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Integrating archival data and remote sensing for landslide inventory: a case study of Polog region, N.Macedonia

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Abstract

Geohazards, including landslides, pose a significant global threat, endangering human lives, economic activities, ecosystems, biodiversity, and cultural heritage. Population growth and urban expansion have increasingly forced communities to settle in landslide-prone regions, amplifying the associated risks. Developing effective landslide risk management strategies requires a comprehensive understanding of past landslide distributions.

In Macedonia, where systematic landslide data collection is lacking, this study focuses on creating a landslide inventory for the most landslide-prone region in the country, the Polog region. Detection and characterization of unstable phenomena in the Polog region started with collection of archival landslide data and establishing the structure of the database. Figuring out that the number of the landslides in the region is significantly higher, the following step was application of Differential Interferometry Synthetic Aperture Radar (DInSAR) and Light Detection And Ranging (LiDAR) for detection of landslides. The DInSAR data for the region were analysed, a control/update of the outline and the state of activity of the already mapped landslides in the landslide inventory was done, hitherto new landslides were also detected, and their kinematic characteristics were defined to the extent possible. Then, based on visual analysis of the digital terrain model obtained from LiDAR scanning, the detection of other landslides in the study area was performed.

The archival landslide inventory for the Polog region consists of 136 phenomena. The DInSAR data for the region were analysed, and 38 positions that show displacements (so-called “hotspots”) were singled out. The identification of landslides from LiDAR digital terrain model based on visual analysis of terrain deformations and recognizable features of landslides resulted in 46 new locations with indications of presence of landslide.

The combined application of these methods resulted in the first comprehensive landslide inventory for the Polog region, offering a valuable tool for regional-scale landslide management. This inventory, designed for continuous updates, provides a critical foundation for developing landslide susceptibility, hazard, and risk models, which are essential for effective risk mitigation and sustainable land-use planning.

Keywords

Landslide, detection, DInSAR, LiDAR, archival landslides

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1 Introduction

Geohazards, such as landslides, represent a significant threat worldwide, with profound implications for human safety, economic stability, and environmental sustainability (Schuster 1996; Kjekstad and Highland 2009). The growing global population, coupled with rapid urbanization, has intensified the vulnerability of human settlements to landslide hazards. In many regions, the demand for land has forced communities to expand into unstable and high-risk areas, such as steep slopes, mountainous terrains, or regions with fragile geological formations.

The distribution of past landslides (including also rock slides, scree deposits, rockfalls) is a critical foundation for developing reliable models of landslide susceptibility, hazard, and risk. Accurate and comprehensive landslide inventories allow to identify patterns, assess triggering factors, and predict future occurrences with greater precision. While this prerequisite is met in data-rich regions with well-documented landslide records, many areas lack such systematic datasets. In these data-limited regions, researchers are often left with the challenging task of mapping landslides from scratch, which can be both labour-intensive and fraught with challenges. Traditional geomorphological field mapping is a time-consuming process, especially when applied over large and geologically complex areas, while fully automated methods can introduce significant errors.

The Polog region of Macedonia exemplifies this challenge. Occupying nearly 10% of the country’s territory, the region is characterized by a unique combination of factors that make it highly susceptible to landslides. Its complex geological formations, rugged and dynamic morphology, and specific climatic conditions collectively contribute to frequent slope instabilities. Considering that no systematic and timely collection of landslide data has been conducted in the region, this paper presents an approach to landslide inventory development, leveraging contemporary techniques for landslide detection and characterization, combined with an analysis of archival landslide data.

The approach for establishing landslide database for the Polog region integrates advanced remote sensing techniques, including Differential Interferometry Synthetic Aperture Radar (DInSAR) and Light Detection And Ranging (LiDAR), alongside an analysis of archival landslide records. DInSAR offers millimetre-accuracy insights into ground displacement velocities and landslide activity, while LiDAR provides high-resolution topographic data for multi-temporal analyses and volumetric estimates of landslides.

The obtained results are not only essential for understanding the distribution of past landslides but also form a critical input for developing robust susceptibility, hazard, and risk models tailored to the region.

2 Landslides in the Polog region

The Polog region is located in the northwest part of North Macedonia, Fig. 1b. It covers an area of approximately 2,500 square kilometres, accounting for about 10% of the country's total territory. The Polog region experiences a moderate continental climate, with notable temperature variations across the seasons and significant precipitation, particularly in the mountainous areas. The region is rich in water resources, with a dense hydrographic network comprising numerous rivers, streams, and lakes. It is characterized by rugged, mountainous terrain and a dense hydrographic network, including torrential streams and rivers. The geological formations in the Polog region span almost all geological periods, from the Cambrian to the Quaternary, with a variety of igneous, sedimentary, and metamorphic rocks present throughout the area.

Historically, the Polog region has been exposed to extreme weather conditions and frequent flooding, which have caused significant human and economic losses. Notably, devastating flash floods occurred in 2015 and 2016, resulting in substantial damages (Peshevski et al. 2017). These catastrophic events were triggered not only by violent streams but also by inappropriate land use, such as construction in floodplains, illegal urbanization in hazard zones, the constriction of river courses, and increased erosion from deforestation. These human-induced changes have disrupted natural hydrological processes, exacerbating the risks of floods and amplifying the associated hazards, in addition to promoting other unfavourable geological processes.

The creation of a landslide inventory for the Polog region is done by applying the following three approaches: (1) Collection and analysis of archival landslide data; (2) Detection of landslides through analysis of satellite data obtained from synthetic aperture radar sensors (SAR) and processed with Differential Interferometry (DInSAR); (3) Detection of landslides based on visual analysis of digital terrain model (DEM) obtained by LiDAR terrain scanning. A detailed description of these approaches and the results alongside, are presented as follows.

2.1 Collection of archival landslides

The process of collecting archival landslide data involved several activities, starting with the analysis of existing data on landslides and progressing to site visits based on surveys completed by municipal representatives. Landslide information was digitized from old geological maps at a 1:25,000 scale and analyzed from the archives of the Geological Survey of Macedonia. Additional data were gathered through interviews with employees and retired colleagues from geotechnical companies and by studying landslides along the channels of the "Mavrovo" hydro energy system. Collaboration with the National University in Tetovo included a joint site visit, while visits to geotechnical companies across Macedonia provided further context. The details of these activities and the processing of the obtained results are elaborated in Nedelkovska et al. 2020. The resulting GIS-based database includes 136 landslide occurrences, detailed with attributes such as location, geology, activity, features (type and direction of movement, extent, triggers, and depth), and data source, where known. The landslide inventory map produced by collection of archival landslide data for the Polog region is shown in Fig. 1c.

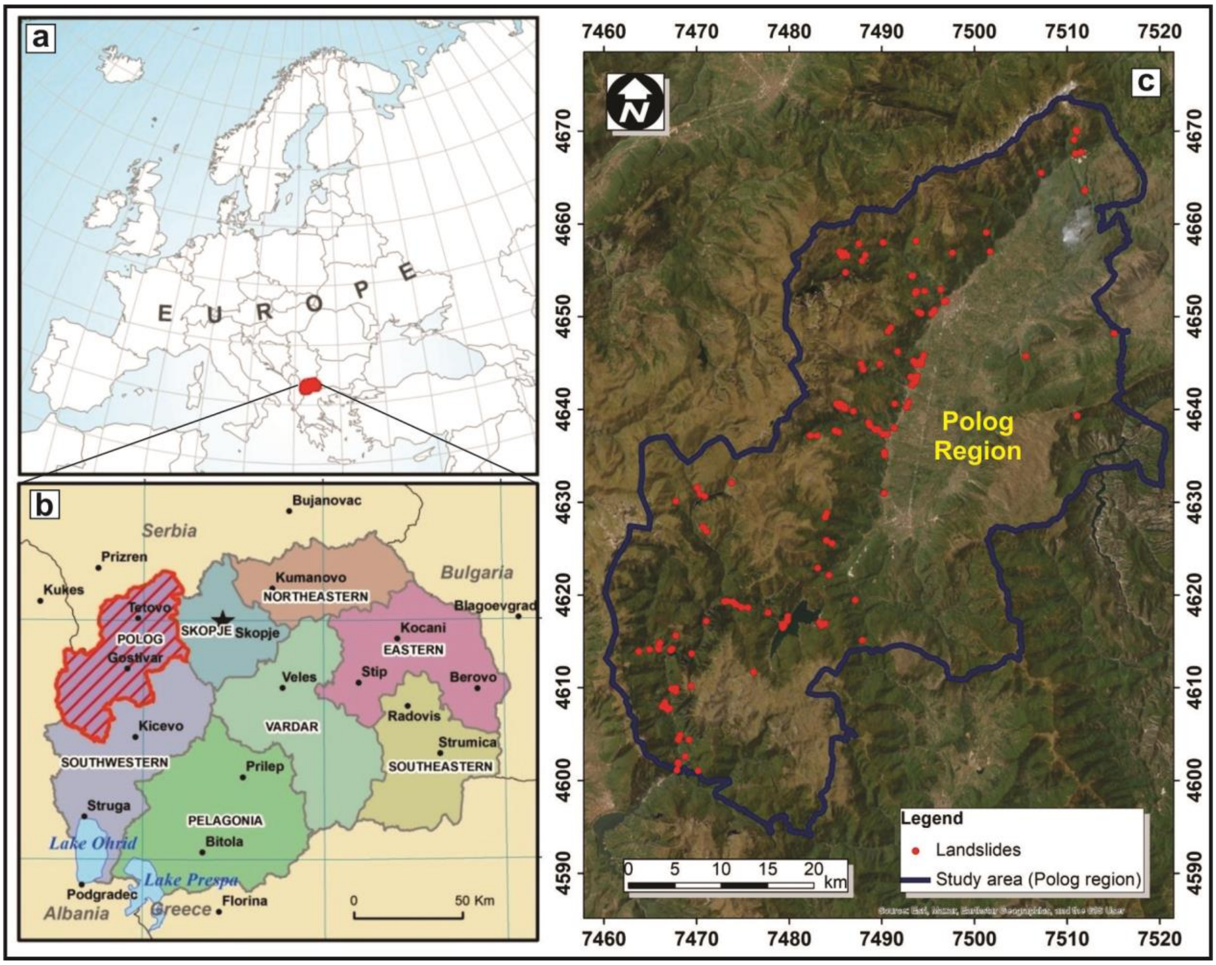

Fig. 1 a) Position of N. Macedonia in Europe; b) Polog region (N. Macedonia); c) Landslide inventory map of Polog.

It can be noted that the contact of the Shar Mountain massif with the Polog valley is a kind of boundary of the distribution of the known landslides. The landslides are located in the mountain part of the study area, whereas a greater concentration is observed in the northwestern part.

The most important parameter controlling the distribution of landslides is the *lithological composition* of the terrain. With the analysis of archival landslide inventory it was concluded that most landslides develop along the debris and schist bedrock contact. Namely, more than half of the landslides occurred in varieties of schists.

The number of landslides in the region was believed to be significantly higher, but many have not been adequately documented in the past.

2.2 Exploitation of DInSAR for detection of moving areas

When landslides occur, they change the land cover. Satellite sensors can measure topographic surface changes, and data obtained by satellite sensors can be used to detect, map, and monitor landslides. Synthetic Aperture Radar (SAR) is a high-resolution radar device mounted on an artificial satellite, operating efficiently during both the night and the day and in all weather conditions. Interferometric Synthetic Aperture Radar (InSAR), or SAR Interferometry, is a method for taking the signal phase difference from two scenes of SAR data, which are observed in the same area at different times. When the point on the ground moves, the distance between the sensor and the point changes, and so the phase value recorded by the sensor is affected too (Ferretti 2014).

Since the past two decades, the processing via Differential Interferometric techniques of images acquired by space-borne Synthetic Aperture Radar (DInSAR) has become a viral tool to study the measurable effects of natural or anthropogenic phenomena (or dangers) in different fields of geosciences (Crosetto et al. 2003), as well as in the civil, geotechnical and environmental engineering. This is essentially due to several advantages offered by DInSAR techniques, such as (1) the possibility of measuring ground surface displacements with sub-centimeter accuracy; (2) the availability of large datasets of SAR images acquired over more than 25 years; and (3) affordable costs for monitoring large areas. As a result, the scientific community analysed many case studies that successfully investigated the potential and limits of the DInSAR techniques in different fields – among which earthquakes (Reale et al. 2011), slow-moving landslides (Peduto et al. 2018), as monitoring (infra)structures and landslides (Nicodemo et al. 2017; Grujic et al. 2022) and for addressing multi-risk issues (Pazzi et al. 2016).

For the Polog region, a set of multipass SAR images acquired over ascending orbits (relative orbit no. 175) by Sentinel-1A and Sentinel-B satellites delivered by the European Space Agency (for the period April 2015 – December 2019) were used. The processing of Sentinel-1 SAR acquisitions is done by radar image processing experts from *CNR - IREA* (Consiglio Nazionale delle Ricerche - Istituto per il Rilevamento Elettromagnetico dell'Ambiente), through the two-scale algorithm by Fornaro et al. 2014.

The processing of the Sentinel-1 data for the Polog Region was restricted to three bursts from the IW2 subswath (Fig. 2a), given the region's extent relative to the wide coverage of a single acquisition in standard Interferometric Wide Swath (IW) mode.

The DInSAR deformation map, Fig. 2a shows the spatial distribution of detected coherent targets with their average velocity along the sensor-target Line Of Sight (LOS) referred to the period of observation. As expected, most of coherent targets concentrate in urbanized areas located in the plain parts. Some targets are also detected on the hillside that represents the focus of this analysis. Western part of the Polog Region, characterized by the presence of high mountains, is affected by severe decorrelation that causes lack of detected PS.

2.2.1 Analysis of Sentinel DInSAR velocity and comparison with the archival landslide data

The landslide inventory for the Polog region consists of 136 phenomena. For 118 of the total landslide number, the outline of the landslide is mapped, while the rest 18 landslides are identified as points. Sentinel-1 SAR acquisitions over Polog Region for the period spanning from April 2015 to December 2019 were analysed and check of the inventoried landslides in which at least one coherent DInSAR pixel was found was carried out within the performed analysis.

Fig. 2b shows the results for the area covered by Burst 1, where the number of covered landslides is 12 (out of the total of 31 mapped in the area covered by Burst 1), and representing 38% out of the mapped phenomena. Fig. 2c shows the results for the area covered by Burst 2, where the number of covered landslides is 14 (out of the total of 52 mapped in the area covered by Burst 2), and representing 27% out of the mapped phenomena. Interestingly, only 9 (2 in Burst 1, and 7 in Burst 2 processing areas) of the covered landslides were fully classified in the archival landslide inventory regarding type and state of activity. Accordingly, a deep analysis of DInSAR data are useful to provide some insights into the kinematics of the abovementioned phenomena.

Finally, a check of the inventoried landslides was also performed for the Burst 3 processing area. Unfortunately, the burst 3 processing area is only partially covered by DInSAR data (see Fig. 2a). In particular, only in the portion located in the southeast - where no landslide polygon is present in the available inventory map - coherent benchmarks are retrieved by the SAR image processing.

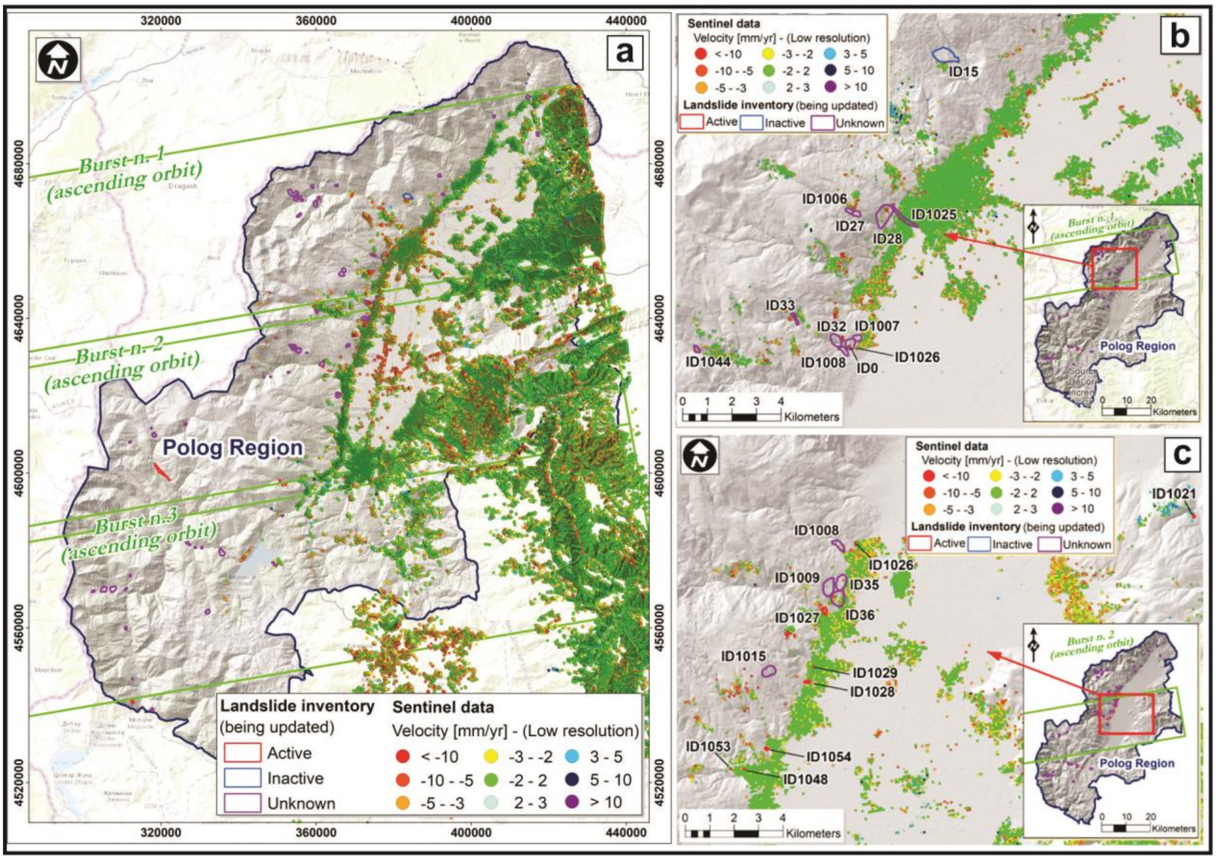

Fig. 2 a) Spatial distribution of the DInSAR data velocity derived by the final processing at low resolution (80m x 80m) of Sentinel images acquired on ascending orbit. b) Map of DInSAR-covered landslides over the Burst 1 processing area. c) Map of DInSAR-covered landslides over the Burst 2 processing area.

2.2.2 Detection of moving areas "hotspots" which are not included in the Polog archival landslide inventory

In addition to aiding in landslide characterization, DInSAR data can effectively complement geomorphological criteria for detecting landslides. Within the study area analyzed using Sentinel data, a subsequent phase of the analysis involved identifying coherent pixels surpassing a velocity threshold deemed indicative of movement. This threshold was set at 2 mm/year, as suggested by Peduto et al. (2015).

Specifically focusing on the regions covered by burst 1 and burst 2, the analysis identified 38 hotspots—18 in the burst 1 processing area and 20 in the burst 2 processing area—where a concentrations of moving coherent pixels were identified beyond the previously mapped landslides. The hotspots (DInSAR indicated zones) highlighted in Fig. 3 are defined as zones containing at least 10 moving coherent DInSAR pixels located in sloping areas.

It can be noticed that the DInSAR coherent pixels uniformly cover the two urbanized slopes. Analysis of the dataset, based on an ascending orbit, indicates an eastward motion with velocities ranging from 2 to 10 mm/year, and can relate to the case of slow-moving landslides in urban areas.

Future research should focus on conducting in-situ investigations and geomorphological analyses to enhance understanding of the processes influencing slope stability.

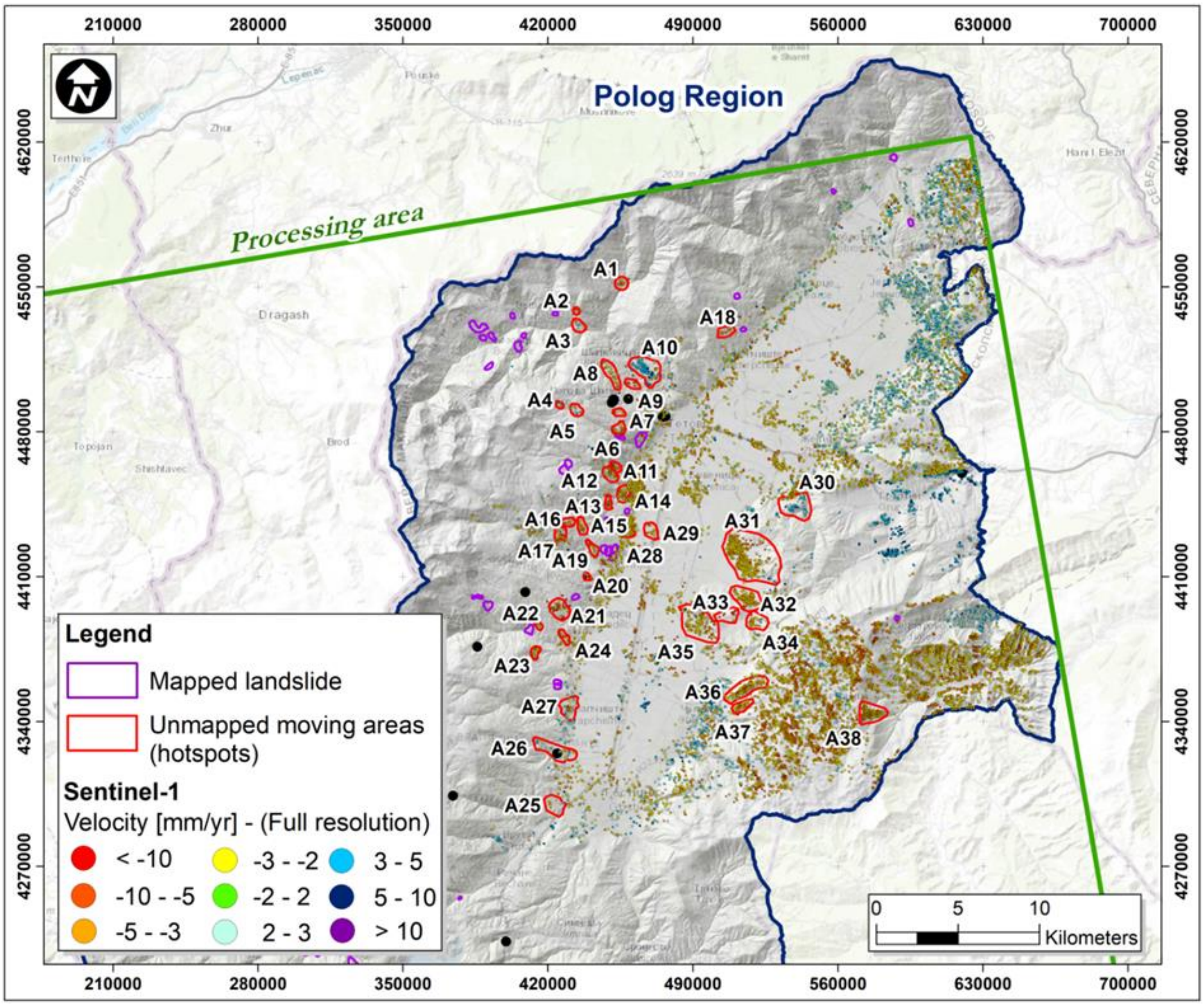

Fig. 3 Map of DInSAR indicated zones using Sentinel data for the Polog region

2.3 Visual analysis of LiDAR DEM for detection of landslides

When a landslide occurs, it changes the topography of the terrain surface, leaving characteristic/specific scars. The recent availability of very high-resolution digital elevation models (DEMs) obtained from airborne laser profilers and LiDAR (Light Detection And Ranging) sensors have provided researchers with opportunities for detecting and mapping landslides (Jaboyedoff 2018). Airborne LiDAR is a consolidated remote sensing technique used to obtain digital representations of the topographic surface for areas ranging in size from a few hectares to thousands of square kilometres. The concept of this technology is based on a laser sensor mounted on an aircraft or helicopter and accurate measurement of the time for which the laser beam is emitted from the corresponding module in the LiDAR system to the ground. Generally, the LiDAR advantages that contribute to obtaining a digital terrain model (DTM) suitable for the analysis and identification of landslides are: (1) high speed for spatial data acquisition (500000 points per second); (2) high data accuracy (+/- 10 cm); (3) great point density (from 5 to 100 points per m^2); (4) the presence of vegetation does not represent an obstacle in the context of defining the morphological structure of the terrain.

LiDAR surveys can be repeated over the same area to obtain representations of the topographic surface for multi-temporal analyses, including quantitative volumetric estimates of landslides. A review of the literature indicates that for landslide analyses, in the detection of landslides, very high-resolution LiDAR DEMs are used primarily for *visual analysis of the topographic surface* (Gazibara et al. 2023), and *automatic or semi-automatic recognition* (Leshchinsky et al. 2015; Bunn et al. 2019) of landslide morphometric features.

Through visual analysis of very high-resolution LiDAR DEMs can be identified and mapped different types of landslides, so this method has proven effective for landslide detection in agricultural lands and forested areas and for identifying old and recent landslides (Guzzetti et al., 2012 and references therein). This procedure for the detection of landslides is also applied for a part of the Polog region, where LiDAR DEM was available.

Visual recognition of landslides is done with the help of topographic derivative data from LiDAR DTM, that is, shaded maps and 10 m contour lines. In addition, orthophoto images were used to check morphological forms along roads and houses, such as landfills or cuts, then forestation or bare terrain. Taking into account the advantage of LiDAR technology for penetrating through vegetation and thus obtaining data on the morphological characteristics of the terrain, and on the other hand, the presence of densely forested zones in the analyzed area, LiDAR images immensely helped to identify new landslides, Fig. 4.

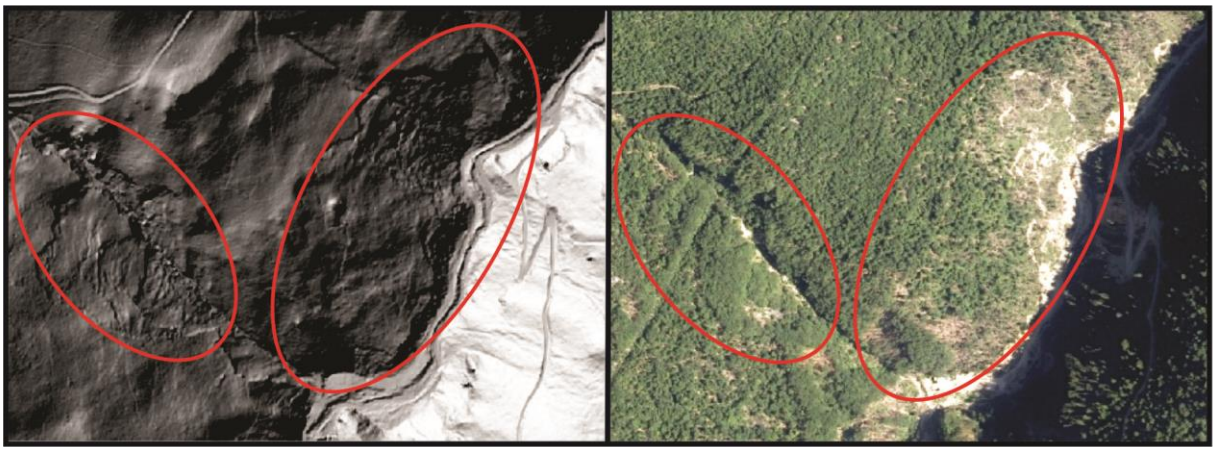

Fig. 4 Detection of landslides – left: view of LiDAR DTM; right: view of orthophoto image.

Landslide identification from LiDAR-derived Digital Terrain Model (DTM) was achieved through a systematic visual analysis of terrain deformations and characteristic landslide features. These features included main cracks, the landslide body, convex areas at the toe, and folded surfaces. Using this method, 46 new locations showing clear indications of landslide activity were identified. These identified landslides were subsequently documented in the GIS database and characterized in as much detail as possible.

Although experienced experts in the field confirmed the detection of new landslides through visual analysis of LiDAR DTM, and additionally evaluation of other datasets or bases that might either validate the presence of landslides or indicate misestimating, was applied, the field verification is essential, at least for some of the identified locations. To strengthen the accuracy of these findings, systematic field geomorphological mapping of all newly identified landslides is recommended as a key component of future research efforts.

3 Conclusions

The integrated approach for landslide detection in the Polog region led to the identification of 136 archival landslides. Following the analysis of DInSAR data, 38 "hotspot" locations exhibiting displacements were pinpointed. Additionally, using the LiDAR digital terrain model and conducting a visual analysis of terrain deformations and recognizable landslide features, 46 new potential landslide sites were identified.

The identification and analysis of past events enable the development of landslide susceptibility maps, which highlight areas at risk, and hazard models, which incorporate probabilities and expected magnitudes of future events. However, in order to make more detailed analyzes related to this issue, systematic data collection is crucial. This can be achieved by continuous and timely updating of the inventory with new landslides, constant monitoring of SAR data, multiple LiDAR scanning of the terrain (especially after specific events – intensive and prolonged rainfall, earthquakes, etc. – during which landslides are activated on the terrain).

In addition to collecting data on landslides of the "place/location of occurrence" type, their more detailed characterization is necessary, such as: type of landslide, state of activity, size, landslide geometry (surface dimensions, depth of failure surface), geology (lithology, structure, and material characteristics), triggering cause, impact, date of occurrence, remedial measures taken. This volume of data opens the possibility for other analyzes related to landslides, that is, hazard and risk assessment, threshold analysis, etc.

Ultimately, the available data show that the lithological composition is the most controlling factor for landslide occurrence in the Polog region, clearly showing that most landslides are concentrated along the contact between debris and schist bedrock. Given that the region's dominant Precambrian metamorphic complex inherently promotes sliding processes, future research must prioritize this geological factor as a key contributor to developing comprehensive and sustainable landslide management frameworks.

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