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Landslide monitoring techniques in the Geological Surveys of Europe

Abstract Landslide monitoring is a mandatory step in landslide risk assessment. It requires collecting data on landslide conditions (e.g., areal extent, landslide kinematics, surface topography, hydrogeometeorological parameters, and failure surfaces) from different time periods and at different scales, from site-specific to local, regional, and national, to assess landslide activity. In this analysis, we collected information on landslide monitoring techniques from 17 members of the Earth Observation and Geohazards Expert Group (from Euro-GeoSurveys) deployed between 2005 and 2021. We examined the types of the 75 recorded landslides, the landslide techniques, spatial resolution, temporal resolution, status of the technique (operational, non-operational), time of using (before the event, during the event, after the event), and the applicability of the technique in early warning systems. The research does not indicate the accuracy of each technique but, rather, the extent to which Geological Surveys conduct landslide monitoring and the predominant techniques used. Among the types of landslides, earth slides predominate and are mostly monitored by geological and engineering geological mapping. The results showed that Geological Surveys mostly utilized more traditional monitoring techniques since they have a broad mandate to collect geological data. In addition, this paper provides new insights into the role of the Geological Surveys on landslide monitoring in Europe and contributes to landslide risk reduction initiatives and commitments (e.g., the Kyoto Landslide Commitment 2020).

Keywords Landslide · Monitoring techniques · Geological data · Geological Surveys of Europe

Introduction

Tremendous progress has been made in landslide research over the last three decades. Landslide investigation has been conducted using surface and subsurface methods that include qualitative and quantitative approaches. Landslide monitoring is a compulsory step in landslide risk assessment. It requires the collection of data in real landslide conditions, the data comprising information on areal extent, speed of movement, surface topography, soil humidity, failure surface location, etc. The data is collected from different periods and at different scales, from site-specific through to local, regional, and national, to assess landslide activity (Mihalić Arbanas and Arbanas 2014; Pecoraro et al. 2019). Monitoring techniques can be classified according to whether the measurements are manual or automatic and conventional or new (innovative) techniques. They can also be in situ or remote (Mihalić Arbanas and Arbanas 2014; Chae et al. 2017). However, Savvaidis (2003) noted that techniques vary from case to case, depending on the expected risk, accessibility of the area, the potential for damage, and the availability of resources. This was also confirmed by many other authors who studied landslide monitoring techniques over the last 20 years (Tofani et al. 2013; Zhang et al. 2013; Notti et al. 2015; Martha et al. 2017; Peternel et al. 2017; Piciullo et al. 2018; Pecoraro et al. 2019; Raspini et al. 2019; Šegina et al. 2020; Bonì et al. 2020; Wang et al. 2022). Landslide monitoring techniques can provide data at different temporal resolutions and at different phases of the event (before, during, or after). The techniques can detect new landslides and can be used for rapid mapping, fast characterization, and long-term monitoring. Moreover, the selection of monitoring technique can provide strategies for the evolution of landslide early warning systems (EWS) (Piciullo et al. 2018; Pecoraro et al. 2019).

The Geological Surveys of Europe, EuroGeoSurveys (EGS), is a non-profit organization representing 38 National Geological Surveys and some regional surveys in Europe, employing a total of several thousand experts who share their expertise and knowledge in the framework of different expert groups. The members of EGS (the European Geological Surveys) are public sector organizations working and researching in the field of geosciences. These organizations have a long tradition of collecting data, processing information, and conducting research focusing on national geology. Today, they have a broad mandate: mapping of the geological features of the country or state; exploration and management of the natural resources of the subsurface (energy, including renewable geothermal energy, minerals and water, soils, underground space, and land); identification of natural hazards of geological origin and monitoring and mitigating their impacts (e.g., the deficiency or excess of trace elements in soils and waters, earthquakes, natural emissions of hazardous gases, landslides and rock falls, ground uplift and subsidence, shrinking and swelling clays); environmental management, waste management and disposal, and land use planning; sustainable urban development and safe construction; promotion of e-government and access to geoscientific metadata and data; and developing interoperable and harmonized geoscientific data at a European level (Vidovic et al. 2020).

Before the year 2000, landslide monitoring was not a high priority at EGS. However, the rapid development of monitoring techniques and the collection of qualitative data on the subsurface

mainly contribute to knowledge regarding the geological setting and structure; this has become almost indispensable in landslide research. The formation of the most destructive landslides is often associated with a complex geological and tectonic structure (Koukis et al. 2009; Huang 2012; Gutiérrez et al. 2015; Jemec Auflič et al. 2017; Gullà et al. 2018; Peternel et al. 2018).

This work was developed by the Earth Observation and Geohazards Expert Group from EGS and provides an overview of landslide monitoring techniques from 2005 to 2021. The landslide monitoring techniques are shown in Fig. 1. Based on the questionnaire, the following objectives were set: (1) to identify the type of monitored landslides, (2) to identify the landslide monitoring techniques, (3) to identify the spatial resolution, temporal resolution, status of the technique (operational, non-operational), time of using (before the event, during the event, after the event), and applicability of the technique to the early warning system. The main contribution of this paper is to show the involvement of EGS in landslide monitoring and discuss the importance of geological data. EGSs are assumed to collect and provide extensive geologic data that are important for landslide research and monitoring. We emphasize the importance of geologic data such as settings, tectonics, faults, and thrusts that provide the natural background for landslide development.

The collaborative work of 17 Geological Survey members of the Earth Observation and Geohazards Expert Group (EOEG) provided the landslide monitoring information and made this paper possible.

Review of landslide monitoring techniques

Remote sensing

Remote sensing has been widely used for landslide detection and monitoring since the launch of the first Landsat satellite in 1972 (Mantovani et al. 1996; Oštir et al. 2003; Canuti et al. 2007; Delacourt et al. 2007; Tofani et al. 2013; Scaioni et al. 2014; Liščák et al. 2016; Casagli et al. 2017; Carlà et al. 2019; Notti et al. 2020; Pandey et al. 2020; Zhong et al. 2020; Wasowski and Bovenga 2022). Remote sensing involves detecting and monitoring the physical features of an area by measuring reflected and emitted radiation from a distance (usually from a satellite or aircraft). Over the past three decades, remote sensing technology has rapidly evolved, in terms of radiometric, spatial, spectral, and temporal resolution. This trend has led to an increasing complexity of data, ranging from low to high spatial and spectral resolution and dimensionality of data, and it enables the assessment of surface changes by analyzing images acquired at different times (Pandey et al. 2020). In the broadest sense, remote sensing imaging instruments can be categorized as having either active or passive sensors, which can be optical, radar, LiDAR (Light Detection and Ranging), or multi-spectral/hyperspectral (Crawford 2018). They can also be classified according to the platforms in which the sensors are installed: satellite-based, aircraft-based, unmanned aerial vehicle (UAV)-based, and ground-based. A passive sensor measures solar energy that is either reflected or emitted from features on the Earth's surface. In landslide detection, identification, and monitoring, passive sensors integrated on multispectral and, most recently, on hyperspectral systems operate over a wide range of spatial resolutions on satellites (e.g., Landsat, SPOT, IKONOS, WorldView, QuickBird, Sentinel) (Casagli et al. 2017, 2018; Chen et al. 2019; Ye et al. 2019; Philipp et al. 2021). The common characteristics of satellite images taken with passive sensors are images taken in VIS–NIR-SWIR, the far-infrared, and the microwave portion of EM, which can be further processed and analyzed using various methods.

An active sensor generates its own signal, which is subsequently measured when it is reflected back from the Earth's surface. Landslide monitoring with an active sensor began with airborne satellite Synthetic Aperture Radar (SAR); ERS-1 was launched in 1991. Since then, many space-borne platforms, such as Radarsat, ENVISAT,
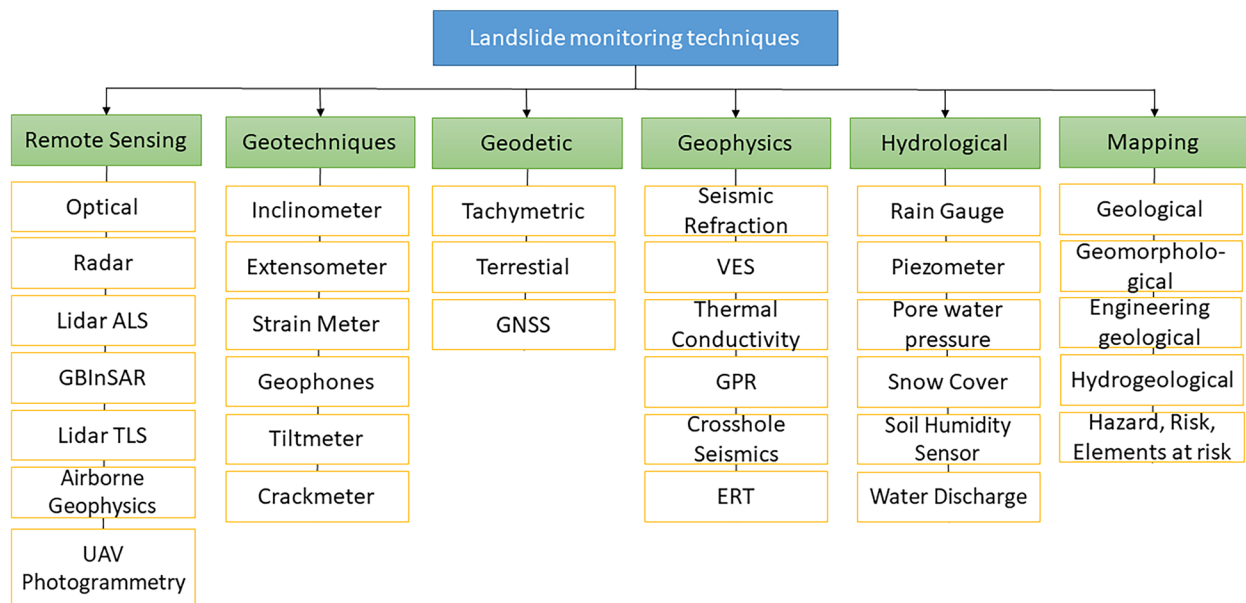

Fig. 1 Landslide monitoring techniques included in the questionnaire

ALOS, TerraSAR-X, Cosmo-SkyMed, Tandem-X, and Sentinel, have monitored landslide motions in the microwave portion of the spectrum (Rott and Nagler 2006; Bianchini et al. 2013; Herrera et al. 2013; Solari et al. 2020). A decade later, the ground-based SAR system (i.e., GBSAR) was introduced as a novel technique for near real-time landslide monitoring (Leva et al. 2003). LiDAR is an active sensor technique that measures ground height. LiDAR is mainly divided into airborne LiDAR (ALS) and terrain LiDAR (TLS). UAVs are also very widely utilized. The main advantage of UAVs is that they can be used in high-risk situations without endangering human life. UAVs can also be utilized in inaccessible areas, at low altitude, and at flight profiles close to the objects where manned systems cannot be flown. All of these benefits arise from the use of UAVs in landslide research (Al-Rawabdeh et al. 2017; Peternel et al. 2017; Rossi et al. 2018; Chen et al. 2019; Xu et al. 2020).

Images acquired by remote sensing sensors differ in terms of spatial, radiometric, and spectral resolution as well as so-called temporal resolution. The temporal resolution provides information about the temporal distance between the acquisitions of two images of the same area. The temporal resolution of a satellite sensor may vary from hours to days, depending on whether the platform orbit is geostationary or not.

Geotechnics

The implementation of geotechnical monitoring is required to recognize slope displacement, depth of sliding surface, and sliding rates of the slopes (Chae et al. 2017). Geotechnical monitoring data represent key inputs for landslide prediction modeling and landslide stability analysis. The most used geotechnical sensors for landslide monitoring are inclinometers, extensometers (crackmeters), tiltmeters, and geophones (Mihalić Arbanas and Arbanas 2014). Geotechnical sensors can be installed in boreholes, to monitor subsurface deformation, and/or at the surface of potential landslides, to identify surface deformation. Measures can be taken in periodic or in continuous mode and near real-time or real-time. Geotechnical monitoring is widely used for all complex landslides, where landslide material can translate into debris flow (Pecoraro et al. 2019).

For determining the sliding surface and to monitor the magnitude, rate, and direction of landslide movement, inclinometers have to be installed in vertical boreholes. Inclinometers monitor deformation normal to the axis of the casing and this provides a profile of horizontal subsurface deformation. Inclinometers are the most used type of instrument when attempting to measure small levels of ground creep or shear zone movement (Stark and Choi 2008). High-resolution tiltmeters provide the same type of data as inclinometers but at a significantly higher resolution. Tiltmeters measure the angle between the instrument body and the plumb line in two horizontally perpendicular directions (García et al. 2010). Tiltmeters are most suitable for monitoring landslides characterized by rotational type movements, while translational movements are unlikely to be detected (Wei and Liu 2020). The wire extensometer is a simple and low-cost device that allows the measurement of relative displacement between two points, of which one should be installed in an unstable area, while the other should be located in a stable area (Corominas et al. 2000). Extensometers

can be installed within boreholes or at the surface. In this case, this instrument is also known as a stain meter, crackmeter, or convergence meter (Mihalić Arbanas and Arbanas 2014). Landslides can also be detected using geophones. Geophones are electrodes that use microseismic monitoring techniques to measure the vibrations associated with landslide movement and can detect landslides based on the characteristics of vibration signal properties, such as frequency composition, amplitude, and duration of the vibration signal (Spillmann et al. 2007). Geophones can receive underground sounds from all types of sources, such as water flow, raindrops hitting the ground, cars passing by, and rocks falling, but can be very useful in detecting debris flows (Schimmel and Hübl 2016; Wei and Liu 2020).

Geodetic methods

Ground-based geodetic techniques allow the monitoring and observation of superficial changes of points in an area of interest. Geotechnical monitoring is often combined with geodetic monitoring, to provide reliable information on the absolute displacements of landslides, with respect to some reference points (Maio et al. 2013; Uhlemann et al. 2016; Pecoraro et al. 2019).

The most common technique for monitoring absolute displacements, based on object points, is the classical terrestrial survey using a total station (tachymetric measurement). A perfect tachymetric geodetic network consists of (a) geodetic reflecting prisms placed in stable areas, for orientation and the establishment of the elevation reference points, (b) a set of reflecting geodetic prisms placed in the study area (object points), and (c) the measuring instrument. The reference points, which must be located in a stable area, are used to determine absolute displacements; otherwise, only relative movements could be calculated (Haberler-Weber 2005). The high accuracy (the position and height accuracy is ± 0.02 m) of the tachymetric geodetic measurements provides an accurate assessment of the displacements of object points. However, these points must be very carefully selected and installed to ensure their stability in a long-term monitoring process (Peternel et al. 2017). GNSS monitoring is preferred over conventional terrestrial methods because it offers a greater flexibility, as the equipment is more reliable, lighter, cheaper, and easier to use (Gili et al. 2000). Surface change monitoring using GNSS techniques can be implemented in two ways. It can be used in repeated surveys of permanently installed object points (benchmarks) using different survey styles, such as RTK (real-time kinematic), fast static, and static GPS/GNSS surveys, or with the installation of permanent GNSS stations (Uhlemann et al. 2016). The following methods, described in Piciullo et al. (2018), Carlà et al. (2019), Notti et al. (2020), and Šegina et al. (2020) can be performed automatically and enable real-time monitoring data. Monitoring with the described methods is restricted to only observing a certain number of ground points.

Therefore, methods that allow the generation of high-resolution digital elevation models (DEMs) and orthophotos are increasingly used to monitor visible surface changes over time. Recent research on landslide monitoring have used very high-resolution DEMs to analyze landslide surface morphology and characteristics (Guzzetti et al. 2012) using terrestrial laser scanning (TLS). TLS is a ground-based, active imaging method that rapidly acquires accurate, dense

3D point clouds of object surfaces by laser range finding. TLS provides the possibility not only to quantify displacement rates and volumes but also to infer the geometry of past and potential future failures through the analysis of structural features (Jaboyedoff et al. 2009).

TLS was successfully applied to landslide monitoring by Prokop and Panholzer (2009) and Travelletti et al. (2014). In addition, TLS technology has been further developed into Automated Terrestrial Laser Scanning (ATLS) with automatic, near real-time change detection, and its application was tested at a landslide site by Kromer et al. (2017).

Photogrammetry is a cost-efficient and very commonly used method for acquiring surface data, such as orthophotos and DEMs (Brückl et al. 2006; Stumpf et al. 2015; Peternel et al. 2017; Devoto et al. 2020; Liu et al. 2021). It is based on the basic principles of image matching and stereo-vision using passive optical sensors (camera). Compared to other remote sensing methods, photogrammetry is limited by its inability to penetrate vegetation, resulting in sparse point cloud in areas covered by vegetation. The generation of high-resolution DEMs of densely vegetated areas can be achieved using LiDAR surveys (Devoto et al. 2020).

Hydrogeological

Water is probably the most important factor promoting slope instability (Casagli et al. 2017). Measuring water-related parameters in landslide-prone areas provides insights into the dynamics of landslide initiation and movement (Cho 2017; Zhang et al. 2019; Bezak et al. 2021). Water affects the strength parameters of geological materials (Zhang et al. 2019) and generally reduces their strength when the materials become saturated. An excess of pore water pressure alters the effective stress state of a slope, typically reducing resistance to shear forces and promoting instability. The following data are most used to monitor hydrogeological landslide conditions: precipitation, groundwater level, pore water pressure, snow cover thickness, soil moisture, and water discharge. Hydrogeological data can be collected periodically or continuously, with automatic near real-time data transmission apparatus. In addition, if the monitoring of hydrogeological data is automatic, it can provide immediate notification of potential landslide activity that may be critical to protecting lives and property.

Mapping

Compared to other monitoring techniques, mapping is one of the most traditional methods used in landslide monitoring (Mihalić Arbanas and Arbanas 2014; Griffiths et al. 2015; Hearn 2019). The fundamental basis for any landslide study is geological, geomorphological, and engineering geological field mapping. Modern geomorphological mapping is strongly set within the technical capabilities of multimedia, digital data, and imagery at different scales, including the presentation of geomorphological mapping using GIS, DEMs, and color (Chelli et al. 2021). The most commonly mapped features are landforms, and their morphogenesis, morphochronology, morphodynamics, and morphometry provide an understanding of the landscape and the processes that formed and continue to modify it. As soon as a landslide is considered for remediation, an engineering geological map must be made available, providing information on the geotechnical parameters of the different lithologies, surface forms, groundwater sources and groundwater levels, tectonic features, etc. (Culshaw 2018). In general, an engineering geological map is the basis for the identification of hazards and subsequent risk management (Culshaw 2018). However, the amount of detail shown on any map depends largely on the scale, where smaller scales naturally disclose finer details. In basic terms, the quality of the mapping depends on the accuracy and precision of the fieldwork. With the development of technology, however, modern maps are more precise than ever before, taking full advantage of a combination of accurate satellite imagery, aerial photographs, high-tech geological equipment, and Geographic Information Systems (GIS).

Methods and data

The review of landslide monitoring techniques in the Geological Surveys of Europe is based on a questionnaire that collected the available information for each landslide monitored during the period 2005–2021. The questionnaire was set up and circulated among the 29 members of EOEG. Sixteen National Geological Surveys participated: Austria, Croatia, Cyprus, Czech Republic, Denmark, France, Greece, Italy, Lithuania, Poland, Portugal, Serbia, Slovakia, Slovenia, Spain, Sweden, and the UK, as well as one regional Geological Survey: Catalonia. For the rest of the EOEG members, either no significant landslides or no monitoring was developed during this period and they did not participate in this research.

The questionnaire was organized into four different sections, as shown in Table 1. In each subdivision, the dropdown list enabled the selection of one or more options, shown here in parentheses. The first section of the questionnaire focused on the general information about the organization and the contact person. The second section focused on the monitored landslide and its characteristics (Table 1, Section 2 Monitored landslide). All monitored landslides were classified according to Varnes (1978). The compilers of the questionnaire provided information on the landslide movement rates and activity state, according to the classification proposed by Cruden and Varnes (1996), the landslide volume proposed by Fell (1994), the landslide activity and the thickness of the rupture surface proposed by WP/WLI (1993), and the landslide triggering mechanism proposed by Guzzetti et al. (2012). In the selection of the type of damage, residential buildings, the infrastructure, the forest, and the meadow were available for selection. The third section focused on the landslide monitoring techniques. Each main group of techniques was further subdivided into various landslide monitoring techniques. Thirty-four different landslide monitoring techniques were listed in the questionnaire. Each technique was determined based on the following criteria: spatial resolution (local, regional), temporal resolution (low, medium, high), monitoring area (size of the area, movement rates, duration), status (operational, non-operational), time of use (pre-event, during event, after event), early warning system (is the technique a potential for EWS, or the technique is integrated into the EWS and is being tested, or the technique is being used for the EWS, or no EWS), total set up cost, practical challenges (installation and maintenance of the instrumentation, weather conditions, site conditions, human resources, funding, other), advantages, disadvantages, additional notes or other explanations, and available references. The last section "Other" provides information on the number of landslides

Table 1 Overview of the questionnaire sections

Questionnaire sections	Concept
1 General information	Organization
	Contact person
2 Monitored landslide	Landslide name
	WGS coordinates of the crown
	Geological settings
	Type of landslide
	Total area
	Estimated volume
	Estimated thickness
	Triggering mechanism
	Year of activation
	Year of reactivation
	Activity state
	Movement rates
	Estimated damage in EUR
	Type of damage
3 Landslide monitoring techniques	Remote sensing
	Geodetic
	Geophysics
	Hydrogeological
	Mapping
4 Other	Number of landslides
	Monitored by Institute/Company
	Techniques

monitored by other institutions in the country, if such information is available.

The questionnaire focused on the collection of data from 75 landslides, monitored by the Geological Surveys during the period 2005–2021. Figure 2 shows the countries that responded to the questionnaire and the locations of the landslides.

Results

Of the 17 participating Geological Surveys in Europe, 13 different Geological Surveys from 12 countries provided information on monitoring techniques for 75 landslides, monitored between 2005 and 2021. Five Geological Surveys (Denmark, Lithuania, Portugal, Serbia, and Sweden) did not report landslide monitoring, but they mainly focused on landslide susceptibility development.

The completeness of the information for each question is shown in Fig. 3. Data on landslide type, activity state, triggering mechanism, at least one monitoring technique, and spatial resolution were provided for all the landslides, while data for the rest of the parameters listed in Fig. 3 were not provided for all the monitored landslides. The most incomplete data are related to damage: only 17% of the monitored landslides gave this information.

Landslide characteristics

Landslide characteristics are presented to provide basic information about monitored landslides. The types of landslides, volume, depth, and rates of movement are important for selecting monitoring techniques and are necessary data for studying the effects of landslides on society and the appropriate mitigation measures to be considered. The characteristics of the landslides considered in this study are first presented in Fig. 4. Half (50%) of all the monitored landslides are classified as earth slides, followed by complex landslides (28%). Less than 10% of the monitored landslides are classified as rock slides, debris slides, rock falls, earth flows, or others. The monitored landslides were mostly triggered by rainfall (65%) and, in a few cases, also by erosion, human activities, tectonics, earthquakes, snowmelt, and others. The total volume is known for 72% of the landslides. Monitored landslides are mostly those with volumes greater than 5000 m³, categorized as small, medium, medium-large, very large, or extremely large. Most landslides are deep to very deep (failure surface at a depth between 5 and 20 m and more) and are considered extremely slow (movement rate < 15 mm/year) but active, causing damage to infrastructure and residential houses and, to a lesser extent, forests and meadows. Almost all earth slides, earth flows, and complex landslides occurred in a geological setting composed of soft claystone, mudstone, siltstone, shale, marlstone, or scree deposits of different ages, while rock slides and rock falls occurred in more compact rocks, composed of carbonate, metamorphic, volcanic, or igneous rocks.

Monitoring techniques

Of all the landslide monitoring techniques used in the Geological Surveys, mapping is the most used (Fig. 5A). It was used in almost 40% of the cases, followed by hydrogeological (18%), remote sensing (17%), geotechniques (14%), geodetic (6%), and geophysics techniques (6%). Similarly, mapping is the most commonly used landslide monitoring technique for all landslide types, with the exception for monitoring earth flows (Fig. 5B). Geodetic and geophysics methods were the least used techniques during the observed period.

Among the remote sensing techniques, LiDAR ALS predominates for landslide detection and monitoring earth flows, followed by radar imagery used for debris slides, earth slides, rock slides, and complex landslides (Fig. 6A). In the use of geotechnics, the inclinometer measurements were practically used in all the landslides types (Fig. 6B). Extensometers and crackmeters have also been relatively widely used for monitoring landslides, rock slides, and rock falls, while tiltmeters and geophones have been used mainly for rock slides and rock falls. None of the observed landslides was equipped with strain meters for monitoring (Fig. 6B). Among the geodetic techniques (Fig. 6C), GNSS was most used for monitoring debris slides, earth flows, earth slides, rock falls, and complex landslides. In a few cases (up to 20%), tachymetry
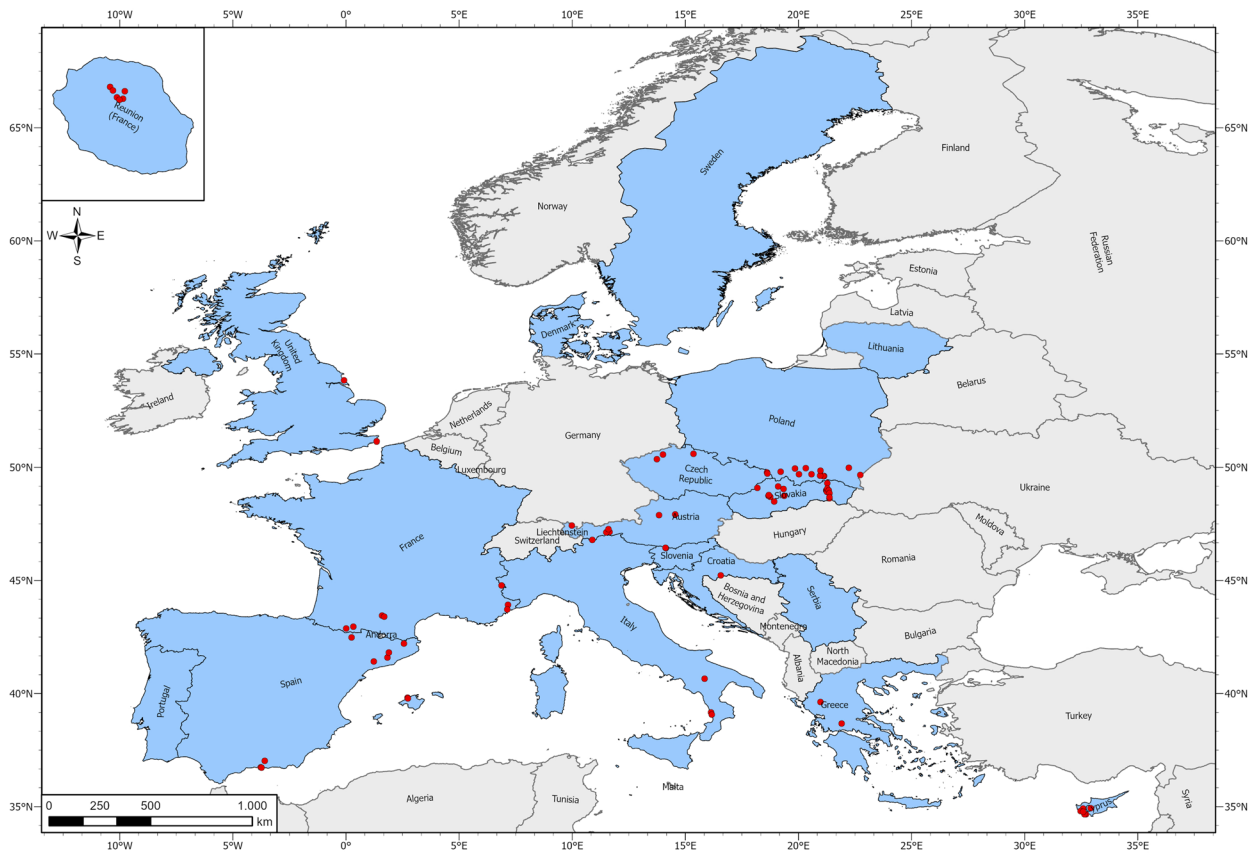
Fig. 2 Map of the 17 participating countries and the location of the 75 landslides monitored by EGS (red points), from 2005 to 2021

was also used to monitor rock slides, earth slides, and complex landslides. In the use of geophysical methods (Fig. 6D), seismic refraction surveys and electrical resistivity tomography have been most commonly used to monitor debris slides, earth slides, rock slides, rock falls, and complex landslides. Vertical electrical sounding and electrical resistivity tomography were also used relatively frequently, mostly for rock slides, earth slides, rock falls, and complex landslides. Thermal conductivity was used to monitor a rock slide, while ground penetrating radar and crosshole seismic survey were not used. Among the hydrogeological methods, piezometers and precipitation records have been the most widely used for all landslide types (Fig. 6E). In some cases, snow cover thickness and water discharge have also been used, while soil humidity has not been measured in any cases. When mapping

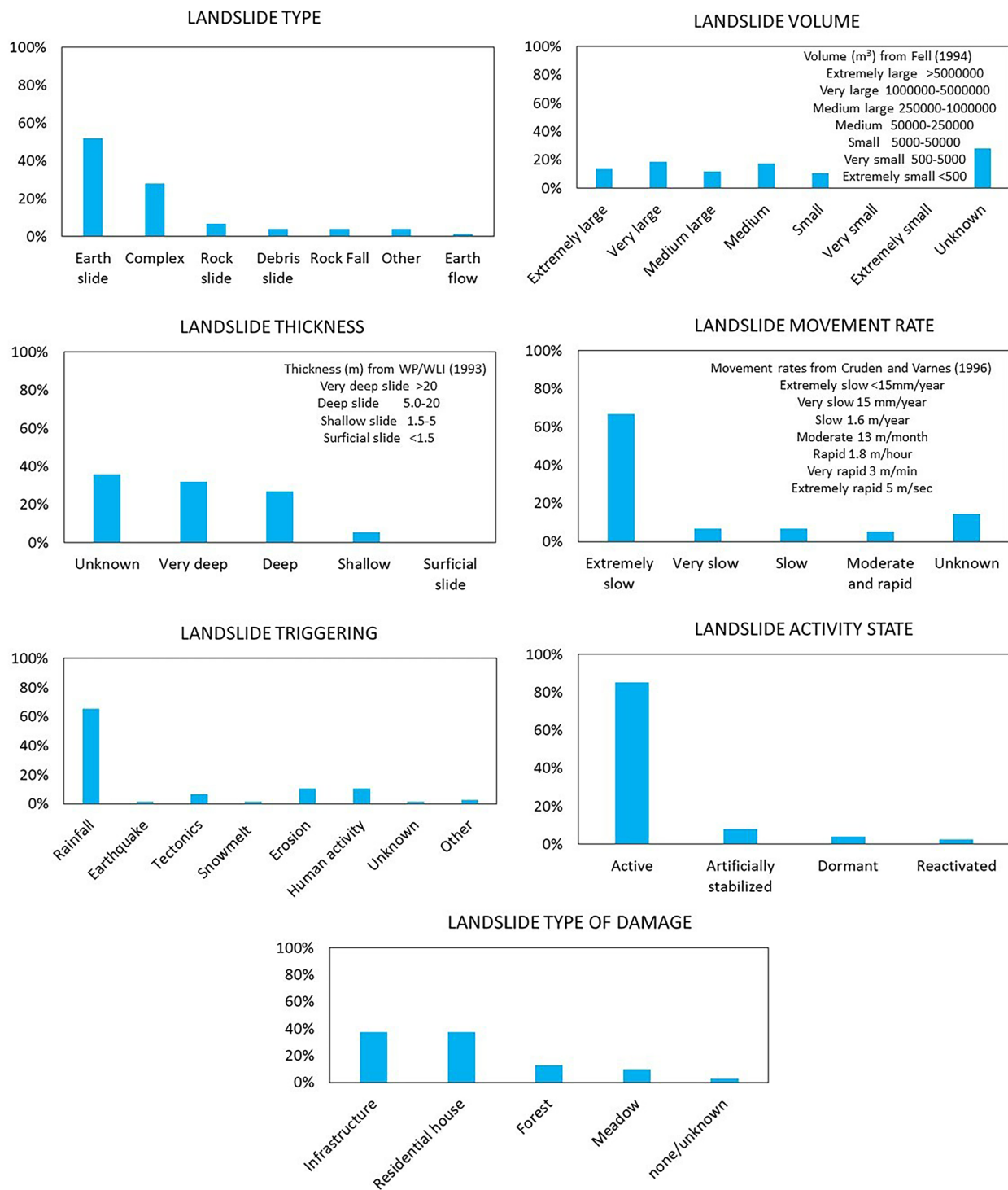**Fig. 3** Completeness of information on all search parameters in the questionnaire
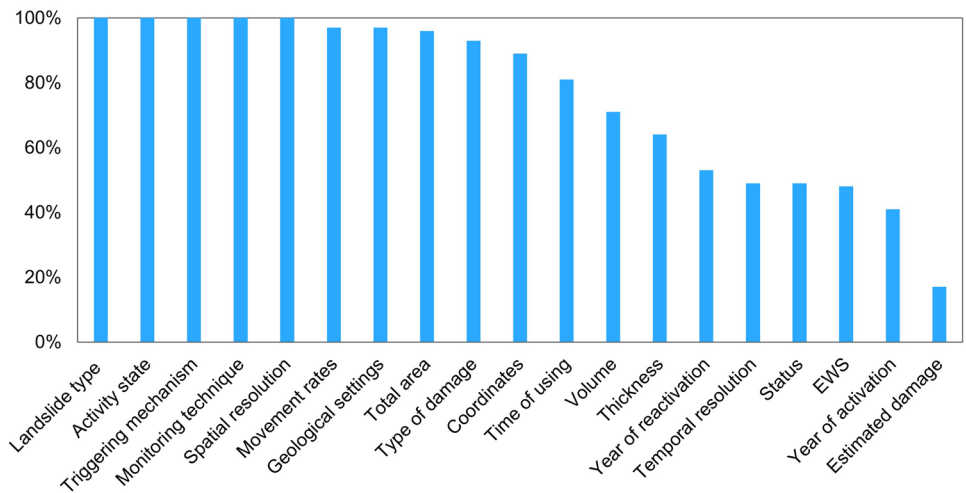
Fig. 4 Landslide characteristics of 75 monitored landslides from 2005 to 2021

methods were used (Fig. 6F), the geological mapping appears to be used to investigate all debris flows, earth flows, rock slides, rock falls, and other landslide types, while it is used somewhat less for the monitoring of earth slides and complex landslides, but, still, for more than 50% of all observed landslides. Geomorphological and engineering geological mapping have traditionally accompanied

geological mapping, as is evident in Fig. 6F. Through this mapping, hazards and risk elements on risk maps for debris slides, earth slides, rock slides, rock falls, and complex landslides were produced for more than 35% of the landslides. Hydrogeological mapping was also little used; it was used to monitor debris slides, earth slides, rock slides, and complex landslides.
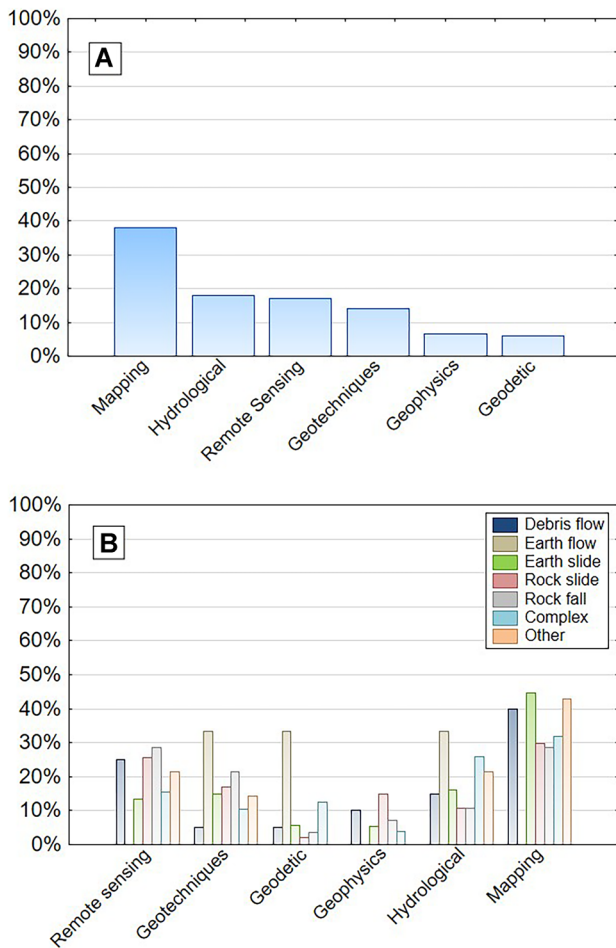
Fig. 5 A Proportion of landslide monitoring techniques. **B** Proportion of monitored landslides according to landslide types

Debris slides were mostly monitored by geological mapping and radar techniques (Fig. 6A, F). Geotechniques (inclinometers), mapping (geological, geomorphological, engineering geological), hydrogeology (precipitation, piezometers), geodesy (GNSS), and ground remote sensing (GBSAR) have been the most used in monitoring earth flows (Fig. 6A–C, E, F). Earth slides, which are the most numerous by type, were monitored using all investigated methods (Fig. 6). Techniques such as inclinometers, piezometers, and geological, geomorphological, and engineering geological mapping and hazard and risk mapping dominate them. Rock slides were mainly monitored by mapping (Fig. 6F) and, to a lesser extent, other monitoring techniques (Fig. 6). Similarly, rock falls were also monitored by mapping techniques (Fig. 6F) and remote sensing (Fig. 6A). Complex landslides, which are the second largest group of landslides in this study, were monitored by mapping, remote sensing, and hydrogeological, geodetic, and geotechnical methods (Fig. 6A, C–F). In investigations of complex landslides, geological and engineering geological mapping, precipitation and piezometers, GNSS, and inclinometers all play an important role. Other types of landslides were monitored by geological and geomorphological mapping, precipitation, inclinometers, and radar data (Fig. 6A, E, F). In summary, the most common monitoring

technique used by EGS during the period 2005–2021 was geological mapping, used in 75% of the monitored landslides, followed by inclinometers (65%) and engineering geological mapping (63%).

For the techniques used, we also asked about spatial resolution, i.e., whether the technique was used for landslide monitoring on a local scale or on a broader regional scale. Among the techniques used, mapping was the most commonly used at a local scale, while geodetic and geophysical methods were the least common (Fig. 7A). To monitor landslides on a regional scale, only mapping and remote sensing (and, in some cases, hydrogeological methods) have been used (Fig. 7A). One of the important parameters for deciding whether to use one technique over another is temporal resolution, which is particularly important when the technique is part of the EWS (Piciullo et al. 2018). Temporal resolution refers to the time between images or two measurements. Usually, temporal resolution is more commonly important data in using remote sensing techniques (Delacourt et al. 2007). The results of the questionnaire showed that low and high temporal resolution are the most significant for mapping and remote sensing (Fig. 7B). As a medium temporal resolution, remote sensing predominates. However, the literature provides no clear evidence of numerical ranges between low, medium, and high temporal resolutions. Moreover, the completeness of the temporal resolution in the questionnaires was less than 50% (Fig. 2). Part of the questionnaire also asked whether the monitoring technique used was operational or non-operational, i.e., whether the technique used is still in use after its initial application. The completeness of this data is only slightly above 50% (Fig. 2), indicating a lack of information on the status of the technique. However, of all the techniques applied, only 38% are still in the operational phase. Of these, geotechniques and hydrogeological methods are those techniques still in use (Fig. 7C). The results for the time of use of the monitoring techniques show that more than 40% of the techniques were used after the landslide occurred (Fig. 7D); 35% were used during the event; and only 3% were used before the event. This shows that landslide investigations mostly started after being triggered and not vice versa. The applicability of techniques for the early warning system (Fig. 7E) showed that 28% of the techniques used were not integrated into it, 14% were considered potentially suitable for the early warning system, 2% of the techniques were tested for the early warning system, and 4% were used for the early warning system. The completeness of the data on applicability of technique for the early warning system is less than 50% (Fig. 2). This indicates that the establishment of an early warning system is more than monitoring and, after Guzzetti et al. (2020), requires experience in design, implementation, management, and verification.

Discussion

This paper builds on landslide monitoring techniques at Geological Surveys, not only providing the review of the most often used techniques but also serving to highlight the importance of geological data in landslide monitoring. In addition, it provides new insights into the role of Geological Surveys in landslide monitoring. The data do not indicate which landslide monitoring techniques are better than others, rather, what extent Geological Surveys implement landslide monitoring and which techniques predominate.
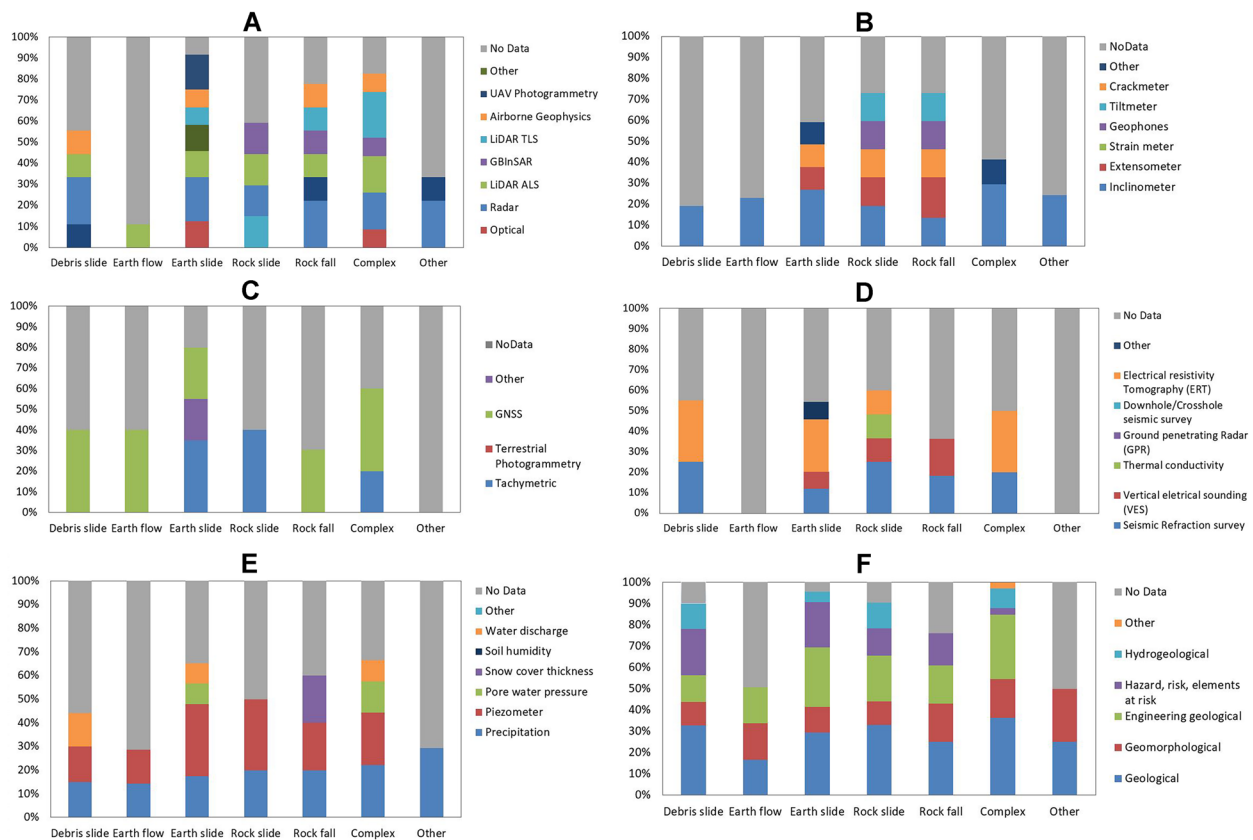
Fig. 6 Distribution of landslide monitoring techniques used in EGS during 2005–2021 according to all monitored techniques in percentage. NoData refers to information on the use of the technique for individual landslide types for which we have not obtained data.

A Remote sensing, **B** geotechniques, **C** geodetic, **D** geophysics, **E** hydrogeological, and **F** mapping techniques. The total percentage is over 100 because several monitoring techniques can be used to monitor landslides

The fact is that Geological Surveys were primarily established to collect and provide information on geological features and natural resources. Since the establishment of the first national Geological Survey in Europe (the British Geological Survey, in 1835), most countries have established their own surveys. The basic tasks of most surveys are to understand the solid earth and surficial deposits and to inventory mineral and energy resources beneath the land and the seabed of territorial waters. Some have expanded their scope to include the study of surface water, groundwater, and ecological resources. The evolution of Geological Surveys from their beginnings to the present day is an adaptation to socially relevant issues and allows management decisions and policies to be based on scientific knowledge (Hill et al. 2020). Similarly, landslide monitoring was not the primary goal of Geological Surveys but, over the years and with technological developments, monitoring has been used in more than half of the Geological Surveys that have landslide databases (Herrera et al. 2018). For example, Fig. 2 shows that the majority of monitored landslides are concentrated in Austria, Cyprus, Poland, Slovakia, and Spain. The distribution of these landslides is closely related to national or regional legislation and the role of geological services in the countries. The fact is that each country has its own laws regulating landslide collection and monitoring, which has also been highlighted by Mateos et al. (2020).

In the work of Herrera et al. (2018), 849,543 landslide records were collected from different landslide databases of geological services in Europe, focusing mainly on the type of landslide and the location of the landslide source. However, the volume of landslides, on which we can estimate the likely number of major and devastating landslides that need to be monitored, is not given. Although, in this study, nine Geological Surveys also reported 44 landslides monitored by other institutions or companies, without providing the name of the landslide to find them in the literature, we can only make assumptions about the number of monitored landslides in Europe. However, according to recently extended literature reviews on landslide early warning systems, consisting of different landslide monitoring techniques (Tofani et al. 2013, Ondrejka et al. 2014; Froude and Petley 2016; Pecoraro et al. 2019; Picciulini et al. 2018; Guzzetti et al. 2020), the estimated number of landslides currently monitored in Europe exceeds the number of landslides included in this paper.

Within the framework of EOEG from EuroGeoSurveys, Mateos et al. (2020) highlighted the damaging landslide events and the integration of landslide hazards into urban planning across Europe. They found that nearly 48 million people in Europe live in areas with a high or very high degree of landslide susceptibility and that half of the participating countries have no legal requirements for
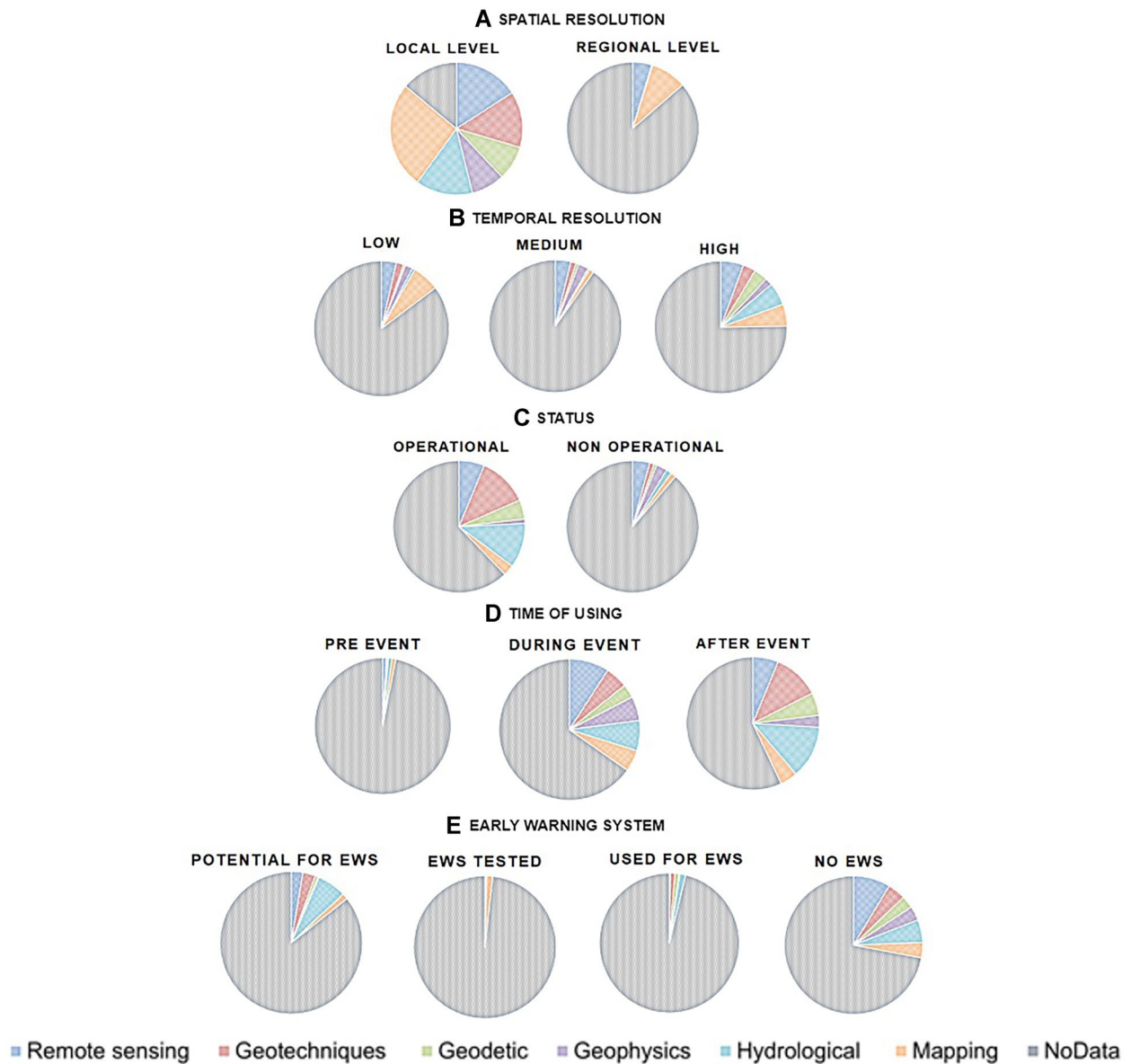
Fig. 7 Application of monitoring techniques by **A** spatial resolution, **B** temporal resolution, **C** status of technique (operational, non-operational), **D** time of usage (pre-event, during event, after event), and **E** applicability of technique to early warning systems

landslides in urban planning. For instance, in this study, we also asked about the estimated damage (in euros) from landslides that have already occurred and the potential damage that would occur in a future landslide. It is recognized that this information was the least completed. For 13 landslides, the damage from already occurring landslides is estimated at 124 million euros, but we assume that a much higher amount of damage actually occurred. Damage from landslides is not always available to research institutions. It is tangible information, especially when it comes to assessing damage from a landslide that has not yet occurred (Pollock and Wartman 2020).

Geological field mapping is essential to any geology-related study and this is the process of selecting an area of interest and identifying all the geological aspects of that area. The amount of detail shown on a map depends largely on the scale, where larger

scales naturally disclose finer details. In basic terms, the quality of a geological map depends on the accuracy and precision of the fieldwork. With the development of technology, however, geological maps are now more precise than ever before, taking full advantage of a combination of accurate satellite imagery, aerial photographs, and high-tech geological equipment. This means that the mapping includes high-quality geological data, which contributes to our understanding of the monitored data.

One of the critical survey findings shows that landslide monitoring typically commences after a failure, because only 3% of observed landslides have been monitored before the occurrence. We assume that this is strongly related to the landslide movement type and rate, as we observed more than 60% of extremely slow landslides categorized as earth slides, which are rarely monitored

before failure. Rapid landslides can completely destroy a structure, whereas slower landslides, no matter how deep, can only slightly damage the structure (mainly cracks and subsidence), and their slow rate of movement can allow monitoring and mitigation measures. Left uncontrolled, however, even slow landslides can completely destroy structures over time.

Although the results clearly show that the most used techniques in Geological Surveys are mainly related to mapping, the following question arises: how important are geological data (settings, tectonics, faults, thrusts) in landslide monitoring, in the context of interpreting the monitored results? Basically, on the one hand, much research on landslide monitoring focuses on identifying surficial movement rates with different conventional or advanced techniques, giving the first insights about velocity and extension (e.g., Tseng et al. 2021). Then, there are those studies which highlight the advantages or disadvantages of tested technology (Pourghasemi et al. 2020). On the other hand, we have research with the aim of understanding the mechanisms of disruptive processes, defining adequate prevention measures for the mitigation of their effects and reducing the loss of human lives and assets (Huang et al. 2018). Moreover, that research encompasses a variety of monitoring techniques, including methods for subsurface and surface investigations. However, the study of the engineering geological characteristics or/and geologic structure of landslides is important in all landslide studies, regardless of their scope or purpose. However, it appears to be critical in understanding landslide dynamics and defining preventive measures. To what extent, however, depends on financial resources, availability, and accessibility of landslide monitoring techniques.

Conclusions

An analysis of the landslide monitoring techniques applied by EGS during the 16-year period 2005–2021 revealed that:

- Among all the types of landslides, earth slides predominate, followed by complex landslides and, to a lesser extent, rock slides, debris slides, rock falls, earth flows, and others;
- The landslides are mostly triggered by rainfall, but also, in a few cases, by erosion, human activities, tectonics, earthquakes, snowmelt, and others;
- The landslides are mostly those classified as small (up to 5×10^4 m³ in volume) to extremely large (over 5×10^6 m³ in volume);
- Most observed landslides are deep to very deep (with a failure surface over 5 m) and considered extremely slow (< 15 mm/year) but active, causing damage (cracks and subsidence) to infrastructure and residential houses and, to a lesser extent, forests and meadows over time;
- The most commonly used method for landslide monitoring is mapping, followed by hydrogeological, remote sensing, geotechnical, geodetic, and geophysical techniques;
- Monitoring techniques are mostly used at the local level, during and after the landslide event, and are rarely part of an early warning system;
- Earth slides, the most numerous in type, were monitored by all the methods studied. Techniques such as inclinometers, piezometers, and geological, geomorphological, and engineering geological mapping and hazard and risk mapping dominate;

- Debris slides were mainly monitored by geological mapping and radar techniques;
- Earth flows were monitored by geotechnics, mapping, hydrogeology, geodesy, and remote sensing;
- Rock slides and rock falls were monitored by mapping techniques and remote sensing;
- Complex landslides, which are the second largest group of landslides in this study, were monitored by mapping, remote sensing, and hydrogeological, geodetic, and geotechnical methods; and
- Other types of landslides were monitored by geological and geomorphological mapping, precipitation, inclinometers, and radar data collection.

This paper concludes that all monitoring techniques have their advantages and disadvantages, operate at different scales, have different temporal repeatability, and have been used in different time phases of landslides. As noted in this analysis, the objective of landslide research determines which monitoring technique is most appropriate, taking into account influencing factors such as type of landslides, volume, the need for EWS, mitigation, financial budgets, and availability of the technique. Landslide monitoring also depends very much on the national regulations that apply in each Geological Survey country.

There is no doubt that the EGS will continue landslide monitoring by using traditional and advanced techniques in a complementary way. The good news is that individual Geological Surveys already provide open access to a very large number of national datasets through the European Geological Data Infrastructure (EGDI). Since Geological Surveys collect a lot of geological data, other engineers and scientists need to recognize this resource, when developing monitoring plans, and EU commissioners need to understand that it can facilitate and support the creation of European landslide mitigation measures.

Author contribution
Conceptualization: Mateja Jemec Auflič and Gerardo Herrera; methodology: Mateja Jemec Auflič, Tina Peternel; analysis: Mateja Jemec Auflič; writing—original draft preparation: Mateja Jemec Auflič; writing—review and editing: Mateja Jemec Auflič, Gerardo Herrera, Rosa María Mateos, Eleftheria Poyiadji, Bernardie Severine, Tina Peternel, Laszlo Podolszki, Stefano Calcaterra, Arben Kociu, Bartłomiej Warmuz, Jan Jelének, Kleopas Hadjicharalambous, Gustaf Peterson Becher, Claire Dashwood, Peter Ondrus, Vytautas Minkevičius, Saša Todorović, Jens Jørgen Møller, Jordi Marturia; visualization: Mateja Jemec Auflič; supervision: Mateja Jemec Auflič. All authors have read and agreed to the published version of the manuscript.

Data Availability
The dataset investigated in this study is available from the corresponding author upon request.

Declarations

Conflict of interest   The authors declare no competing interests.

Disclaimer   The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

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