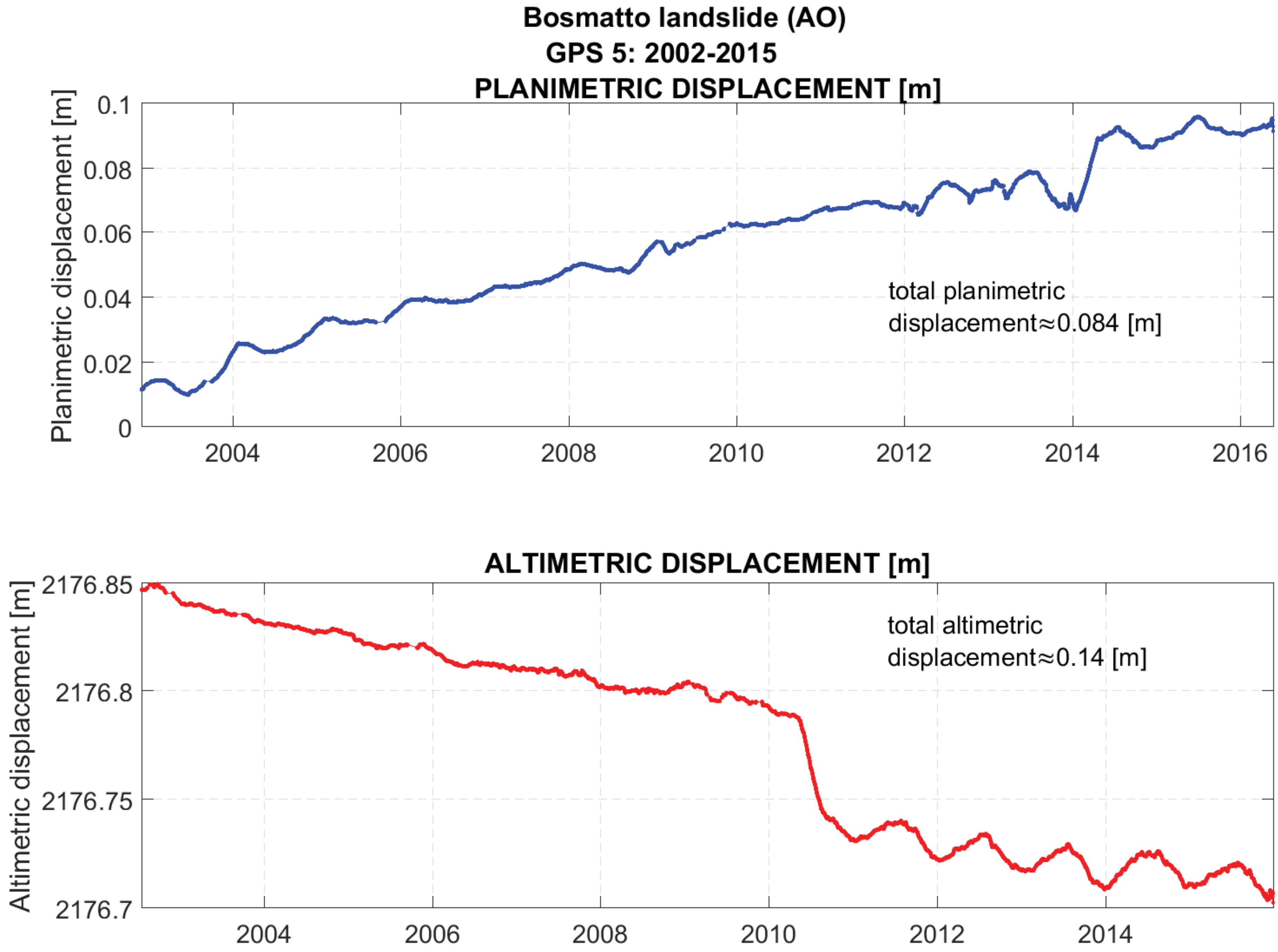

Bosmatto landslide (AO)
GPS 5: 2002-2015
PLANIMETRIC DISPLACEMENT [m]
Planimetric displacement [m]
0.1
0.08
0.06
0.04
0.02
0
2004
2006
2008
2010
2012
2014
2016
total planimetric
displacement≈0.084 [m]
ALTIMETRIC DISPLACEMENT [m]
Altimetric displacement [m]
2176.85
2176.8
2176.75
2176.7
2004
2006
2008
2010
2012
2014
total altimetric
displacement≈0.14 [m]

FIGURE 9: AUTOMATIC GPS 6 FOR THE PERIOD 2002 – 2015

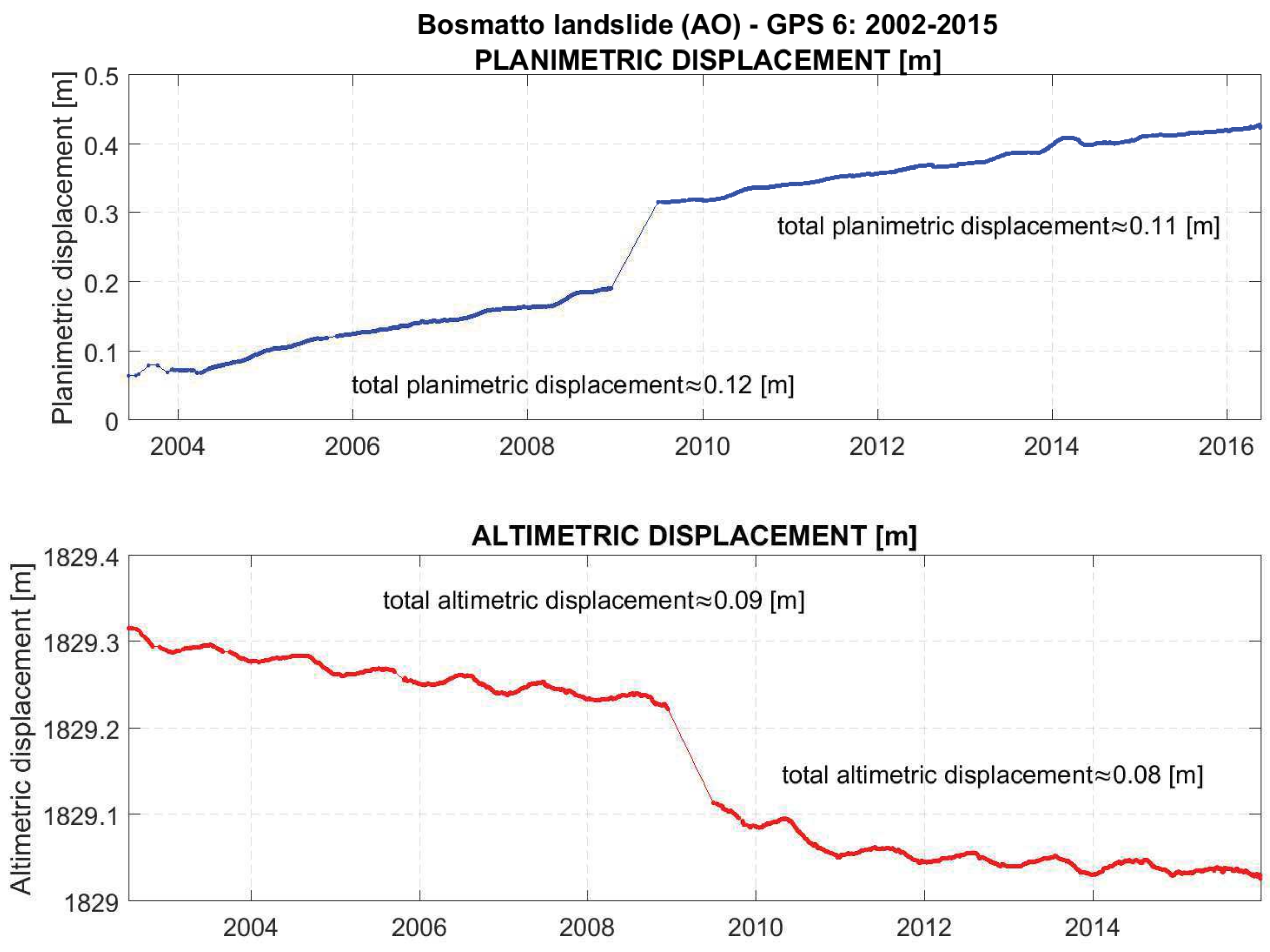
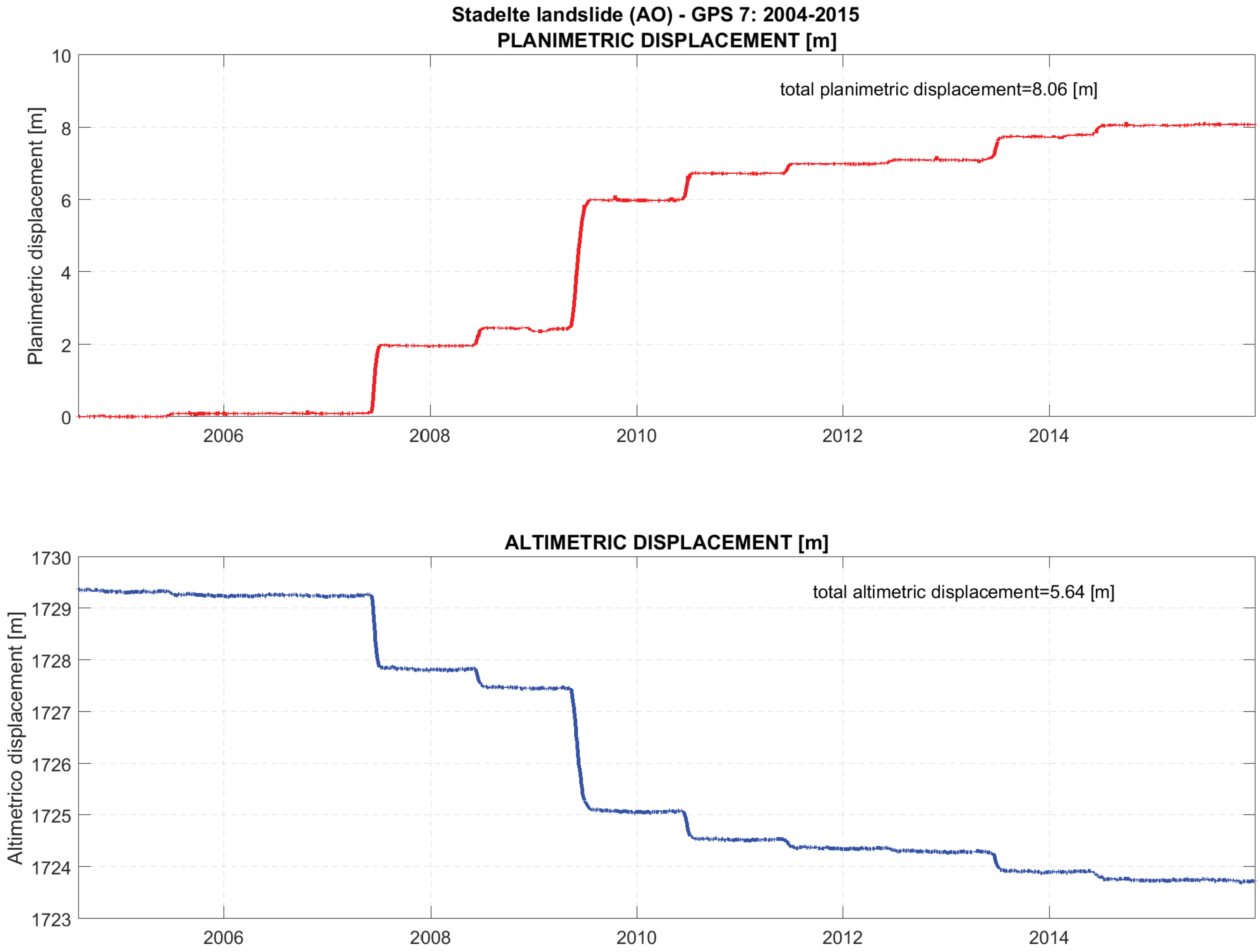

Bosmatto landslide (AO) - GPS 6: 2002-2015
PLANIMETRIC DISPLACEMENT [m]
Planimetric displacement [m]
0
0.1
0.2
0.3
0.4
0.5
2004
2006
2008
2010
2012
2014
2016
total planimetric displacement≈0.12 [m]
total planimetric displacement≈0.11 [m]
ALTIMETRIC DISPLACEMENT [m]
Altimetric displacement [m]
1829
1829.1
1829.2
1829.3
1829.4
2004
2006
2008
2010
2012
2014
total altimetric displacement≈0.09 [m]
total altimetric displacement≈0.08 [m]

FIGURE 10: AUTOMATIC GPS 7 FOR THE PERIOD 2004 – 2015



Stadelte landslide (AO) - GPS 7: 2004-2015
PLANIMETRIC DISPLACEMENT [m]
total planimetric displacement=8.06 [m]
Planimetric displacement [m]
0
2
4
6
8
10
2006
2008
2010
2012
2014
ALTIMETRIC DISPLACEMENT [m]
total altimetric displacement=5.64 [m]
Altimetrico displacement [m]
1723
1724
1725
1726
1727
1728
1729
1730
2006
2008
2010
2012
2014

FIGURE 11: PLANIMETRIC DISPLACEMENT OF GPS 7 ON ONE YEAR TIME WINDOW FOR THE PERIOD 2004 – 2015

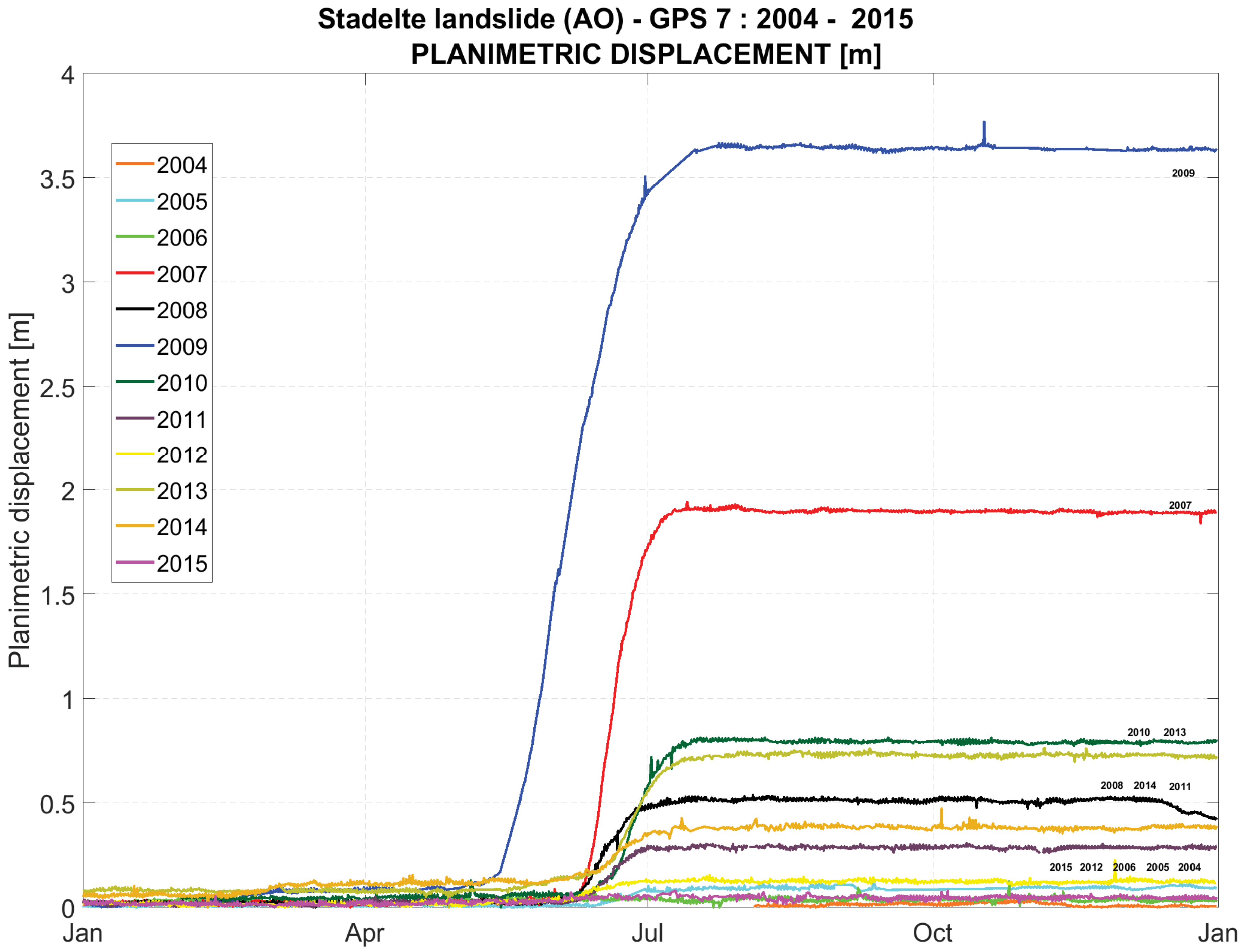
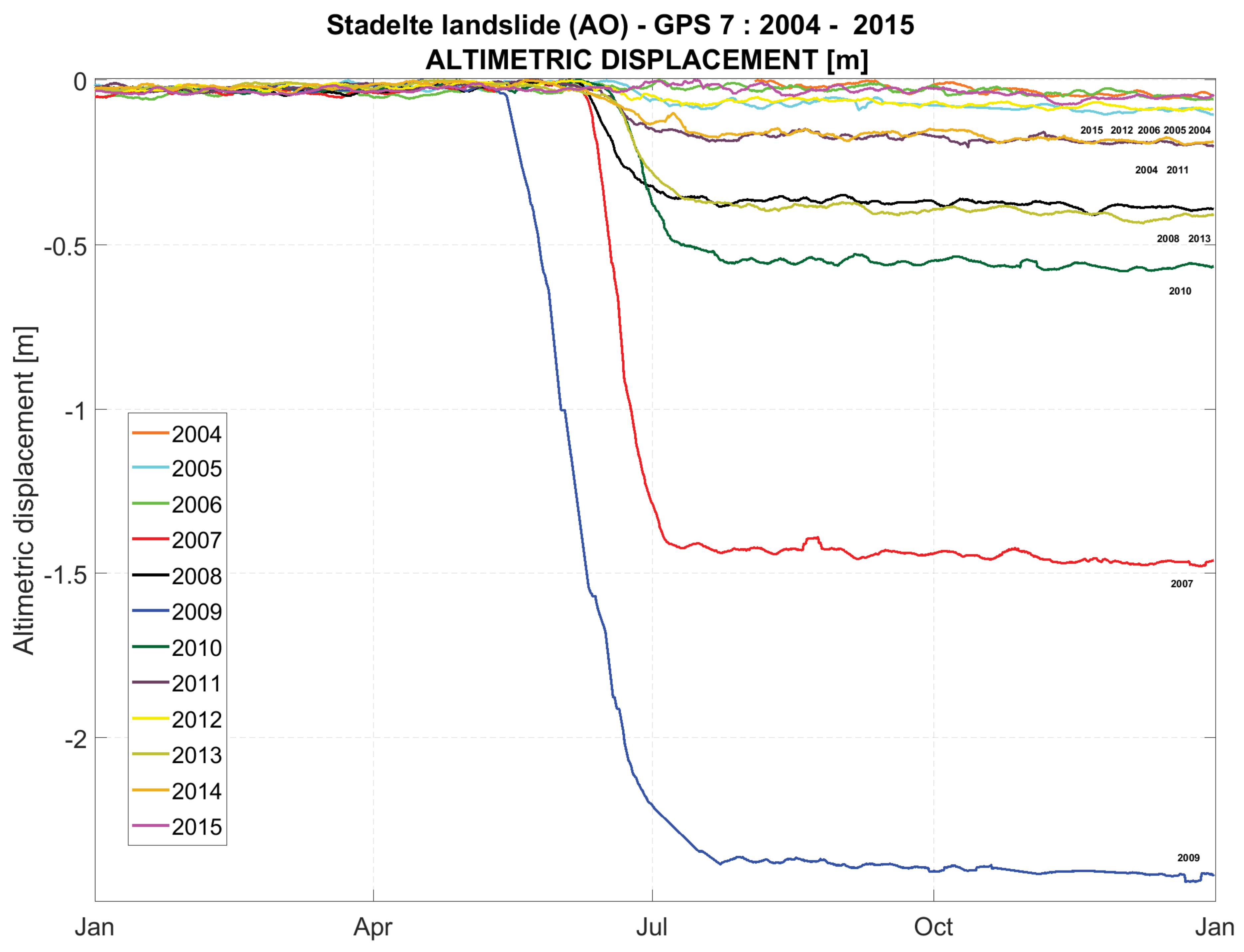

Stadelte landslide (AO) - GPS 7 : 2004 - 2015
PLANIMETRIC DISPLACEMENT [m]
Planimetric displacement [m]
0
0.5
1
1.5
2
2.5
3
3.5
4
Jan
Apr
Jul
Oct
Jan
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
2009
2007
2010 2013
2008 2014 2011
2015 2012 2006 2005 2004

FIGURE 12: ALTIMETRIC DISPLACEMENT OF GPS 7 ON ONE YEAR TIME WINDOW FOR THE PERIOD 2004 – 2015



Stadelte landslide (AO) - GPS 7 : 2004 - 2015
ALTIMETRIC DISPLACEMENT [m]
Altimetric displacement [m]
0
-0.5
-1
-1.5
-2
Jan
Apr
Jul
Oct
Jan
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
2015 2012 2006 2005 2004
2004 2011
2008 2013
2010
2007
2009

STADELTE LANDSLIEDE- EXTENSOMETERS OPERATIONAL STATUS					
	RELIABILITY				NOTE
	E1	E2	E3	E4	
2007	High				E1: installation in June 2007
2008	High				
2009	High				
2010	High	High	High		E2 - E3: installation in Myy 2010
2011	High	Low	High		E2: located on a neoformation fracture, close to the main scarp. This extensometer records the landlslide displacement plus the area close to the main scarp of the landslide.
2012	High	Not reliable	High Noisy measurements	Low	E2: Operational problems. E4: installation in December 2011.
2013	Not reliable	Not reliable	High	High	E1: Operational problems. E2: instrument removal, October 2012.
2014	High	---	High	High	
2015	Medium Noisy measurements	---	Low	Low	E3: no data measurement from June to September. E4: no data measurement from March to August.

Table 9 – Opeartional status of the extenometer monitoring network of the Bosmatto landslide, and assessment of its reliability.

FIGURE 13: ANNUAL DISPLACEMENT OF EXTENSOMETER 1

FOR THE PERIOD 2007 – 2015

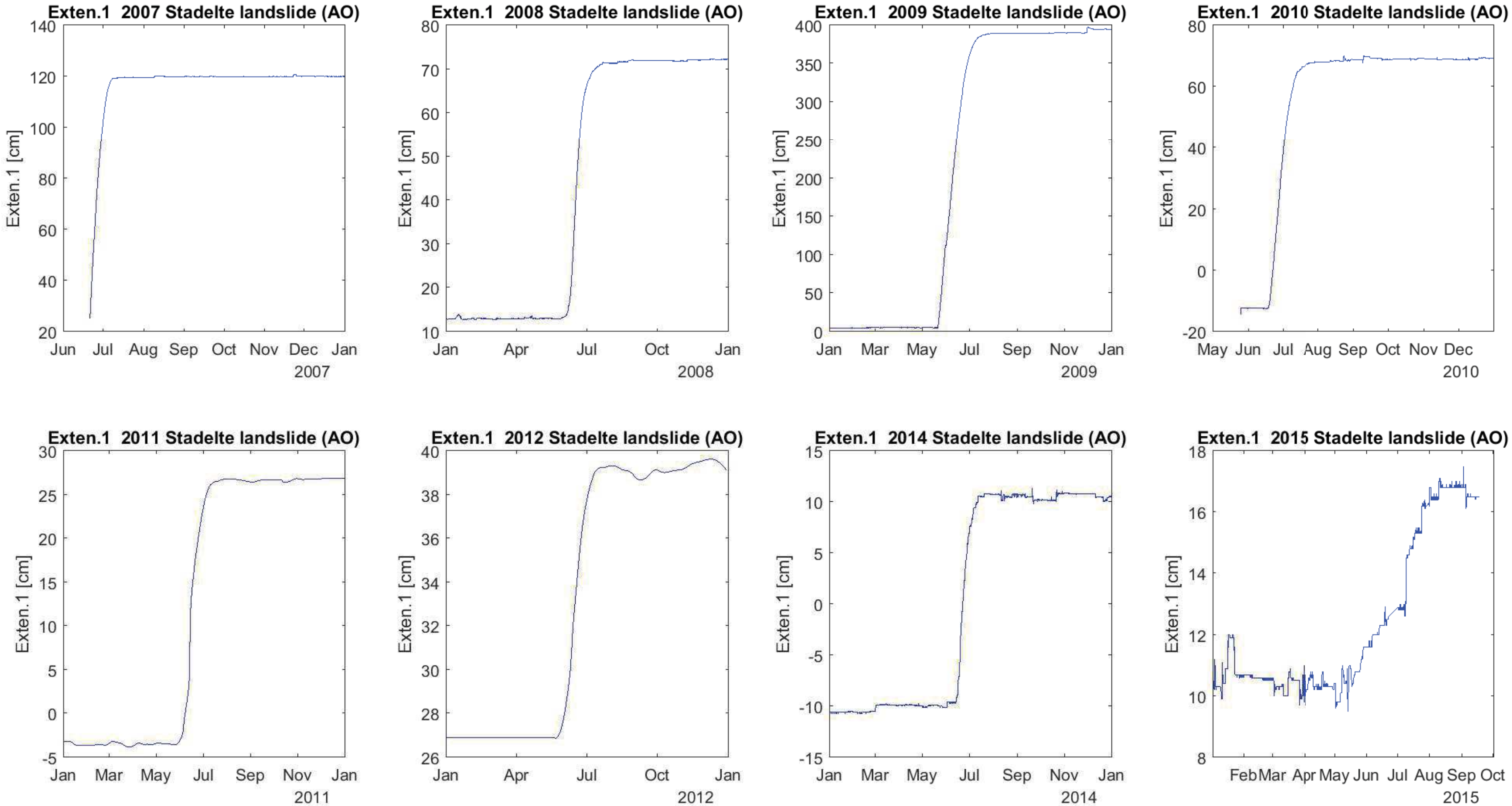
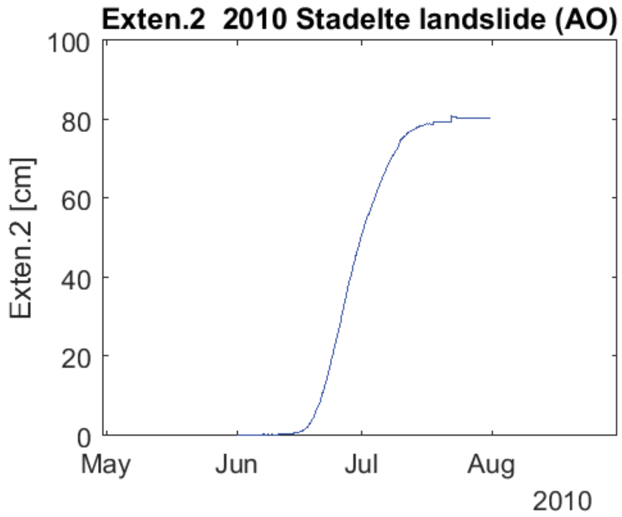

Exten.1 2007 Stadelte landslide (AO)
Exten.1 2008 Stadelte landslide (AO)
Exten.1 2009 Stadelte landslide (AO)
Exten.1 2010 Stadelte landslide (AO)
Exten.1 2011 Stadelte landslide (AO)
Exten.1 2012 Stadelte landslide (AO)
Exten.1 2014 Stadelte landslide (AO)
Exten.1 2015 Stadelte landslide (AO)
Exten.1 [cm]

FIGURE 14: ANNUAL DISPLACEMENT OF EXTENSOMETER 2

FOR THE PERIOD 2010 – 2011


Exten.2 2010 Stadelte landslide (AO)
Exten.2 [cm]
100
80
60
40
20
0
May
Jun
Jul
Aug
2010

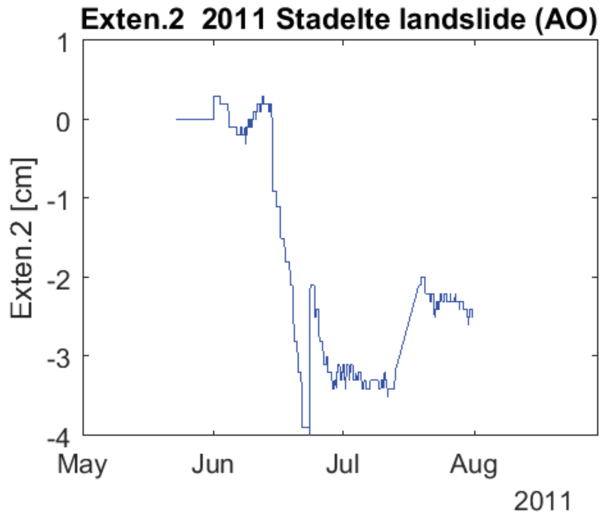
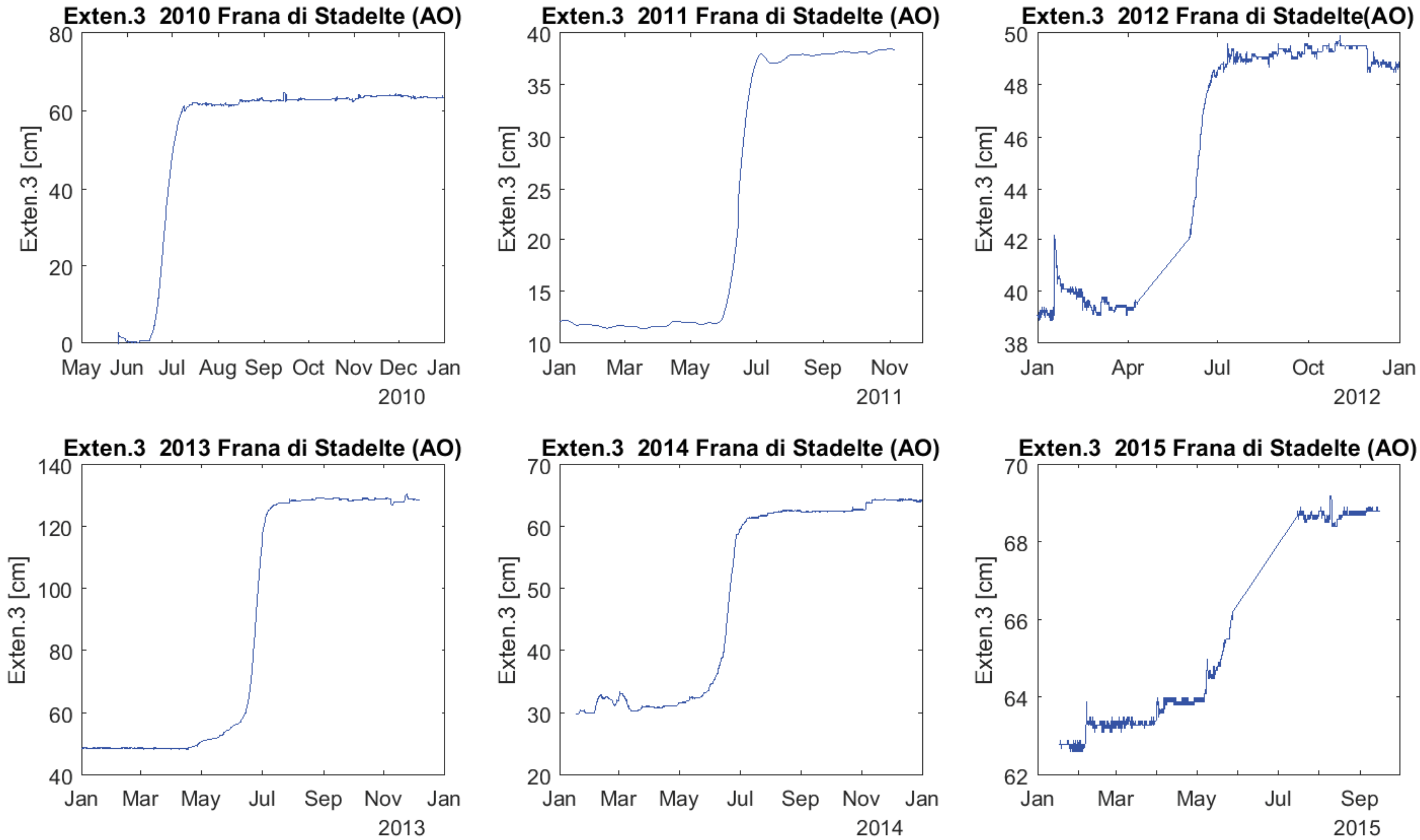

Exten.2 2011 Stadelte landslide (AO)
Exten.2 [cm]
1
0
-1
-2
-3
-4
May
Jun
Jul
Aug
2011

FIGURE 15: ANNUAL DISPLACEMENT OF EXTENSOMETER 3

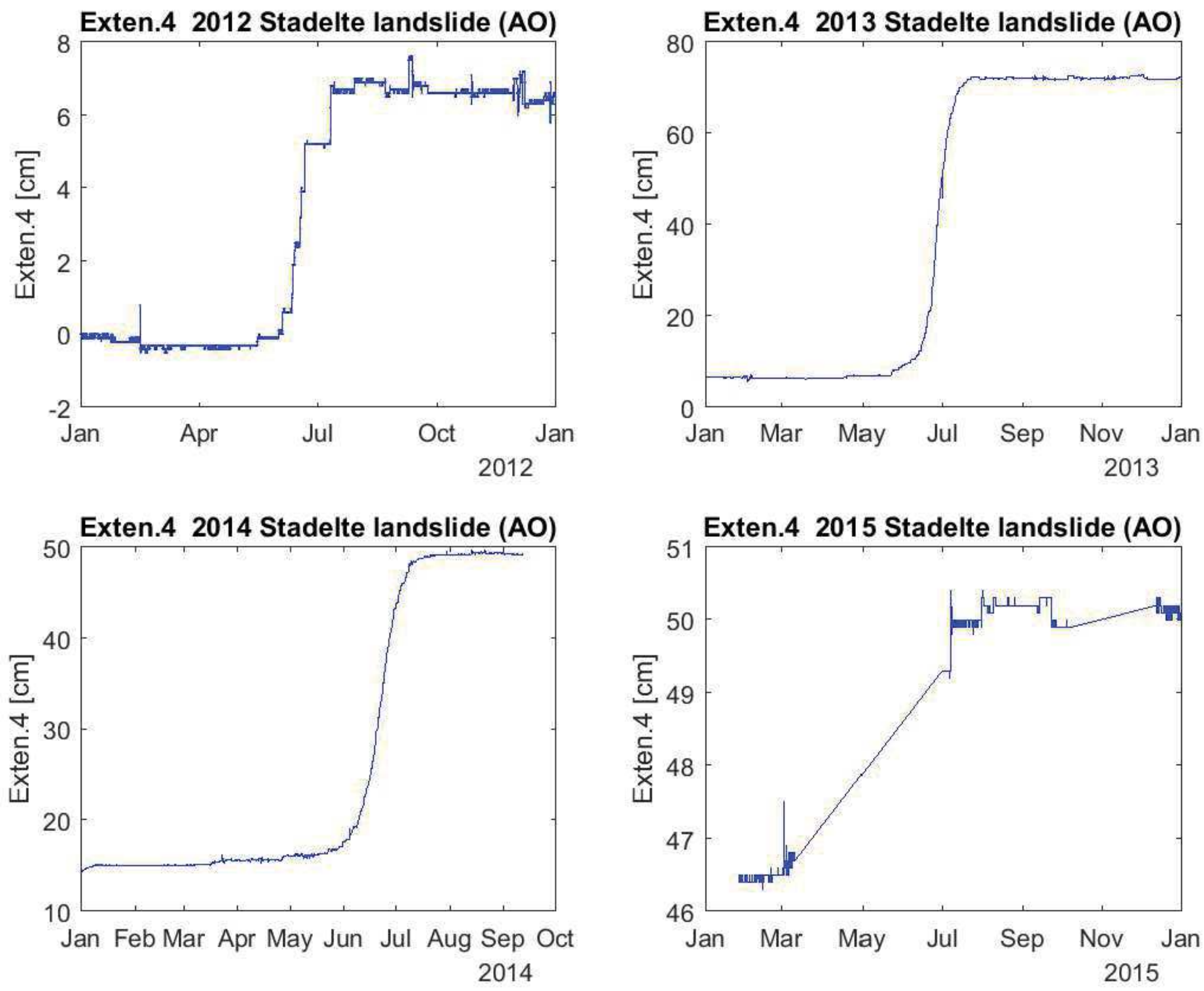
FOR THE PERIOD 2010 – 2015



Exten.3 2010 Frana di Stadelte (AO)
Exten.3 [cm]
May Jun Jul Aug Sep Oct Nov Dec Jan
2010
Exten.3 2011 Frana di Stadelte (AO)
Exten.3 [cm]
Jan Mar May Jul Sep Nov
2011
Exten.3 2012 Frana di Stadelte(AO)
Exten.3 [cm]
Jan Apr Jul Oct Jan
2012
Exten.3 2013 Frana di Stadelte (AO)
Exten.3 [cm]
Jan Mar May Jul Sep Nov Jan
2013
Exten.3 2014 Frana di Stadelte (AO)
Exten.3 [cm]
Jan Mar May Jul Sep Nov Jan
2014
Exten.3 2015 Frana di Stadelte (AO)
Exten.3 [cm]
Jan Mar May Jul Sep
2015

FIGURE 16: ANNUAL DISPLACEMENT OF EXTENSOMETER 4

FOR THE PERIOD 2012 – 2015



Exten.4 2012 Stadelte landslide (AO)
Exten.4 [cm]
8
6
4
2
0
-2
Jan
Apr
Jul
Oct
Jan
2012
Exten.4 2013 Stadelte landslide (AO)
Exten.4 [cm]
80
60
40
20
0
Jan
Mar
May
Jul
Sep
Nov
Jan
2013
Exten.4 2014 Stadelte landslide (AO)
Exten.4 [cm]
50
40
30
20
10
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
2014
Exten.4 2015 Stadelte landslide (AO)
Exten.4 [cm]
51
50
49
48
47
46
Jan
Mar
May
Jul
Sep
Nov
Jan
2015

3 SYNTHESIS and FINAL PROPOSALS

Considering both the available data review and the ground deformation time series analysis, the general framework of Bosmatto and Stadelte landslides behavior has been outlined. In this section, strengths and weaknesses have been summarized, and some improvements for a proper definition of future activities aimed to increase the comprehension of the considered landslide behavior have been suggested.

Relative to the previous data review and analysis, a comprehensive overview of the geological, geomorphological, structural and hydrogeological setting has been observed. A possible point of confusion concerns the landslide body definition. Indeed, there are some studies concerning only the Bosmatto landslide or the Stadelte landslide, other concerning both landslides, by assigning diverse name (e.g. Bosmatto or Letzè landslide), and different internal subdivision based on their state of activities. Only one agency describes a comprehensive overview of the Letzè catchment, by reporting data of all the eight identified categories (see Table 1). Therefore, it is recommended to use this study as reference for civil protection plans redaction.

In this study the recognized landslide bodies are:

- Stadelte landslide divided in two sectors (vegetated and active portion; not vegetated dormant portion)
- Bosmatto landslide divided in Letzè landslide (vegetated active portion; not vegetated dormant portion), and Mussolier landslide.

The delineation of the Stadelte and Bosmatto landslides model is a key element for the landslide hazard assessment and an appropriate land use planning. However, one of the observed weakness concerns the landslide surface definition. Indeed, the landslide surface interpretations are prevalently based on seismic data, integrated with the geological-geomorphological surface data. Only one borehole has been carried out for the Bosmatto landslide. So, it is recommended the acquisition of depth measurements, to improve the evolution models of each landslides, useful for the implementation of civil protection plans. Moreover, diverse risk scenarios and spatial prediction model have taken place, prevalently related to the computation of the areas involved in the landslide occurrence. Even though, the OM objectives are not related to the Civil Protection plans definition, but to suggest proper improvement for the landslide behavior definition. So, it is highly recommended an in-depth analysis of these aspects in order to obtain a clear and defined model useful for the land use planning and the Civil Protection plans establishment.

Relative to the monitoring networks of the Bosmatto and Stadelte landslides, they seem to be partially suitable for the landslide behavior definition. For the Bosmatto landslide, the GPS monitoring network records displacement variable from 6 mm to 1.5 cm/year, without a clear relation between landslide activation and rainfall precipitation and/or snow melting. Instead, for the Stadelte landslide, an evident seasonal trend has been outlined. It is to be noted that, in general, the GPS network do not guarantee a proper near real time monitoring network, due to their acquisition rate, particularly during paroxysmal events. Moreover, the extensometers removal for the Bosmatto case, remove the redundancy of monitoring data, crucial during the emergency cases.

Furthermore, one of the main weaknesses highlighted regards the ground deformation time series graphs presentation. Indeed, actually the report concerning the monitoring network analysis report the Bosmatto and Stadelte landslides measurements all together, without a clear distinction between the two phenomena. A great effort has been done by the Aosta Valley Region authorities that from the 2009 drafted internal report relative to the monitoring network analysis, to keep track of the critical issues observed over time. However, every year, the data are variable represented, reporting time series relative to the calendar year measurements only, and not the complete time series relative to the entire acquisition period. Moreover the time series often report diverse component (e.g. East, North, planimetric, altimetric, 3D), without a precise scheme. Therefore, it is recommended a standard format for the presentation of the data, with ground deformation time series over the entire monitoring period, with an every year update. By this way, it is possible to points out the potential seasonal accelerations or other pattern of the observed phenomenon. It is also recommended the generation of planimetric and altimetric displacement graphs, which is the most convenient and representative way to describe the landslide behavior. This procedure is recommended for both the Bosmatto and Stadelte landslides, with the generation of two separate reports.

Geohazard Monitoring Group

Geohazard Monitoring Group
Istituto di Ricerca per la Protezione Idrogeologica – IRPI
Consiglio Nazionale delle Ricerche – CNR
Strada delle Cacce, 73, 10135 Torino, Italy
Phone: +39-011-3977-811, fax: +39-011-3977-821
E-mail: geomonitoraggi@irpi.cnr.it
http://gmg.irpi.cnr.it

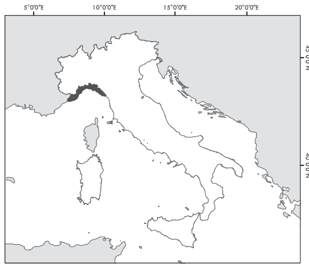
Appendix IV – Main Map of the Paper VI

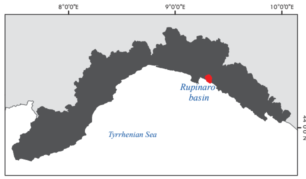
Paper VI: *Shallow landslide susceptibility, Rupinaro catchment, Liguria (northwestern Italy)*

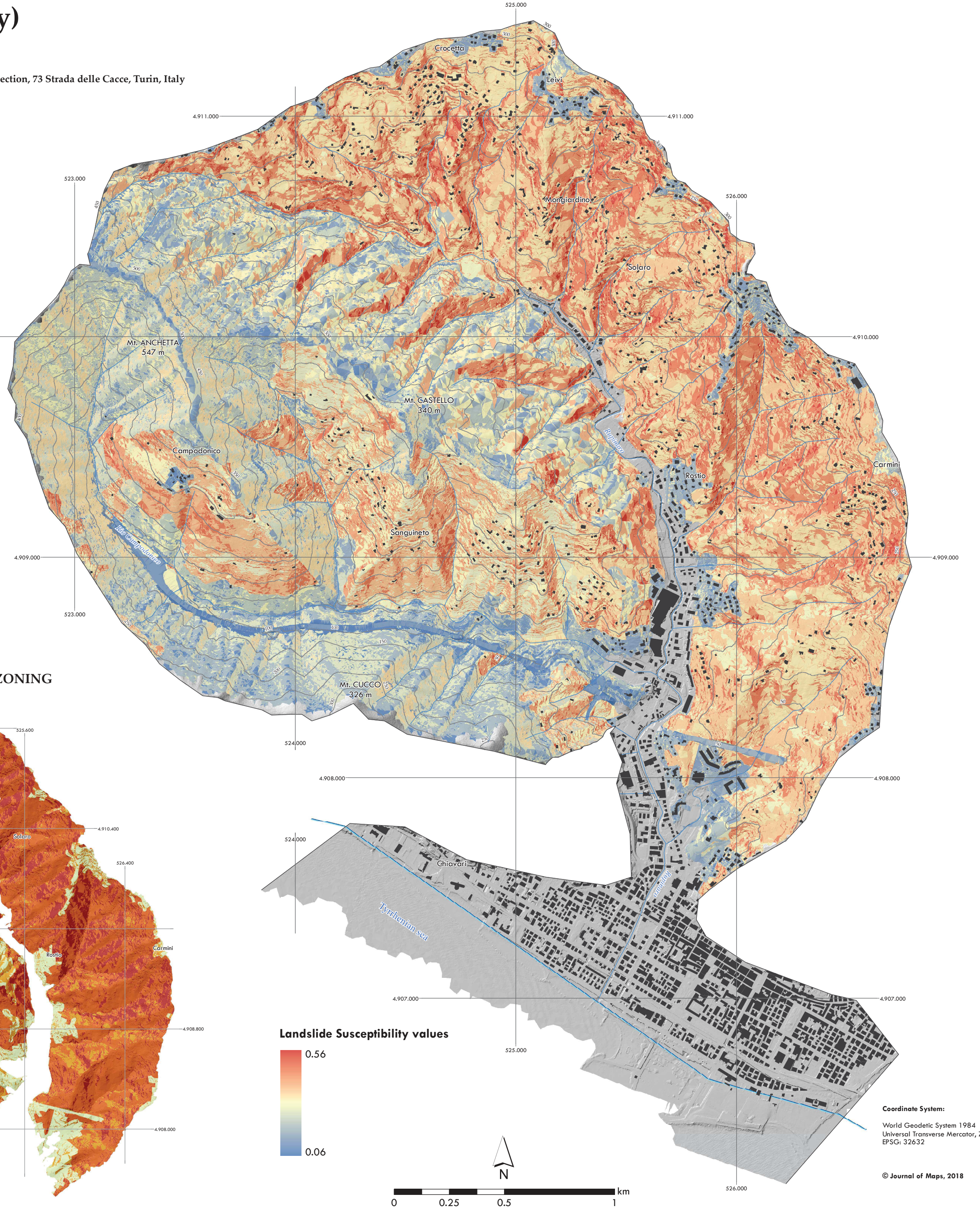
Shallow Landslide Susceptibility Map of the Rupinaro catchment, Liguria (northwestern Italy)

Cignetti M.[1], Godone D.[1*], Giordan D.[1]

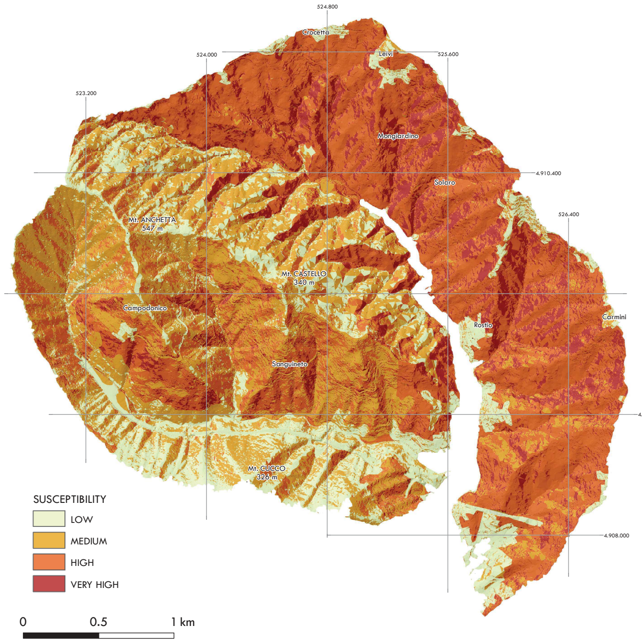
[1]National Research Council, Research Institute for Geo-Hydrological Protection, 73 Strada delle Cacce, Turin, Italy

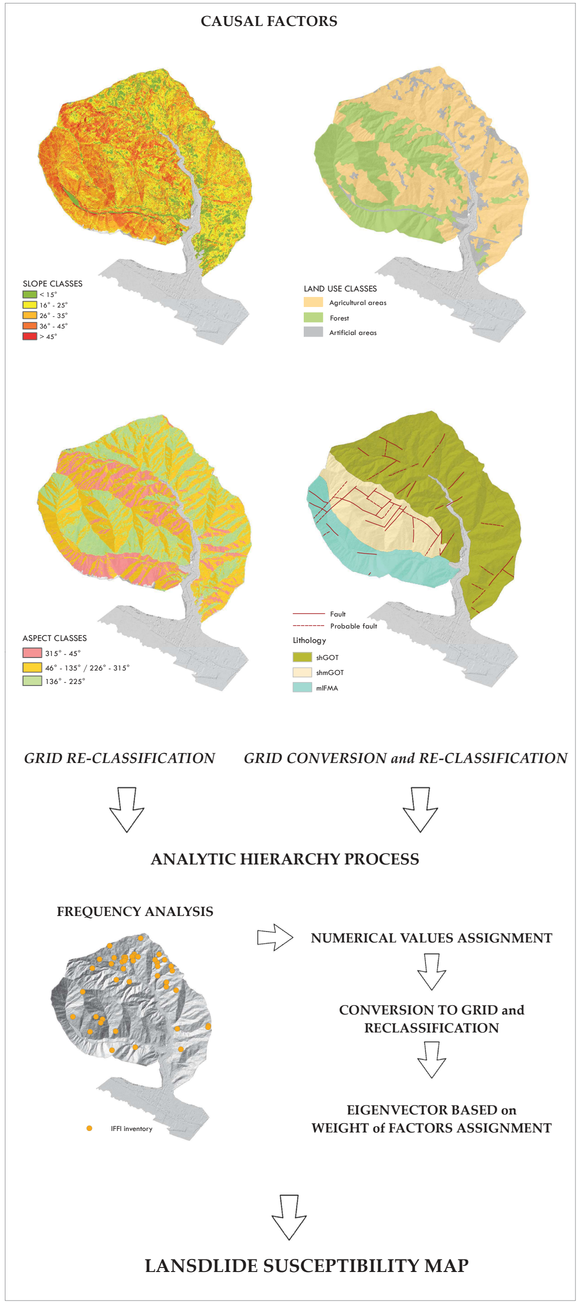






LANDSLIDE SUSCEPTIBILITY ZONING





Coordinate System:

World Geodetic System 1984
Universal Transverse Mercator, Zone 32N
EPSG: 32632

Base map:

© OpenStreetMap contributors, CC BY-SA

IFFI Catalogue:

IFFI Catalogue
National Landslides Inventory
Format: shape file

Digital Terrain Model

Lidar survey by: CNR-IRPI, Turin
Founded by: Liguria Region
Sensor - RIEGL LMS-Q680i
Survey date - January 2015
DTM cellsize - 25 cm
Horizontal Datum - ETRF2000 UTM Zone 32 N
Vertical Datum - EGM2008

Land Use:

Online resource from
Geoportal Liguria Region
Land Use Map 2015 - Scale1:10.000
Format: shape file

Lithology:

Online resource from
River basin management plan
Ambito 16
Geolithologic Map - Scale 1:10.000
Format: raster

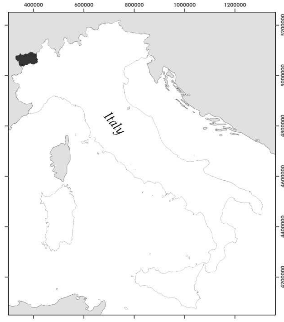
Appendix V - Main Map of the Paper VIII

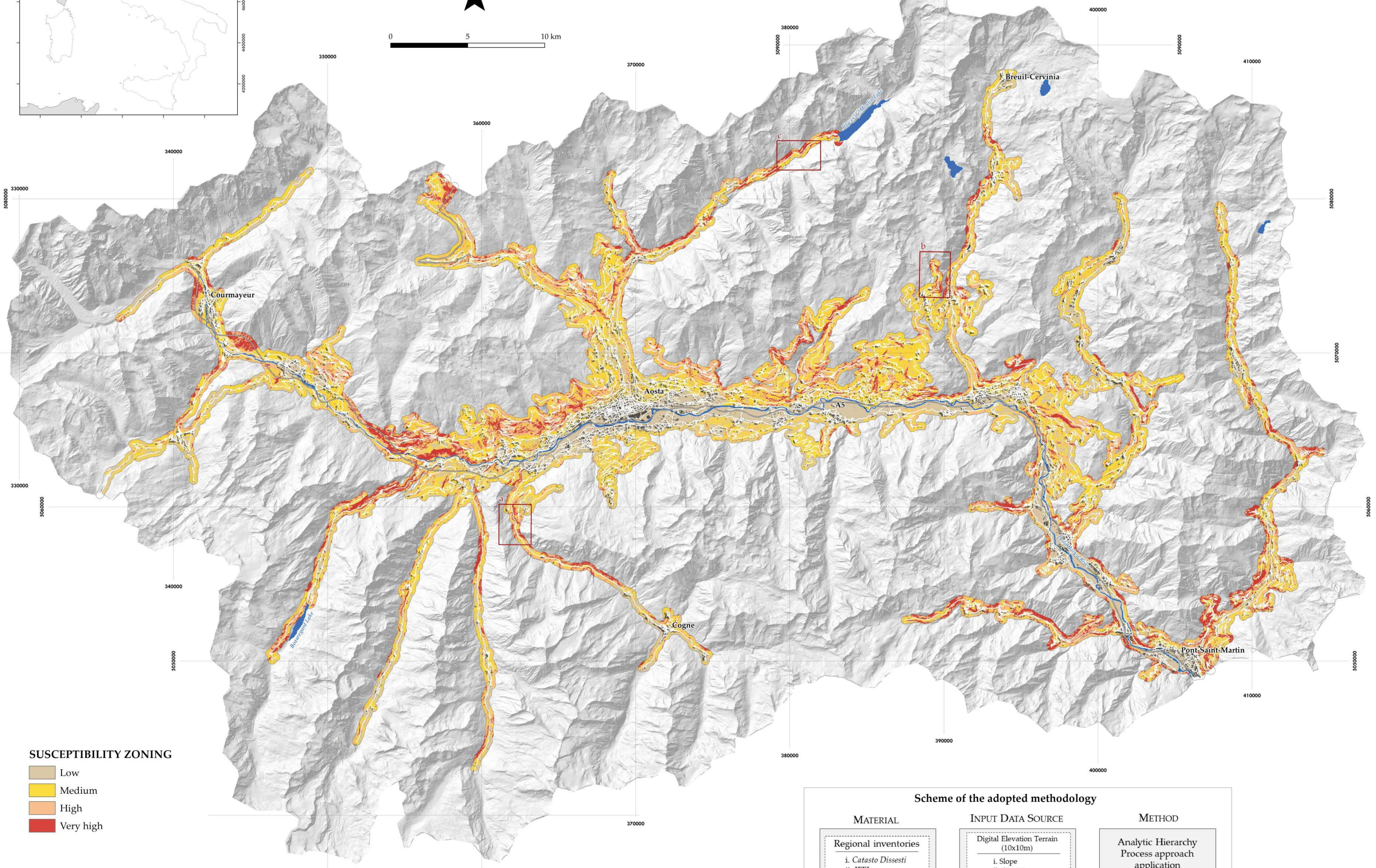
Paper VIII: *Rockfall susceptibility along the regional road network of Aosta Valley Region (northwestern Italy)*.

Rockfall susceptibility along the regional road network of Aosta Valley Region (northwestern Italy)

Cignetti, M.[1,2], Godone, D.[1,*], Bertolo, D.[3], Paganone, M.[3], Thuegaz, P.[3], Giordan D.[1]

[1] National Research Council of Italy, Research Institute for Geo-Hydrological Protection (CNR IRPI), Torino 10135, Italy; martina.cignetti@irpi.cnr.it (M.C.); danilo.godone@irpi.cnr.it (D.G.a); daniele.giordan@irpi.cnr.it (D.G.b)
[2] Department of Earth and Environmental Sciences, University of Pavia, 27100, Italy;
[3] Strutture Attività Geologiche, Regione Autonoma Valle d'Aosta, Quart 11020, Italy; d.bertolo@regione.vda.it (D.B.); m.paganone@regione.vda.it (M.P.); p.thuegaz@regione.vda.it (P.T.).
* Correspondence: danilo.godone@irpi.cnr.it (D.G.a)





SUSCEPTIBILITY ZONING

- Low
- Medium
- High
- Very high

Coordinate System:
European Datum 1950
Universal Transverse Mercator, Zone 32N
EPSG: 23032

Digital Terrain Model
Source: Regional Technical Map
Founded by: Aosta Valley Region
Date: 1991
DTM cellsize - 10 m
Reference System: European Datum 1950
Universal Transverse Mercator, Zone 32N
EPSG: 23032

Base map:
Online resource from:

Road Inventory - Geoportal SCT
Private Data made available by the Aosta Valley Region authorities
Format: shapefile

Other symbols - Landscape Territorial Plan (PTP)
Open Data Licence CC0
DGR 1620, 25 November 2016
Format: shapefile

Scheme of the adopted methodology

MATERIAL
Regional inventories
i. *Catasto Dissesti*
ii. IFFI
Derivable information
a. Typology
b. Time distribution
c. Spatial distribution

INPUT DATA SOURCE
Digital Elevation Terrain (10x10m)
i. Slope
ii. Aspect
iii. Elevation
iv. Distance to Road
CARG (1:25.000)
i. Lithology
Corine Land Cover 2018 (1:100.000)
i. Land Use

METHOD
Analytic Hierarchy Process approach application
SUSCEPTIBILITY MAP
Map validation

(a) Pondel, Aymavilles, SR47

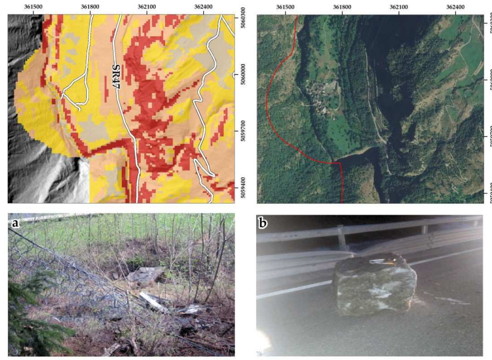


Photo online resource - "Catasto Dissesti" web-portal: a) 01-05-2013 event; b) 09-06-2014 event
Digital Terrain Model 2 m cellsize - online resource SCT geoportal AVR
Ortophoto 2006 source "Portale Cartografico Nazionale" (pcn.minambiente.it)

(b) Petit Monde, locality Triatel, Tognon AO

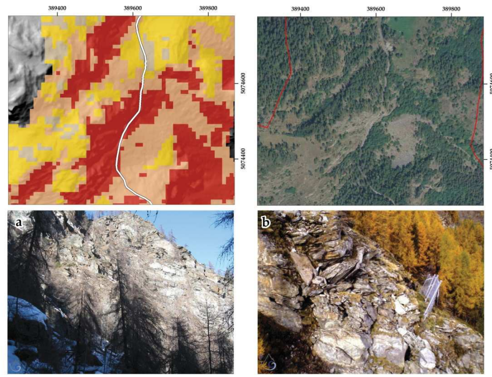


Photo online resource - "Catasto Dissesti" web-portal: a) 13-01-2011 event; b) 05-11-2014 event
Digital Terrain Model 2 m cellsize - online resource SCT geoportal AVR
Ortophoto 2006 source "Portale Cartografico Nazionale" (pcn.minambiente.it)

(c) Valpelline, Place de Moulin Dam

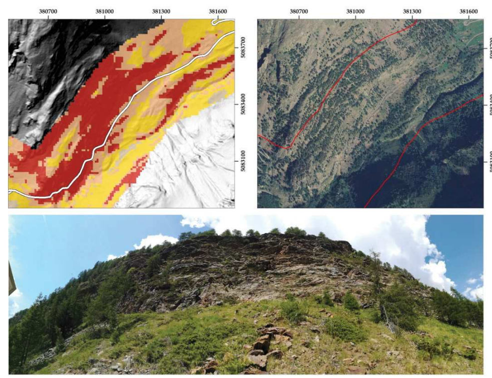


Photo of Danilo Godone, GMG group CNR IRPI of Turin
Digital Terrain Model 2 m cellsize - online resource SCT geoportal AVR
Ortophoto 2006 source "Portale Cartografico Nazionale" (pcn.minambiente.it)

Appendix B – Correlated external publications

Giordan, D., Cignetti, M., & Bertolo, D. (2017a, May). The Use of Morpho-Structural Domains for the Characterization of Deep-Seated Gravitational Slope Deformations in Valle d'Aosta. In *Workshop on World Landslide Forum* (pp. 59-68). Springer, Cham.

Giordan, D, Cignetti, M., Baldo, M., Godone, D., 2017b. Relationship between man-made environment and slope stability: the case of 2014 rainfall events in the terraced landscape of the Liguria region (northwestern Italy). Geomatics, Nat. Hazards Risk 8, 1833–1852

4th WLF 2017
4th World Landslide Forum
LJUBLJANA SLOVENIA EU

The use of morpho-structural domains for the characterization of Deep-seated Gravitational Slope Deformation of the Valle d'Aosta

Daniele Giordan[(1)], Martina Cignetti[(1)] and Davide Bertolo[(2)]

Abstract

Deep-seated Gravitational Slope Deformation (DsGSD) are a widespread phenomena in mountain regions. In the Valle d'Aosta alpine region (northern Italy) DsGSD occupy the 13.5% of the entire regional territory. A total amount of 280 phenomena has been inventoried in the IFFI project (Italian Landslide Inventory). These large slope instabilities often may affect urbanized areas and strategical infrastructures, involved entire valley flanks. The presence of different settlements over DsGSD leads the regional Geological Survey to assess the possible effects of these phenomena over the human activities. This study is aimed at implement a methodology, based on SAR data observation and elaboration, to recognize the most active sectors of these phenomena. Starting from the available RADARSAR-1 dataset, we try to purpose a methodology for the identification of the main morpho-structural domains that characterized these huge phenomena, and the definition of the different sectors that compose the DSGD characterized by different level of activity. This subdivision is important to link those different kinematic domains inside the DsGSD to the level of attention that should be done in the study that supported the request of authorization of new infrastructures. We apply this method over three case studies represented by significant phenomena involving urban areas of the Valle d'Aosta region. In particular, we analyse the study area of: the Cime Bianche DsGSD; the Valtourenenche DsGSD; the Quart DsGSD. These phenomena present different levels of evolution controlled by the interaction of diverse factors, and involving buildings and other infrastructures. This setting has been useful to test the development methodology that taking advantage of remote-sensing investigations together with the local geological, geomorphological and structural setting of each case study analyzed. This method aims at achieve a useful instrument to trying to delineate a sort of guidelines for the realization of new infrastructures, as support of the Regional Agency.

Keywords

Deep-seated Gravitational Slope Deformation; DInSAR techniques; RADARSAT-1

Introduction

The large slow-moving slope instability play an important role in the mountain landscape evolution, representing a significant natural hazards respect to urbanized area and their possible effects on structure and/or infrastructure. For a Regional Authority of a mountainous area, the estimation of the state of activity of those phenomena is fundamental for the natural hazard assessment and the land prevention stating.

Deep-seated Gravitational Slope Deformations (DsGSD) represent well-known widespread phenomena in the Alpine chain (Mortara and Sorzana, 1987; Ambrosi and Crosta, 2006; Martinotti *et al.*, 2011).

In the last decades, several authors have been investigated about the DsGSD (Zischinsky, 1966, 1969; Mahr, 1977; Savage and Varnes, 1987; Varnes *et al.*, 1989; Crosta, 1996; Crosta and Zanchi, 2000; Agliardi *et al.*, 2009; Martinotti *et al.*, 2011), highlighting as has been long and complex the way to codify those phenomena. These large slope instabilities involve entire valley flanks, ranging from some kilometers in length and hundreds of meters in depth, and present several typical morphological and structural features (e.g. scarps, trenches, double ridges, tension cracks) (Varnes *et al.*, 1989; Agliardi *et al.*, 2001; Tibaldi *et al.*, 2004).

These huge phenomena are the result of a complex geological, geomorphological and structural setting often characterized by a long evolution. In specific, their evolution is controlled by the interaction of different factors: i) lithology; ii) geology; iii) geomorphology; iv) climate-weathering; v) seismicity; vi) deglaciation (Crosta *et al.*, 2013). They present an initial stage evolution, which during the advanced stage can involve in a creep mechanical behavior, until a complete collapse. These phenomena generally present a very slow-slow deformation rates, variable from few millimeters per year to a maximum of some centimeters per year, in uncommon cases (Agliardi *et al.*, 2012). In this context, the Differential Synthetic Aperture Radar Interferometry (DInSAR) techniques represent a suitable tool to investigate slow-moving phenomena over wide area (100 km x 100 km), and for long time period covered by the vast satellite system (e.g. ERS-1/2, Envisat ASAR, COSMO SkyMed, Radarsat-1).

In this paper, we propose a methodology based on SAR data available by the Valle d'Aosta Regional authority. We exploited the RADARSAT-1 dataset processing by the TRE S.r.l. by the SqueeSAR™ technique, from March 2003 to December 2010. Our methodology is aimed to analyze and elaborate the Permanent Scatterers (PS) and the Distributed Scatterers (DS) together with the geomorphological and structural evidences, in order to identify the possible morpho-structural domain of three DsGSD case studies, located within the Valle d'Aosta region (northern, Italy). By this way, the most affected area should be identify, providing significant information to natural hazard assessment and the land use planning.

The Valle d'Aosta region case studies

The Valle d'Aosta is a small alpine region (3,200 km²) located in the northwestern Italy, with a complex topographic relief ranging from 400 m a.s.l. over the 4800 m a.s.l. (Fig.1). Due to the high topographic relief and the steep slope gradient, landslide processes are widespread and affect about 520 km² of the entire regional territory. In specific, the DsGSD occupy the 13.5 % (Fig.1) of the regional territory (Trigila, 2007).

The actual analysis has been focused over three different case studies those represent significant examples of DsGSD of the Valle d'Aosta region (Fig.1).

The first example is the Cime Bianche DsGSD, located in the upper part of Valtourenenche valley, above the Breuil-Cervinia settlement. This phenomenon presents a complex evolution, characterized by the presence of recent signs of glacial activity and several active periglacial processes. The lower and the marginal portions of this mass movement present the main degree of deformation.

The second case is located in the middle portion of the same valley and affects the town of Valtourenenche. This phenomenon is characterized by a local geomorphology conditioned by the recent evolution of the homonymous stream and by the presence of several active slides superimposed over the DsGSD.

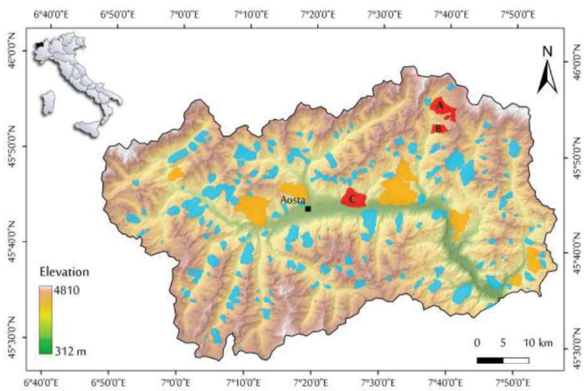


Fig. 1 Relief terrain of the Valle d'Aosta region, northwestern Italy. The map shows the DsGSD (from IFFI project) distribution (blue polygons); the red polygons correspond to the three case study: A) Cime Bianche; B) Valtourenenche; C) Quart; while orange polygons correspond to the other phenomena which involve the principal urban area within the regional territory.

The last one is the Quart DsGSD, the more complex phenomenon respect to the other one, located on the left side in the middle of the main valley, not far away from Aosta municipality. This DsGSD presents evidences of a long-time evolution controlled by glacial activity, tectonic processes, and deep dissolution (Martinotti *et al.*, 2011). The main displacement is parallel to the slope, to which has been added an extensional and lateral component.

These three cases have been chosen because of their affect several of the principal settlement of the region and present different stage of evolution within.

Methods

Slow mass movements represent suitable cases for the DInSAR techniques application (Colesanti and Wasowsky, 2006; Cascini *et al.*, 2010). Starting from RADARSAT-1 dataset available by the Regional authority of the Valle d'Aosta, and elaborated by

SqueeSAR™ technique, a good agreement has been declared in the analysis performed by TRE S.r.l..

As part of urban development planning, the use of SAR data (i.e. Permanent Scatterers (PS) and Distributed Scatterers (DS)) should cause problems for no expert users. In the case of the DsGSD, the PS/DS analysis should be a starting point to assess the most active sectors, although considering the well-known intrinsic limitation of these techniques (Ferretti *et al.*, 2001; Ferretti *et al.*, 2011). However, in order to assess the complex evolution of these phenomena, the SAR data have been integrated with geological, geomorphological and structural local setting. In this context, we operate to define the morpho-structural domains within the DsGSD. This requires an identification of the possible kinematic domain of the DsGSD, taking also into account any other active phenomena (i.e. landslides, rock glacier, talus), superimposed on the DsGSD area. We operate with the discretization of SAR data in GIS environment. In specific, we apply an interpolation of the PS/DS LOS velocity values, taking into account specific barriers previously identified on account of geomorphological and structural analysis and literature knowledges. However, the discontinuous PS/DS distribution must be addressed, because it can generate some limits on the application of interpolation functions.

Appling this method, it is possible to subdivide the DsGSD in diverse sectors, trying to aggregate ground deformation data by specific limits obtained on the basis of geomorphological/structural constraints. By this way, we obtain areal deformation maps, more suitable respect to the classical PS/DS distribution maps, representing a useful tool in the land-use planning and natural hazard assessment.

Results

We apply and test our method to three specific DsGSD of the Valle d'Aosta region (see Fig.1) classified in IFFI (Italian Landslide Inventory). The RADARSAT-1 images available from Regional authority cover the period from March 2003 to December 2010. These images have been elaborated by the SqueeSAR™ technique, providing the PS/DS data resulting over this alpine region, along descending and ascending orbit.

Cime Bianche DsGSD

By considering the PS/DS within Cime Bianche DsGSD, a good coverage and distribution have been observed. In specific, along descending orbit the best coverage has been resulted. In Fig.2 and 3 are presented the maps resulting from, respectively, Kernel and Diffusion interpolation applied with barrier, along the descending orbit. We operate considering all the landslides superimposed over the DsGSD, and subdividing this phenomena in several distinct kinematic domains, based on morpho-structural evidences and in specific on the rock mass structure and discontinuity surface conditions.

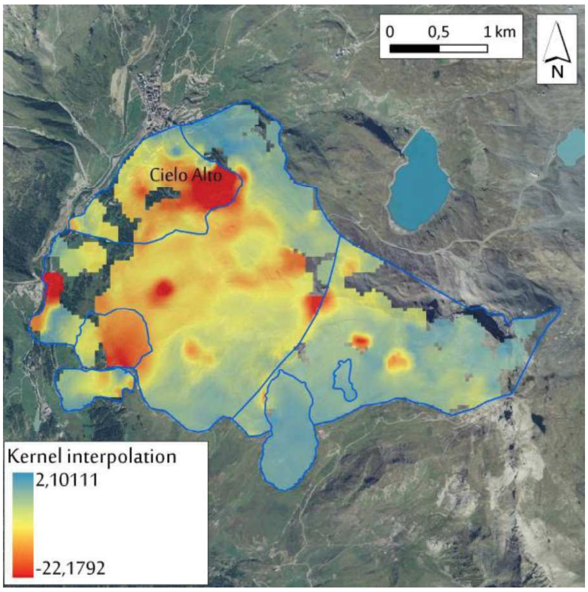


Fig. 2 Map of Kernel Interpolation with barrier (cell size 40 m) on the Cime Bianche DsGSD, based on the RADARSAT-1 PS in descending orbit.

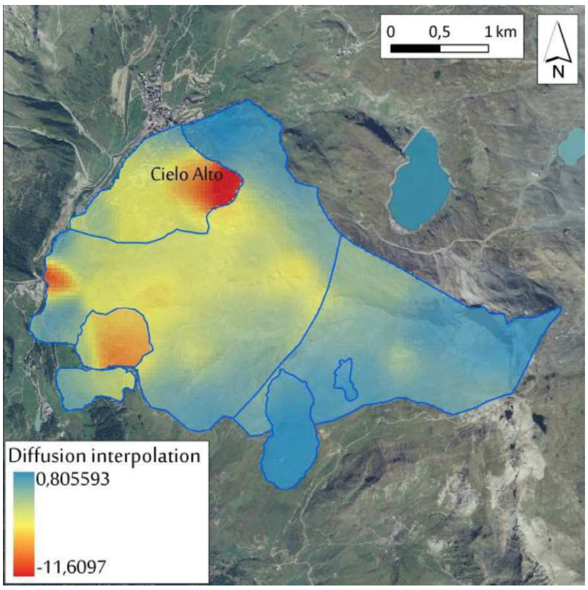


Fig. 3 Map of Diffusion Interpolation with barrier (cell size 40 m) on the Cime Bianche DsGSD, based on the RADARSAT-1 PS in descending orbit.

In both cases, the most active domains correspond to the lower and marginal portions of the DsGSD in according to the literature information. In specific a more active domain in correspondence of the Cielo Alto location, has been revealed.

Valtourenenche DsGSD

Also in the case of Valtourenenche DsGSD a good PS/DS coverage and distribution have been observed. In Fig. 4 and 5 the maps resulting from Kernel and Diffusion interpolation with barrier application, respectively, are presented, along the descending orbit. As in the previous case, all the landslides (form IFFI) have been considered, together with the identification of several other gravitational processes that are responsible for the topographic displacement measured by SAR. The identification of all of the processes that are able to generate surficial deformation is important to asses a correct identification of the morpho-structural domains. In the upper part a significant ground deformation in correspondence of two main landslide bodies, east-west oriented, has been revealed; while the most active sector of the DsGSD correspond to the lower portion, delimitated by a main scarp in the upper part, close to the Valtourenenche village. It is to be noted the presence of several landslide bodies superimposed over this sector, which are added to the DsGSD movement. A middle level sector, corresponding to a transitional domain presenting modest ground deformation, has been revealed.

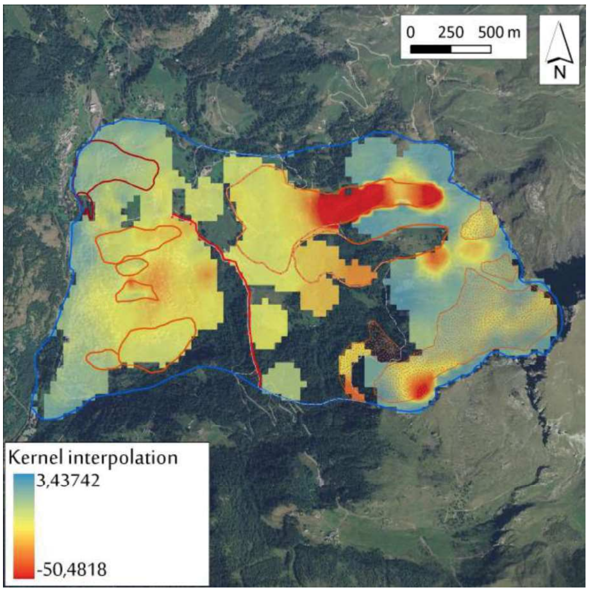


Fig. 4 Map of Kernel Interpolation with barrier on the Valtourenenche DsGSD, based on the RADARSAT-1 PS in descending orbit.

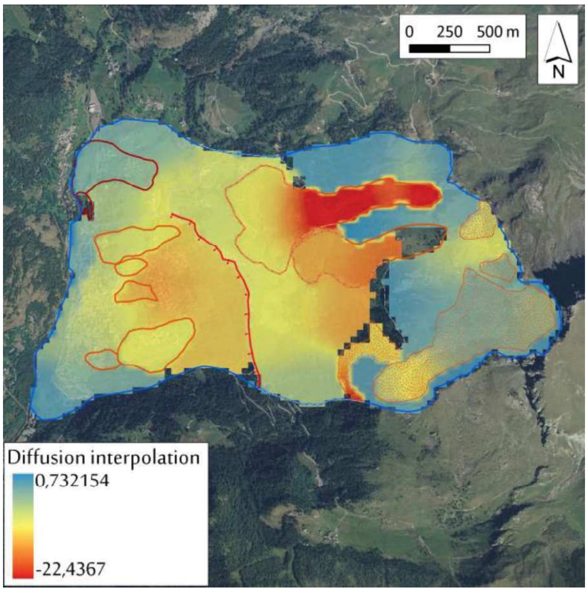


Fig. 5 Map of Diffusion Interpolation with barrier on the Valtourenenche DsGSD, based on the RADARSAT-1 PS in descending orbit.

In both cases, the complex evolution of this phenomenon is well-drawn by imposing as limit all the numerous geomorphological and structural elements observed.

Quart DsGSD

In the Quart DsGSD a good PS/DS coverage and distribution have been observed for both the ascending and descending orbit.

Quart DsGSD represents the most complex phenomenon considered in this study for his long evolution and for the presence of a lateral valley, which causes the presence of two different direction of displacement. In this case, the cinematic domains proposed in IFFI have been used for the application of Kernel and Diffusion interpolation (Fig. 6 and 7, respectively). A single modification has been introduced in the western portion of the DsGSD, in order to separate the more active upper from the stable lower portion. In general, a ground deformation decrease has been revealed going from the upper to the lower portions of the DsGSD. Finally, it is to be outline the presence of the Vollein active landslide in the eastern part of the DsGSD.

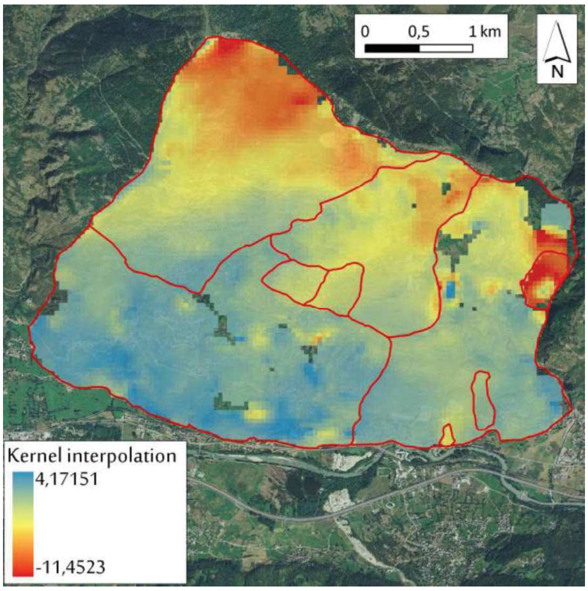


Fig. 6 Map of Kernel Interpolation with barrier on the Quart DsGSD, based on the RADARSAT-1 PS in ascending orbit.

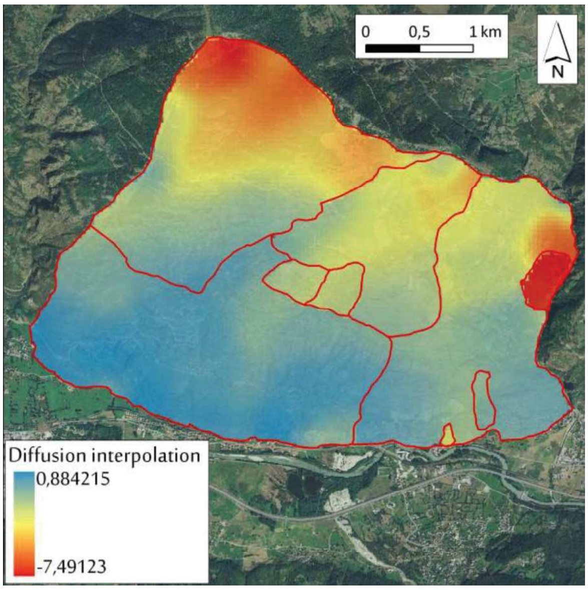


Fig. 7 Map of Diffusion Interpolation with barrier on the Quart DsGSD, based on the RADARSAT-1 PS in ascending orbit.

Discussion and Conclusion

The results obtained for the three case studies highlight how the DsGSDs are very complex phenomena, which require a specific approach for their interpretation. The morphological elements recognition is fundamental, but sometime difficult to interpret, given that they result from a very long and composite framework of deformation. The geological and geomorphological aspects lead to define those kind of phenomena and their characterization, but only partially to define their state of activity.

In the last decade, the introduction of the relatively new DInSAR techniques have led to obtain ground deformation information over wide area with millimeter accuracy (Ferretti *et al.*, 2011). Nevertheless the intrinsic limitations of these techniques (Ferretti *et al.*, 2001) their application over DsGSD result suitable (Colesanti and Wasowsky, 2006; Cascini *et al.*, 2010).

The improved methodology allow to assess the state of activities of three DsGSD case studies. This methodology of SAR data combination with geological and geomorphological knowledges, allow to recognize the morpho-structural domains of those phenomena. The rasterization of the SAR data, based on specific and reasoned limits, allows obtaining maps of ground deformation LOS velocities interpolation. In the cases, with a good PS/DS coverage and distribution the interpolation result more reliable and best represent the real kinematic context.

The aim of this methodology is to divide the DsGSD into sub-domain, though the definition of usage constraints that taking into account the geological and geomorphological setting and the rates of mean ground deformation velocities of the SAR data available.

By this way, those morpho-structural domains may be used for a more efficient land management. The DsGSD subdivision in domains with similar characteristics can make it easier the land management approach, allowing a better management of hydro-geological constraints.

For the purpose of land management, the assessment of the morpho-structural domain of DsGSDs is to be seen as a qualitative indicator, which must be integrated with field data and *in situ* monitoring.

A good practice will be to maintain this approach over time, including a constant revision of SAR data. By the integration of the more recent and the new satellite images (i.e Sentinel-1) should represent a good opportunity to analyse these phenomena over the coming years.

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Daniele Giordan

National Research Council of Italy, Research Institute for Geo-Hydrological Protection, Strada delle Cacce 73, 10135 Torino, Italy.

E-mail: daniele.giordan@irpi.cnr.it

Tel.: +039 011 3977830

Martina Cignetti

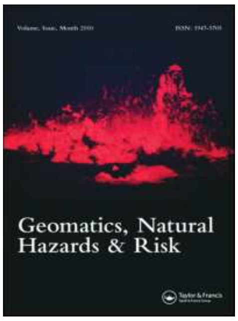
National Research Council of Italy, Research Institute for Geo-Hydrological Protection, Strada delle Cacce 73, 10135 Torino, Italy.

E-mail: martina.cignetti@irpi.cnr.it

Davide Bertolo

Strutture Attività Geologiche, Regione Autonoma Valle d'Aosta, Località Amérique 33, 11020 Quart, Aosta, Italy

E-mail: davide.bertolo@regione.vda.it



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Relationship between man-made environment and slope stability: the case of 2014 rainfall events in the terraced landscape of the Liguria region (northwestern Italy)

D. Giordan, M. Cignetti, M. Baldo and D. Godone

National Research Council of Italy, Research Institute for Geo-Hydrological Protection (CNR-IRPI), Torino, Italy

ABSTRACT

In the autumn of 2014, a series of rainfall events affected several sectors of the Liguria region, triggering many shallow landslides and causing three casualties and severe structural damages. The most intensely unstable area covered 385 km^2, in which more than 1600 landslides have been identified. After these events, an airborne Light Detection and Ranging survey was carried out. The survey yielded a high-resolution digital terrain model (DTM) and aerial images that provided a means of identifying and mapping all the occurred landslides. The distribution analysis of slope instabilities highlighted the link with various human activities. In fact, the majority of the detected landslides occurred in man-modified areas. Geospatial and statistical analyses provided the identification of three main anthropic factors: terraces, their level of maintenance and road network. Moreover, they quantified their role in landslide triggering. These factors were not analysed as separate elements, but as a continuous process, overlapping in time, in man-made influence on landscape. The identification of such factors is a key element for a correct behaviour characterization of this landscape towards extreme flash floods events.

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Human impact; anthropic terraces; road network; shallow landslides; statistical analysis

1. Introduction

In the past centuries, human intervention has caused remarkable changes in hilly and mountain landscapes (Remondo et al. 2005; García-Ruiz 2010). Human activities principally modified the natural drainage patterns, the original slope profile and cut forest for farming. In the literature, it has been recognized that land use change associated to landscape morphology is one of the main factors influencing landslide occurrence and, in particular, of rainfall-triggered ones (Glade 2003; Beek and Asch 2004; Bruschi et al. 2013). Many authors analysed the relationship between geo-hydrological processes, triggered by intense rainfall events, and the landscape characteristics (Wasowski 1998; García-Ruiz et al. 2008; Galve et al. 2015). In Liguria region (northwestern Italy), man-made intervention represented noteworthy morphogenetic impact. The acknowledgments of the human effect were achieved already in the Middle Ages, when anthropic terraces have been principally employed for cultivation (Canuti et al. 2004; Cevasco et al. 2014; Tarolli et al. 2014). The employment of such structures was prolonged over time, recording an overlapping with the accelerating rate of human intervention during the following century, principally represented by urban areas and road network development. The current landscape setting offers the opportunity to observe a long-term land use

CONTACT M. Cignetti martina.cignetti@irpi.cnr.it

history, arising from the overlap of various factors, (1) terraces, (2) their level of maintenance and (3) road network, developed by the man over time.

As previously stated, in Mediterranean area, terraces induced deep anthropic landform changes on steep slope (Lasanta et al. 2000; Varotto 2008; Kizos et al. 2010), and have been recognized as a European cultural heritage (Varotto 2008; Arnaez et al. 2011). In Italy, terraces are widespread features (Agnoletti et al. 2011; Cullotta and Barbera 2011; Camera et al. 2014). Particularly, in Liguria region, anthropic terraces are widely spread throughout the territory, with and important presence on the valley flanks of the hills (Sereni 1997). Generally, terrace building modified terrain profile, varying the original profile with bench structures, constituted by vertical dry-stone walls supporting the cultivated portion. These anthropogenic modifications reduce the slope gradient and the hydrological connectivity, decreasing erosion by controlling surface run-off (Gallart et al. 1994; García-Ruiz 2010; Stanchi et al. 2012). However, terraces assure their positive role in slope stability, by regulating run-off and rainfall infiltration, only through their constant maintenance.

Since the twentieth century, a progressive abandonment of agriculture has been recorded (Ales et al. 1992; García-Ruiz and Lana-Renault 2011; Tarolli et al. 2014; Arnáez et al. 2015). This condition determined a progressively decrease of terrace maintenance. Its lack promotes water erosion processes, local collapses of vertical stone walls and an increase of soil loss and slope failure (Koulouri and Giourga 2007; García-Ruiz and Lana-Renault 2011; Dotterweich 2013; Tarolli et al. 2014). Among these occurrences, shallow landslides are one of the most common phenomena that can arise on terraced territories (Crosta et al. 2003; Canuti et al. 2004; Camera et al. 2014). Shallow landslides are small volume of earth featuring reduced thickness (less than 2 m). They are triggered either by high-intensity rainfall, or by prolonged low-intensity rainfall (Caine 1980; Guzzetti et al. 2004; Frattini et al. 2009). Due to their high-velocity and high-impact forces, strongly conditioned by morphological and geological settings, these phenomena are a recurrent problem in steep slope regions. Consequently in Liguria, due to its landscape, urban settlements are exposed to severe threats (Brandolini et al. 2008; Cevasco et al. 2013; Galve et al. 2015).

It should be noted that in Liguria region, the current population growth rate represents a huge push factor for the development of urbanized areas also in hazardous areas (Brandolini et al. 2008; Cevasco et al. 2008; Brandolini et al. 2012; Faccini, Luino, et al. 2015) in both flat and slope areas (Brandolini et al. 2012; Faccini et al. 2016). This demanded a communication lines improvement across the valleys flanks, to enhance the accessibility to urban facilities and causing a further change of the original profile of the slope. These conditions, associated to the severe morphological setting, composed by hill and mountain hinterland, with steep slope, surrounding restricted flat areas principally distributed along the coast, constitutes a rainfall-induced landslides prone area. A meaningful aspect causing a likely increase of shallow landsliding and potential erosion in mountain areas is represented by road network (Wemple et al. 2001; Borga et al. 2004; Tarolli et al. 2013). Roads could provide remarkable alterations of the natural water flow. They alter the flow direction, concentration of run-off on the road surface and the subsurface interception by the cut-slope. All these aspects lead to the modification of the erosion pattern and the slope stability, supporting rainfall-induced landslides and mass movement (Borga et al. 2004; Cevasco et al. 2008; Tarolli et al. 2013; Jaboyedoff et al. 2016).

After a heavy rainfall event, landslides inventory and mapping constitute a reliable instrument to define the landslides distribution, types and patterns in relation to morphological, geological and land use settings. Nowadays, various methods and techniques for mapping the surface characteristics of landslides are available (Guzzetti et al. 2012). Depending on the extent of the area of interest, a long and wasteful fieldwork could be necessary, with potential problems of inaccuracy or incompleteness. The renown Light Detection and Ranging (LiDAR) technique can provide three-dimensional digital representation of the topographic surface, of large areas, by generating high-resolution digital terrain models (DTMs) (Cavalli et al. 2008; Tarolli and Dalla Fontana 2009). A DTM is able to provide enough resolution to detect and identify landslides, observing not only their sizes, but also their effects with respect to the landscape analysed (Ardizzone et al. 2007; Jaboyedoff et al.

2012). The LiDAR survey and associated aerial photos allow acquiring qualitative and quantitative data for morphological features (Ardizzone et al. 2007; Baldo et al. 2009; Razak et al. 2013). High-resolution DTM and derivative products (e.g. shaded relief, slope, aspect, roughness and contours) constitute a fundamental tool aimed to the analysis of topographic surface and the identification of morphometric landslide features, otherwise recognizable with laborious and time-consuming fieldwork.

In the autumn of 2014, a number of rainfall events occurred over wide areas of the central and the eastern part of the Liguria region (Faccini, Giostrella, et al. 2015; Silvestro et al. 2016). These heavy rainfalls occurred from October to November. They generated widespread floods and triggered thousands of shallow landslides, leading to severe structural damages and, unfortunately, three causalities. The most affected areas are three sectors of Liguria region: (1) Masone-Genova (MG), (2) Polcevera-Scrivia (PS) and (3) Chiavari (C). The presented study focuses on these areas, totaling 385 km^2 approximately, for the following purposes: (1) inventorying the occurred landslides, (2) analysing type and extent of these phenomena and (3) identifying the linkages between this widespread man-made environment and slope instability. Based on the dedicated post-event LiDAR survey data (high-resolution DTM and aerial photos) high quality morphometric variables have been computed and collected. Produced data were statistically analysed to quantify the most significant relationship between landslide occurrence and man-made land use features. These human evidences (i.e. terraces, their level of maintenance and road network) that should affect slope stability, are considered as sequence of factors, which display an overlap over time that produce the current landscape setting. The proposed approach should provide data for a better awareness of the deep interrelationship between landslide occurrence and natural and human land use modifications. Furthermore, they represent a preliminary step toward landslide susceptibility definition in a high-human modified landscape.

2. Materials and methods

A preliminary analysis of the landscape settings in the damaged areas, after autumn 2014 rainfall, was performed. The methodology, aimed to the assessment of the landscape response to these rainfall events, is made of the following steps (Figure 1):

(1) LiDAR survey and post-processing;
(2) Landslides survey (by visual analysis of aerial photos and DTM derivative products) and field checks;
(3) Landslides inventory validation;
(4) Geospatial processing;
(5) Statistical analysis.

2.1. Study area

The study focuses on the three above-mentioned sectors of Liguria region (Figure 2). The MG and PS areas are both located in the central-western '*Centro-Ponente*' portion of the region, and their extension is 121 and 185 km^{2,} respectively. C area is located in the eastern part '*Levante*' and covers a surface of approximately 79 km^2. All areas feature mountain landscape overlooking the sea, consisting of small catchments with high relief, steep slopes and abrupt descend to the coastline (Brancucci and Paliaga 2006). Restricted flat areas, surrounded by hill and mountain hinterland, are occupied by the main settlements (i.e. Genova, Chiavari), and display a widespread overbuilding.

The geological context is rather complex, going through the Ligurian Alps in the west to the Northern Apennines in the east. The PS and MG areas fall entirely within the junction sector between the Alps and the Apennines. This complex structural asset, derived from two opposite

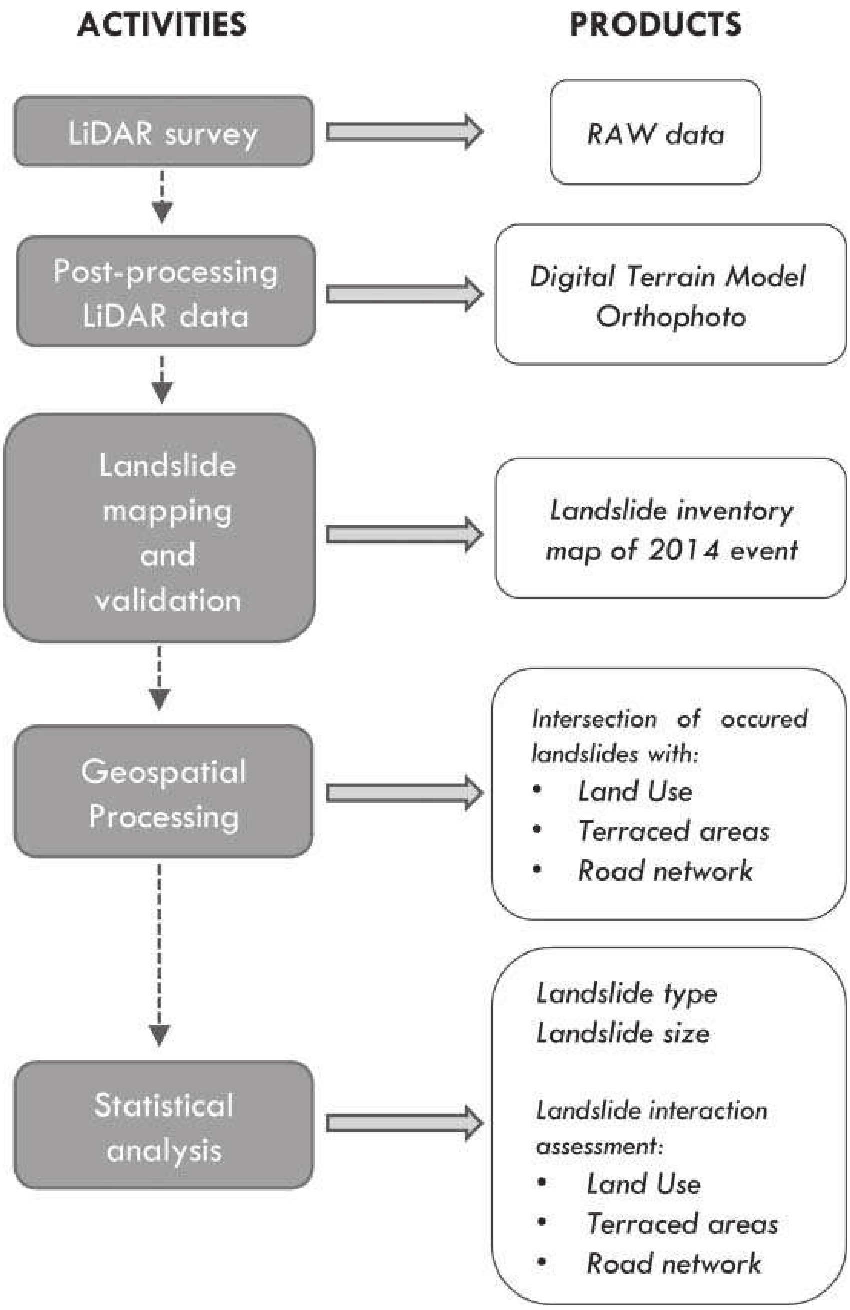

Figure 1. Flow chart of the methodology applied.

vergent orogenic belts (Abbate et al. 1970; Piana and Polino 1995), is joined by a transition zone, represented by the '*Sestri-Voltaggio Zone*' (Vignaroli et al. 2009; Molli et al. 2010).

The structural setting presents a complex evolution, involving stack of tectonic units, correlated to the distinct Alpine phase (i.e. subduction and exhumation phases), and Apennine phase (i.e. convergent trend). A post-orogenic phase, characterized by brittle tectonics, generated important N-S oriented fault system, which generates a strictly control for the drainage network (Marini 1987). Proceeding from west to east, different tectonic units outcrop. The MG sector is completely included in the Voltri Unit, consist of oceanic crust and mantle units. The bedrock, in this area, is mainly represented by two lithological formations, consist of serpentine schists (Bric del Dente Fm.) and calceschists (Turchino Fm.) (Capponi and Crispini 2008). In the western sector of PS, outcrops the Gazzo-Isoverde Unit, included in the '*Sestri-Voltaggio Zone*', between the Figogna Unit and the Palmaro-Caffarella Unit. The bedrock consists of a meta-sedimentary succession of dolomites (Monte Gazzo Fm.), gypsum levels (Rio Riasso Fm.), limestones (Gallaneto Fm.) and mudstones

Figure 2. Relief terrain of the study area within the Liguria region (northwestern Italy); the three areas of Masone-Genova (MG), Polcevera-Scrivia (PS) and Chiavari (C) are highlighted in light red; red dash-dot line represents the '*Ligure-Padano*' watershed.

(Bessega Fm.). Proceeding from west to east, outcrop: (1) the Monte Figogna Unit, consists of oceanic crust and mantle units and included in the '*Sestri-Voltaggio Zone*'; (2) and a number of units consisting of flysch succession and including the Mignanego Unit, the Montanesi Unit and the Ronco Unit (Capponi and Crispini 2008). The bedrock is mainly composed of turbiditic with fine- and medium-grained sandstone and mudstone flysch. The C area falls entirely within the Northern Apennines flysch succession (Abbate et al. 1970; Marroni et al. 2002). The area is included in the Internal Ligurian Units, which consist of the most complete and preserved section of the '*Ligure-Piemontese*' ocean basin (Abbate 1980). These units comprise an ophiolitic sequence and a hemipelagic cover (Calpionella Limestone and Palombini Shales, Upper Jurassic to Lower Cretaceous), associated with a complex turbiditic sequences (Molli et al. 2010). The bedrock of this latter sequence consists of siliciclastic and carbonate turbidites, represented by a series of formations: (1) Magnesiferous Shale, (2) Mt. Verzi Marl, (3) Zonati Shale and (4) Gottero Sandstone.

Morphologically, in MG and PS areas, the main watershed '*Ligure-Piemontese*' (Figure 2), with an average height of 600–700 m a.s.l., divides the northern side (Po plain side) to the southern side (Tyrrhenian sea side). Generally, the Po flank basins have gentle slopes and longer grade toward the bottom of the valleys, presenting wide and meandering watercourses (Lorenz 1984; Spagnolo and Firpo 2007). MG and PS areas cross part of two of the principal northern basins, respectively the Stura River and the Scrivia River basins. Instead, Tyrrhenian flank shows limited extension coastal basins, characterized by valleys prevalently N-S oriented, very-steep slopes, with presence of regressive erosive landforms and short watercourses (Brancucci and Paliaga 2006). The main southern basins of the MG and PS areas are, respectively the Leira River and the Polcevera River basins. Instead, C area shows the typical morphological feature of the Tyrrhenian side, crossing the terminal portion of the Entella River and Lavagna River, and the Rupinaro catchment, close to the Chiavari municipality, characterized by small sub-basins with very high relief and short watercourses. The average slope angle of the three study areas is

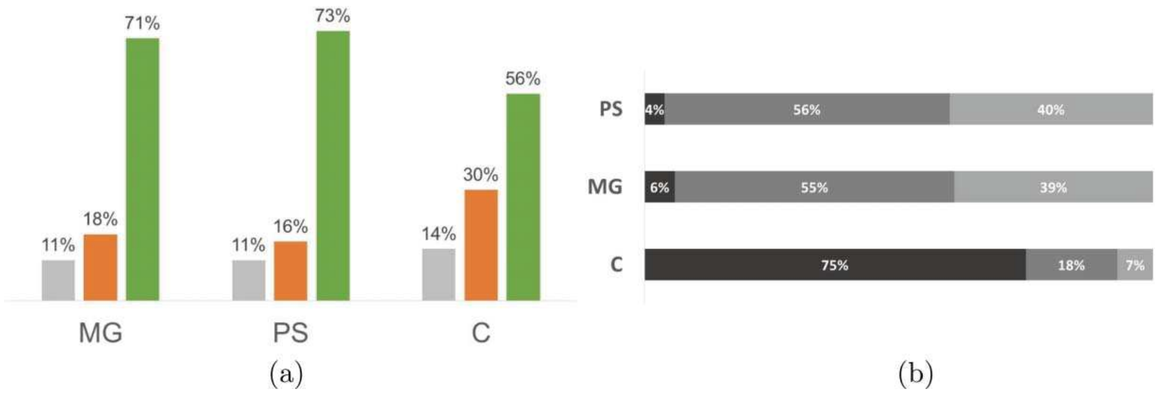

Figure 3. (a) Percentages of land use types in the three study areas; light grey = artificial surfaces, orange = agricultural areas, and green = forest and semi-natural areas (from Land Use of 2015, 1:10.000 scale, Liguria Region). (b) Percentages of the main agricultural areas sub-classes observed in the study areas; in dark grey vineyards and olive groves, in grey cultivated lands and pastures and in light grey agricultural areas with significant natural vegetated areas.

approximately 25°, due to the presence of terraces and other man-made structures, but there are local sectors reaching values up to 60°.

The land cover of the three areas prevalently consists of forests and natural grasslands, ranging from 55% (C area) to 70% (MG and PS areas) (Figure 3(a)). The greatest part consists of mesophylous, conifer and chestnut forest, and of sclerophyllous vegetation and transitional woodland-scrub. This indicates a landscape marked by human presence and signal of progressive transformation process from cultivated areas through their abandonment and spontaneous renaturation.

The agricultural areas, in MG and PC sectors, occupy less than 20% of their extents; while in C sector the 30%. Generally, in MG and PS sectors, the agricultural areas consist prevalently of non-irrigated arable lands, pastures and complex cultivation patterns (Figure 3(b)), and only a minor part of vineyards, olive groves and greenhouses. Relevant part of these areas also consists of land principally occupied by agriculture, with remarkable areas of natural vegetation. Instead, in C area, most of the agricultural areas consist of vineyards, olive groves and greenhouses (Figure 3(b)). The artificial areas occupy less than 15% of the landscape. The urbanized areas are prevalently distributed along the coast and the main valleys bottoms, with local distribution along the valleys flanks. Generally, the restricted flat areas are overurbanized, showing a growth also toward steep slopes. Communication lines through the slope and road network cross and cut the high-relief valleys flanks, connecting the scattered hamlets along the slope.

2.2. The autumn of 2014 rainfall events

In the autumn season of 2014, many severe and prolonged rainfall events affected the central and eastern part of the Liguria region. The most intense events occurred over a rather short period between mid-October (9–13) and mid-November (9–13). Heavy rainfalls, which prevalently affected Genova municipality and Tigullio hinterland (central Liguria), have characterized the meteorological event of 9 October. The storm began at 7:00 am, lasted about 9 hours, affecting the coastal sectors, and presenting a gradual precipitation reduction during the afternoon. In the Genova hinterland, a second event began at 8:00 pm featuring a heavy and prolonged rainfall with a paroxysmal phase between 10:10 pm and 11:10 pm. The maximum cumulated rainfall rate was recorded at the Genova-Geirato weather station (141 mm/1 h, 396.6 mm/24 h) (Silvestro et al. 2016). The heavy rainfall occurred during the evening caused the Carpi stream flooding, close to the Montoggio municipality, and subsequently the Bisagno catchment flooding, with the overflow of Genova. This event caused high number of landslides in the Upper Scrivia catchment, particularly in the Montoggio municipality with serious damage and one casualty, as reported by the Regional Authority (ARPAL - CFMI - PC 2014a).

The following event on 10–13 October displayed very heavy rainfall, characterized by persistence for several days, concentrated in the central portion of the region. The phases of great intensity occurred at different times and in diverse places. First, the event affected the central part of the region (10–11 October), subsequently moved down east in the '*Levante*' sector (11–12 October), and finally affected the central-western sector recording a precipitation reduction (ARPAL - CFMI - PC 2014b). The Genova hinterland and the upper Scrivia valley, close to Montoggio, were the most affected areas by the 10–11 October rainfall with cumulative rainfall of 294 mm/24 h (Vicomasso raingauge) and local peak of 110 mm/1 h (Genova-Pegli raingauge). During 11–12 October, the storm front moved to the eastern sector, recording cumulative rainfall of 156 mm/24 h, and peak of 79 mm/1 h (Casale Pignone raingauge). On 13 October, a stationary event affected the Genova hinterland, in particular Campoligure, Rossiglione and Montoggio municipalities, with cumulative rainfall of 268 mm/24 h and peak of 94 mm/1 h (Rossiglione raingauge). The Scrivia stream overflowed repeatedly on 10 October, and on the 11 October night, the Stura stream flooding has been recorded. Again, on 13 October the Stura stream tributaries overflowed close to Campoligure and Rossiglione municipalities. This event caused many shallow landslides, predominantly in Genova hinterland.

Finally, on 9–13 November a weather event with widespread and heavy rainfall, with local strong thunderstorms and a paroxysmal phase on 10 November between 5:00 pm and 0:00 pm, affected the Tigullio hinterland. The rainfall maximum rate was 67 mm/1 h as measured at Panesi raingauge and 60 mm/1 h (Chiavari-Caperana raingauge) (ARPAL - CFMI - PC 2014c). The cumulative rainfall reached its peak in the Entella catchment (170 mm/6 h); in the Lavagna catchment it amounted to 150 mm/6 h (Cevasco et al. 2015; Faccini, Giostrella, et al. 2015). This event caused the Entella catchment flooding, particularly affecting Chiavari municipality, triggered many shallow landslides, more meaningful in Leivi municipality, causing serious damages and two casualties (ARPAL - CFMI - PC 2014c).

2.3. LiDAR survey and post-processing

After the above-described rainfall events, the most intensely affected areas have been investigated. An airborne LiDAR survey, of the post-event damaged areas, was carried out between January and the beginning of April, covering a total area of about 385 km^2. The LiDAR survey was performed later than the autumn rainfall events, due to the presence of snow cover in the higher elevation sectors, in order to minimize gaps in data acquisition. The selected survey interval ensured to avoid the presence of ground coverages, including foliage, too.

A helicopter-borne RIEGL LMS-Q680i sensor (Horn, Austria) scanned the original LiDAR acquisition. The scanning was performed at 300 KHz pulse-rate with a FOV (field of view) of 60° (+7°–30°). The accuracy of the laser instrument is 20 mm at 250 m above groud level (AGL), with a beam divergence of 0.5 mrad (50 cm at 1000 m AGL); variable under unfavourable conditions (e.g. weather conditions, poorly reflecting of the surface, roughness). The laser resolution gives the level of detail of the point cloud preformed, and is divided into range and angular resolution (Jaboyedoff et al. 2012). These parameters depend on the sampling interval, and on the laser beamwidth. The point density of acquisition varied from 4 to 9 points/m^2, recording the elevation of both the first and the last return. The raw point cloud in LAS format has been georeferenced in ETRF2000 UTM zone 32N system, and in EGM2008 as vertical datum. Then, a TIN interpolation of the scanned data has been done to obtain a DTM with a 0.25 × 0.25 m resolution, with Terrascan™software suite.

The instrument was also equipped with a digital HASSELBLAD Digicam CH39 camera (39Mpixel), with 50 cm focal length objective, capable of generating terrestrial digital orthoimages, with ground resolution of 15 cm/pixel.

2.4. Landslides identification and validation

In the autumn of 2014 rainfall events, thousands of landslides occurred across the MG, PS and C areas. We operated over a large portion of the region with elevation ranges from the coastline to hill and mountain hinterland (Bric Prato d'Ermo 761 m, in MG; M.te Cappellino 703 m, in PS; M.te Anchetta peak 547 m, in C). Due to the great extent and the complexity of the involved areas, we prevalently operated by exploiting LiDAR data. This procedure is confirmed by several authors who analysed ground surface processes by means of high-resolution DTMs (Glenn et al. 2006; Ardizzone et al. 2007; Haneberg et al. 2009; Tarolli 2014; Pirasteh and Li 2016), also in forested areas (Eeckhaut et al. 2007; Razak et al. 2013; Chen et al. 2014) and for large territories (Eeckhaut et al. 2007). We employed a visual analysis methodology combining the high-resolution DTM and orthoimages. Simultaneously, in the post-event phase, ground verifications have been executed in order to define the principal morphological characteristics of the occurred phenomena. In addition, constant updates and communication with local authorities (e.g. regional technicians, municipal technicians, mayors), concerning information of phenomena location, were carried out.

The high-resolution DTM supplied a detailed representation of the topographic surface able to provide a tool for recognition of landslides, and all the occurred surface morphology signatures (McKean and Roering 2004; Ardizzone et al. 2007; Derron and Jaboyedoff 2010; Razak et al. 2011; Chu, Chen, et al. 2014; Břežný and Pánek 2017). Several investigations demonstrated the effectiveness to perform landslide types recognitions and morphological parameters identification through high-resolution DTMs (Chigira et al. 2004; Glenn et al. 2006; Ardizzone et al. 2007; Chu, Wang, et al. 2014). We operated by processing the DTM in order to obtain several derivative products: (1) shaded relief, (2) slope and (3) roughness. The roughness has been calculated by the method proposed by Cavalli and Marchi (2008). The comparison of the morphometric layers with the high-resolution orthoimages allowed investigating and mapping all the occurred morphological features (Figure 4).

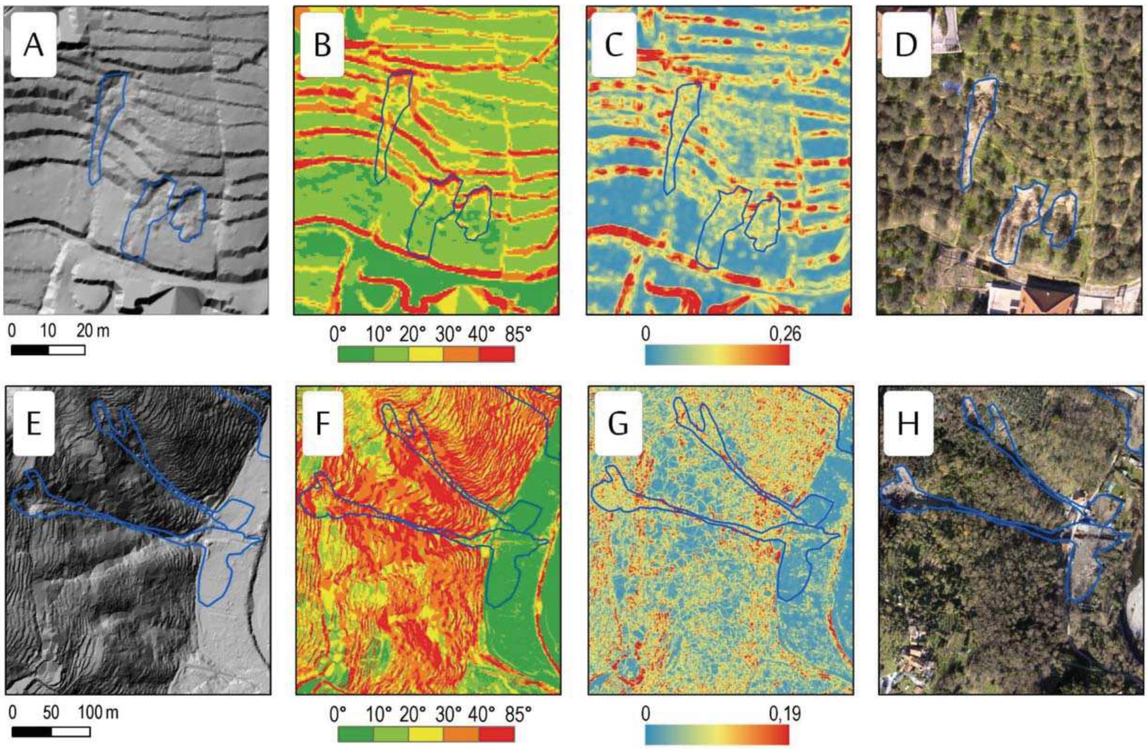

Figure 4. Examples of individuation and analysis of several rainfall-induced landslides located in C area. (A) shaded relief, (B) slope, (C) roughness and (D) orthoimage of three soil slips; (E) shaded relief, (F) slope, (G) roughness and (H) orthoimage of two debris flows, which caused two victims.

According to the described work flow, we identified landslides, their type and main morphological parameters (e.g. crown area, accumulation zone, body extent) at metric scale. We operated in an open source geographic information system (GIS) environment, particularly QGIS 2.18 (QGIS Development Team 2009), and we stored all the collected data in a spatial database. A landslide inventory map was then performed, and landslides were classified according to Cruden and Varnes (1996). Simultaneously, we performed a validation analysis of the inventoried phenomena. This comparison intended to identify previous phenomena and possible reactivation cases and to verify the effective number of the landslides that occurred during the autumn of 2014. We compared the mapped landslides with the freely available Italian Landslide Inventory (Trigila et al. 2008). An additional analysis was performed using aerial photos available on regional web-portal ('*Liguria Geo-Portale*', AGEA 2013; '*Portale Cartografico Nazionale*' 2012).

The resulting landslide map was constantly checked and updated in cooperation with local authorities. By a continuous cross-check between the mapped landslide and field surveys, operated by municipalities coordinated by regional authorities, the map was improved and updated.

2.5. Geospatial processing

In the described GIS environment, the landslide polygons were processed in order to retrieve spatial metrics such as their surface. Moreover, the intersection between each geometrical entity and several map layer was checked.

In order to compute the statistical test, independent variables were pre-processed in GIS environment. We started by grouping homogeneous categories from the land use data-set, available from the geoportal of Liguria region (Regione Liguria 2016) in vector format at 1:10.000 scale, in order to optimize classes and their distribution:

(1) Artificial surface;
(2) Agricultural areas;
(3) Forest and semi-natural areas.

The artificial surfaces category included all small localities, urban terrain and build-up areas, industrial and commercial factories, and road/rail networks. These areas show a general reduction in terrain permeability and can affect the natural drainage pattern (May 1996; Chin 2006; Kang and Marston 2006; Hall et al. 2014; Nardi et al. 2015). Concerning agricultural areas, generally, we observed that vineyards and olive groves are set in anthropic terraced areas presenting bench structures with dry-stone walls, in terrain with steep to very-steep slope. The cultivation patterns and pasture are still set in terraced areas presenting both bench with stone-walls and edge-structures without walls, in terrain with more gentle slope. Finally, the land occupied by agriculture with relevant areas of natural vegetation is featured by a reduced human intervention or a progressively renaturation. Based on our observation, a further subdivision of agricultural areas for the statistical analysis was done in:

(1) Vineyards, olive groves and greenhouses;
(2) Non-irrigated arable lands, pastures and complex cultivation patterns;
(3) Land principally occupied by agriculture, with significant areas of natural vegetation.

Those categories gather the main crop types related to the landscape characteristics. Finally, forest and semi-natural area class included broad-leaved forest, chestnut forest and coniferous forest. Furthermore, all transitional woodland-scrub areas, in which a natural degradation of the forest or recolonization of not-forested areas took place, were included.

We have then chosen to carry out more in-deep analyses of the road network sub-category. According to several authors (Jones et al. 2000; Duke et al. 2003; Borga et al. 2004;

Jordán-López et al. 2009; Fu et al. 2010), communication lines can increase the susceptibility of terrain to erosion and shallow landslides. These linear elements constitute preferential material and energy transport routes across the land, crossing steep slopes and cutting and/or surmounting the downslope flow of drainage network. Roads can act as a barrier, a source or as flow-path corridors, thus conditioning lateral movement of the drainage network and favouring the occurrence of shallow landslides (Jones et al. 2000; Luce 2002; Tarolli et al. 2013). We identified all the possible intersections between landslides source areas and the road network. To avoid a long visual analysis of each inventoried landslides, we took advantage of a buffer analysis around road features, provided in vector format by the Liguria geoportal (Regione Liguria 2016), by setting a distance of 5 m, considered as reasonable distance of road infrastructure influence as it considers not only the road itself, but also drainage ditches or other features usually not mapped in the vector layer.

Moreover, another peculiar aspect of the region was considered. Anthropic terraces constitute the most widespread feature of the landscape in Liguria region. In our work, the high-resolution DTM and its derivative products provide a detailed representation of the topographic surface, useful to discriminate the presence of terraced areas. This also highlighted their presence in correspondence of forestland, normally not visible using traditional aerial photos analysis.

2.6. Statistical analysis

The landslide data were used to calculate descriptive statistics, and characterize the occurred landslides according to their type and size. Then, land features were statistically tested against landslide crown area with the purpose of pointing out potential relationships between land use and landslides occurrence. In fact, when analysing rainfall-induced landslides in a deeply human-modified landscape, its setting constitutes an important element in determining its hydrological response (Cevasco et al. 2014; Camera et al. 2015; Galve et al. 2015).

We applied the Pearson χ^2 test for categorized data in a statistical open source environment (R Development Core Team 2011). This test leads to computation of the significance of relationship between occurred landslides and environmental parameters by comparing observed counts and expected values, which are the counts under the null hypothesis. It is an non-parametric test, used to gain an understanding of potential relationships between two classifications or variables (Gibbons, 1985). It highlights associations that should be a subject of further investigation.

We tested the significance of relationships between rainfall-induced landslides and the above-listed parameters (Remillard and Welch 1993). In order to point out the land use type more associated to landslides occurrence, we tested the three categories against each one pairwise. We performed an analogous test among ‘Agricultural areas’ subclasses. We computed contingency tables counting landslides according to their belonging to geographical area (C, MG, PS) and to the selected environmental variable. The null hypothesis is that the landslides are equally distributed across the landscape, if the null hypothesis is rejected it is possible to argue that occurrence of landslides is associated to the considered land features.

We applied the described procedure to test the association between shallow landslides and man-made structures, such as terraces and road, too.

3. Results

The landslide investigation, operated after the autumn of 2014 rainfall events, allowed the identification and mapping of 1641 rainfall-induced landslides in the 385 km^2 analysed area, of Ligurian territory. In specific, in MG we mapped 493 phenomena, in PS 841 and in C 307 landslides. Further data are reported in Supporting Information . The landslides classification is based on the prevalent type of movement and material, according to the Cruden and Varnes (1996) classification. Most phenomena corresponded to shallow landslides, including: (1) soil slips (98%), (2) debris flows (1%) and (3) debris avalanches (1%) (Figure 5(a)). Few cases of rotational slides were also identified. The

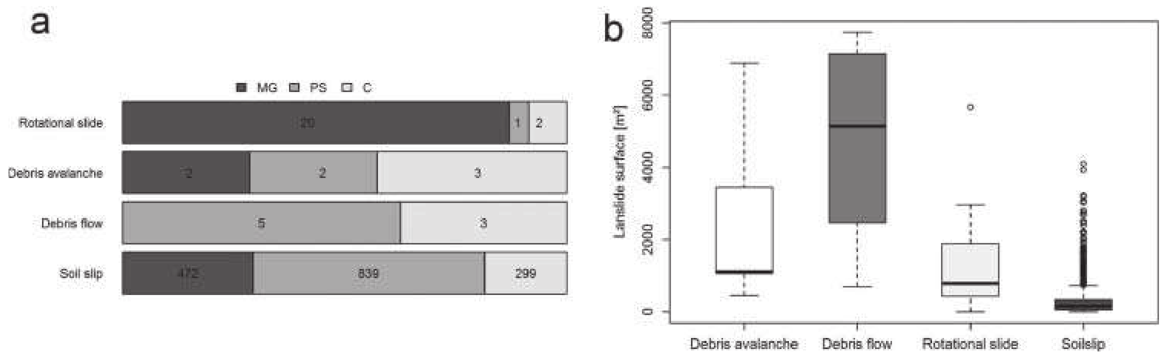

Figure 5. (a) Number of landslides for each study areas divided for type; (b) box plot of the landslide areas for each type of inventoried landslide. The black line corresponds to median. Dots are the outliers.

soil slips class includes shallow failures of colluvial soil with moderate volume. Generally, they present initial rotational or translational slide followed by an overflowing of the involved mass onto adjacent land. They normally occurred on steep slope, and should evolve in flowing debris that caused inundation and lateral impact, which could generate damages. The debris flows class defines all those water-laden mass of loose sediment and rock, canalized into stream channels. They rush down the slope by the erosion through the gullies and forming thick deposits at the base of the slope (Hungr et al. 2001). Finally, debris avalanches are the moving down mass of rock and soil. The debris flows are channeled movements, while debris avalanches are open-slope mass movements.

The shallow landslides mainly consisted of soil slip and generally exhibited reduced areal dimension ranging from tens to hundreds of square meters (Figure 5(b)). Several extended debris flows and debris avalanches occurred in the three study areas, reaching meaningful size of thousands of square meters, one of which caused two fatalities in Leivi municipality. The main rotational slides occurred in MG area and presented reduced extents, ranging from hundreds to thousands of square meters. Concerning the full extent of the three study areas, we identify a mean distribution of approximately 4 slides/km^2, primarily represented by shallow landslides. Observing the areal dimension respect to the land use classes, we noticed that in the 'Forest and semi-natural areas' classes are distributed the largest phenomena, in comparison with the other classes (Figure 6).

Concerning land use and its relationship with landslides distribution, the Chi square test allowed us to carry out further in-depth analysis. It has highlighted a link between land use classes and landslide occurrences (χ^2= 276.25, df = 4, p = ***). Table 1 shows the counts of observed and expected landslides among the considered land use classes.

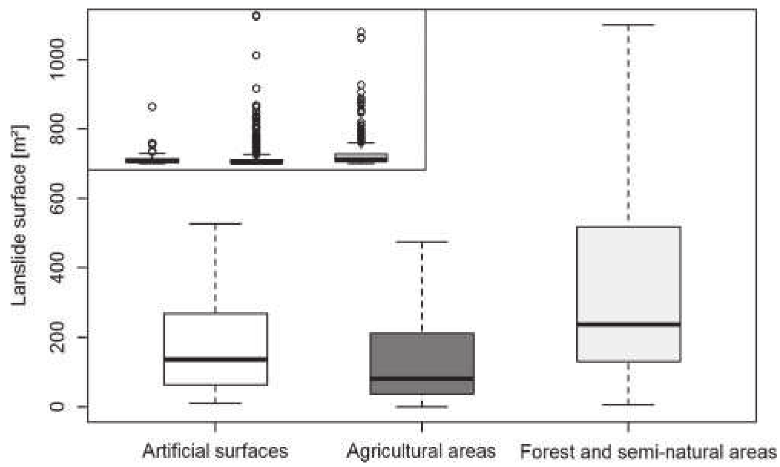

Figure 6. Box plot of landslide areas for each type of land use intersection. The inset plot shows the same box plot with outliers.

Table 1. Observed and expected distribution of landslides in the three areas according to the three land use classes.

	Observed			Expected		
	Artificial	Agricultural	Forest	Artificial	Agricultural	Forest
C	9	197	100	10.848	137.58	157.58
MG	15	327	148	17.36	220.31	252.33
PS	34	212	595	29.80	378.12	433.09

Table 2. Pairwise comparison of land use classes and test results.

	Observed					
	Artificial	Agricultural	Forest	Artificial	Agricultural	Forest
C	9	197	197	100	9	100
MG	15	327	327	148	15	148
PS	34	212	212	595	34	595

	Expected					
	Artificial	Agricultural	Forest	Artificial	Agricultural	Forest
C	15.05	190.95	138.44	158.56	7.02	101.98
MG	24.98	317.02	221.41	253.59	10.49	152.51
PS	17.97	228.032	376.161	430.84	40.49	588.51

Sub-variable 1	Sub-variable 2	χ^2	df	p
Artificial	Agricultural	22.35	2	***
Forest	Artificial	274.92	2	***
Agricultural	Forest	3.78	2	-

Table 3. Observed and expected distribution of landslides in the three areas according to the three agricultural sub-classes; 2a = vineyards, olive groves and greenhouses, 2b = non-irrigated arable lands, pastures and complex cultivation patterns, 2c = land principally occupied by agriculture, with significant areas of natural vegetation.

	Observed			Expected		
	Class a	Class b	Class c	Class a	Class b	Class c
C	166	19	12	46.57	86.72	63.70
MG	4	199	124	77.31	143.95	105.74
PS	4	106	102	50.12	93.33	68.55

The relative importance of the above-listed independent variables is presented in Table 2, which shows in the first subtable the observed and expected counts and in the second one the statistical significance of pairwise analyses. The Chi square values, calculated for each one, suggest that the 'Agricultural surfaces' categories are most strongly related to landslides distribution (Table 3).

In detail, among agricultural subclasses, the analysis points out 'Vineyards, olive groves and greenhouses' as the most associated one in terms of landslides occurrence (Tables 4 and 5). Tables framework is the same as the previous ones.

Concerning man-made structures both terraces and roads have shown similar behaviour on landslide occurrence (Table 5), thus showing their effective influence.

In light of these information, we inspected the field characteristics of the 'Agricultural surfaces' sub-categories, significantly to the level of maintenance of the terraces. In 'Vineyard, olive groves and greenhouses', terraces are prevalently characterized by bench structures with dry-stone walls, which likely show high level of maintenance and dry retaining walls (Figure 7(a)). In some cases we observed local wall failures (Figure 7(b)). In 'Non-irrigated arable lands, pastures and complex cultivation patterns', we observed a variable presence of stone-walls terraces and edge-structures without walls (Figure 7(c)),which feature variable levels of maintenance and consequently diverse run-off responses. Finally, 'Land principally occupied by agriculture, with significant areas of natural vegetation' sub-class shows a heterogeneous landscape, still

Table 4. Pairwise comparison of agricultural sub-classes and test results.

	Observed					
	Class b	Class c	Class a	Class c	Class a	Class b
C	19	12	166	12	166	19
MG	199	124	4	124	4	199
PS	106	102	4	102	4	106

	Expected					
	Class b	Class c	Class a	Class c	Class a	Class b
C	17.87	13.13	75.17	102.83	64.64	120.36
MG	186.21	136.79	54.06	73.94	70.93	132.07
PS	119.91	88.09	44.77	61.23	38.43	71.57

Sub-variable 1	Sub-variable 2	χ^2	df	*p*
2b	2c	6.0541	2	-
2a	2c	334.47	2	***
2a	2b	388.79	2	***

Table 5. Observed and expected distribution of landslides intersecting anthropic features and test results.

Observed	Intersection	No intersection
Terraces	895	742
Roads	1311	326
Expected	818.5	818.5

Variable	χ^2	df	*p*
Terraces	14.3	1	***
Roads	592.68	1	***

occupied by terraces, with a general poor maintenance of stone walls, and presenting a natural recolonization by forest and shrubs (Figure 7(d)).

4. Discussion

Since the Middle Ages, the effect of human activities has been particularly evident in Liguria territory, which has been progressively and intensely modified landscape structure and appearance (Faccini et al. 2009; Brandolini et al. 2012). The landscape, almost completely occupied by hills and mountains with steep slopes, has been subjected to hundreds of years of human management, primarily represented by anthropic terraces, and later by road and urban area developments. Many authors analysed the influence of land use setting on rainfall-induced landslides occurrence during intense rainfall event in Liguria region (Cevasco et al. 2013, 2014; Galve et al. 2015; Brandolini et al. 2017). Most of them focused on restricted areas affected by rainfall-induced landslides. These studies surely constitute a detailed description of an unusual, but visible in the most part of the region, land use setting. This should provide a valuable starting point for the analysis of a wider area as that affected by the autumn of 2014 rainfall events (385 km^2) and described in the present paper. Furthermore, our study analysed not only terraces, but also their interaction, their level of maintenance and road network, too. Our study, in fact, shows that the current scenario is the result of the progressive interaction and overlap of these three factors. These findings are based not only on expert-based evaluation, as carried out in previous works, but also on the results of statistical analyses. The availability of high-resolution DTM and orthoimages allowed us to acquire an accurate representation of the topographic surface and to detect anthropic features inducing landslides. Considering the land use classes adopted in the statistical analysis, ‘Agricultural areas’ (20% –30% of the land use

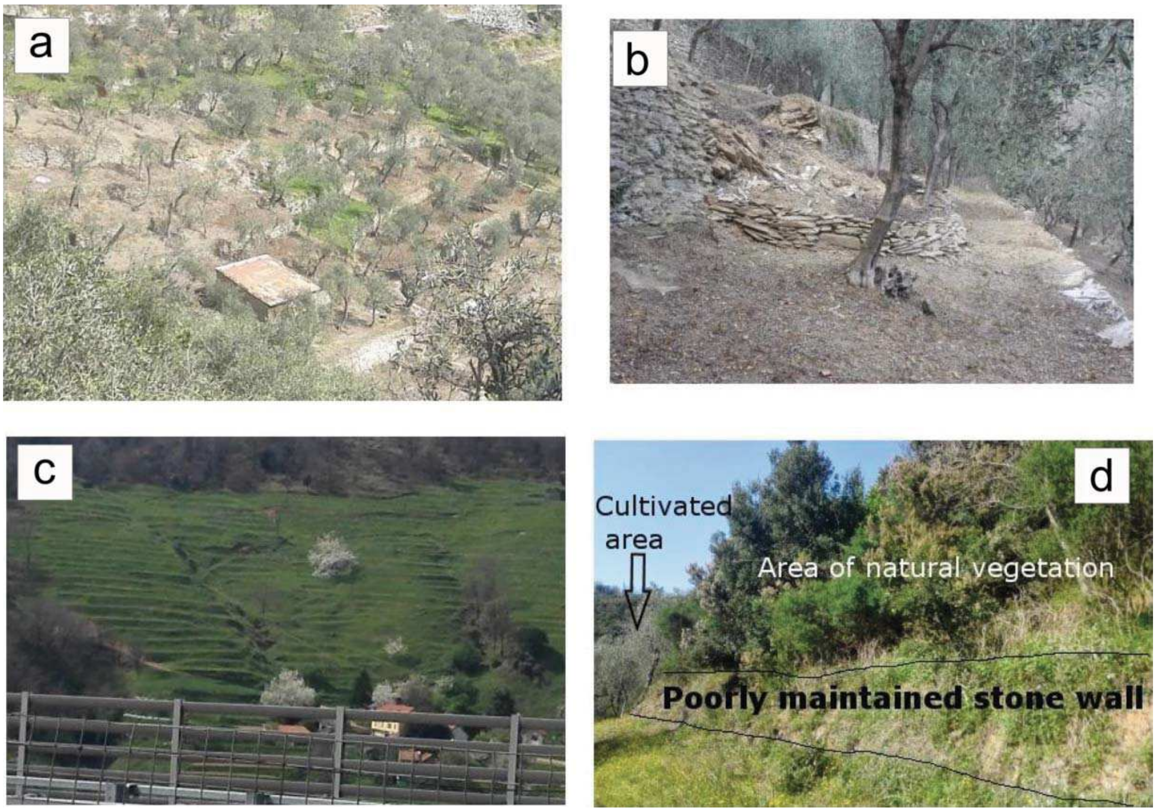

Figure 7. Observed terraces typologies; (a) bench structure with dry-stone walls; (b) small shallow landslide involving stone wall; (c) edge-structures; (d) poorly maintained dry-stone walls.

of the entire analysed territory) are the most affected areas by shallow landslides than the forested and scrubland ones. We divided this category in the three most representative sub-classes, which generally present specific physiographical characteristics. Most of the detected territory display an anthropic terraced environment, and we opted for discerning from bench structure with dry-stone walls to edge-structures without stone walls. Through the statistical analysis, we have observed that further factor associate to landslides occurrence was represented by the presence of terraces. Connecting this feature with the considered agricultural sub-classes, we could deduce several considerations. Great attention was paid to the kind of terraces in these sub-classes, and their level of maintenance, as they may influence local or slope stability. It also displays different behaviours and responses to heavy rainfall event. In the cases of high level of maintenance, the wall of terraces responds with greater hydraulic conductibility and drains correctly the above run-off. We have noticed that a higher landslides density occurred in correspondence of cultivated terraced (Agricultural areas, Vineyard, olive groves and greenhouses), characterized by intermediate or progressive drop of wall maintenance, as already reported by Cevasco et al. (2013, 2014). Instead, high-magnitude landslides seemed to be more concentrated in forest and semi-natural areas, in which a complete abandonment of terraces has been noticed.

Concerning other considered anthropic element, the statistical analysis highlighted significant linkage between road structures and landslides occurrence. Communication lines building and development induced a slope re-profiling, linked to the decrease of slope stability and landslides occurrence induced by cut and fill for road constrictions (Jaboyedoff et al. 2016). We noticed that during the autumn heavy rainfall events, the pathways acted as a corridor, in which water and sediment transport have been gathered (Figure 8). Often a cut and pass of the road network by the slides was detected during the field checks. In the study areas, a wide road network affects steeply slope territory, modifying the water flow direction and increasing the susceptibility to slope instability. In this context, roads are an influential factor in slope instability, and their occurrence is significantly correlated with shallow landslide.

Figure 8. Shallow landslides interaction with road network.

5. Conclusion

On the autumn of 2014 a series of rainfall events hit the '*Centro-Ponente*' and the '*Levante*' portions of Liguria, triggered thousands of shallow landslides and causing severe damages and three casualties. A total of 1641 shallow landslides were inventoried and analysed by airborne LiDAR survey of an area of 385 km^2, associated to local field survey. A combined visual analysis of high-resolution DTM derived products (e.g. slope, shaded relief, roughness) and aerial photos, associated to field survey, implemented a landslide characterization, including type and principal morphological feature definition. The land use factor, strictly associated with human intervention, resulted a key issue in the occurrence of rainfall-induced landslides. The Liguria region has a long history of human impacts. It is characterized by widespread terraces and overbuilding, accompanied by stream modification and road network extensions. In this peculiar landscape, the influence of human management on slope stability during heavy rainfall and flash floods is a dominant factor. The comparison between occurred landslides and land use displays that terraced agricultural areas are the most prone area to shallow landslides than forest and semi-natural areas. The majority of landslides source area involved agricultural area occupied by vineyard, olive groves and greenhouses, although the degree of maintenance seems to be higher. In these sectors, the occurred landslides display small size, and often involved the terraces stone walls, while in woodland the landslides size were bigger. Furthermore, factor was represented by road network that indicates a significant relationship between communication lines and landslides occurrence. In conclusion, this paper provides a starting point to solve complex problems relating shallow landslide occurrence and land use changes over time, with a focus on the role of human impact on a landscape that has been significantly modified over the past few centuries. The results achieved should contribute to the assessment of the relationship between landslide occurrence and natural and human land use modifications, and constitute a preliminary step toward landslides susceptibility definition in a deeply human modified landscape.

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Disclosure statement

No potential conflict of interest was reported by the authors.

ORCID

D. Giordan http://orcid.org/0000-0003-0136-2436
D. Godone http://orcid.org/0000-0003-1455-6862

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