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Merging Historical Archives with Remote Sensing Data: A Methodology to Improve Rockfall Mitigation Strategy for Small Communities

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Abstract: Both in the literature and in practical applications, several works have dealt with rockfall analysis and the planning of mitigation measures. It is also possible to find inventories and papers that describe historical events. However, it is challenging to find methodologies or studies about inventorying rockfall mitigation or their efficiency over time. In Italy, many rockfall barriers and other mitigation solutions have been built in the last decades, and one of the most urgent problems is their correct management and maintenance. Lauria, a small town in southern Italy, can be considered an example of this common condition exacerbated by a wildfire in 2017. This work presents a methodology for assessing rockfall risk and creating a geodatabase of mitigation structures focused on small communities. We used digitalization of archival sources to reconstruct and geocode the record of mitigation works. An available database of historical landslides was used to reconstruct the most relevant rockfall events. Moreover, we coupled this with Sentinel-2 images and high-resolution orthophotos to map the wildfire area. Data obtained from the UAV-LiDAR survey were used to map the mitigation structures. The aim was to create a reliable state-of-the-art method, described in an operational monograph, to be used by experts for the design of new rockfall mitigation structures in both an affordable and efficient way. Moreover, we created a simple webGIS and a 3-D interactive view, helpful in disseminating rockfall hazards and mitigation strategies among the population at risk.

Keywords: historical archive; LiDAR; rockfall mitigation; wildfire; Sentinel-2; webGIS

1. Introduction

Rockfall mitigation needs a multidisciplinary approach [1] including research tools such as inventory maps and susceptibility models [2,3], numerical modelling [4], the effect of extreme events such as wildfires [5], and the design of mitigation structures [6].

Most rockfall events happen in small villages or similar settings and, except for the local communities, they are often overlooked. However, even if limited to a very local scale, rockfalls can threaten several people's lives and restrict access to significant portions of small villages and urbanized areas.

Rockfalls that affect small towns or villages are often little studied, and the local authorities do not have enough resources and technical background to define a long-term strategy to manage rockfall-prone areas. In most cases, local authorities focus only on the immediate resolution of the localized problem without a general overview of a larger extent.

Local administrations often commission their studies on rockfall risk assessments over small areas to different companies that make general assessments without a global view of the problem. Up to a few years ago, these studies were stored in local archives and only in paper format in the town hall. Often, such documents are forgotten or lost. Consequently, a considerable amount of knowledge cannot be accessed when new studies and projects are made, resulting in difficult evaluation of the affordability of the different scenarios [7].

In the literature, it is possible to find many studies on rockfall modelling and the design of mitigation strategies [8], but few studies have evaluated the degradation of mitigation [1,9]. Moreover, wildfires in several parts of the world, such as the Mediterranean climate regions, exacerbate instability and threaten rockfall mitigation structures [5,10–12]. Thus, correct maintenance of infrastructures to reduce the rockfall risk is critical. For this reason, even good remedial works can be affected by irreversible degradation without a clear maintenance plan. Moreover, these plans are not easily applied and, in the past, they have not been provided by companies. The problem of correct infrastructure maintenance is critical, particularly in areas such as Italy, where many different technical solutions have been adopted in the last three decades. Due to the recent substantial evolution of the rockfall barriers, many ancient installations are not compliant with the actual rules. In addition, in the past the installation of barriers did not require the definition of an adequate maintenance plan. For this reason, in a large part of the country, the most important aspects of rockfall risk reduction are not related to the installation of new solutions but the correct management of already installed ones. In many cases, the only possibility is the replacement of old structures. The replacement, of course, requires a new analysis of the studied area to design the new installations correctly. This procedure is often very complex and the first important element that should be accessible is a detailed description of the state-of-the-art and the implementation of a user-friendly solution for proper support and the upgrade procedures for the installed systems. The digitalization of old archive studies [13–15] is the first low-cost solution to create a (geo)database of available information. Digitalization is often a partial and preliminary solution because the amount of data can be very high. For this reason, using a dedicated document, such as the Operative Monograph (OM) proposed by [16], can add value by making a collating essential information organized in a predefined structure.

The availability of high-resolution DTMs could significantly help study rockfall-prone areas. In recent years, LiDAR [17] and uncrewed aerial vehicles (UAV) [18–20] have mapped areas affected by rockfalls at a very-high resolution and relatively low cost. Moreover, proximal remote sensing techniques also reduce risk for the operators, limiting (or eliminating) the need for direct access to the most dangerous areas [21]. In addition, a very high-resolution DTM can be used to compute a more effective GIS-based rockfall simulation [22]. This work presents a methodology based on digitalizing an old mitigation work archive, and integrating it with ancillary data, high-resolution LiDAR DTM and other remote sensing data. The procedure aims to create an integrated geodatabase of rockfall mitigation works and their state of maintenance. The method was tested on a small site in Lauria municipality, southern Italy, but can be applied on a large scale for scientific applications or risk management plans.

Since the late 1980s, the municipality of Lauria and a regional civil engineering board set up a series of studies and mitigation works. The most important works were done from 1997 to 2001. Several rockfall events happened after the 1996 wildfire and the 1998 earthquake [23]. Geo-structural survey borehole investigation and rockfall modelling were commissioned for this mitigation work. The results of geo-structural surveys and geomechanical analysis were adopted to detect potentially unstable sectors. This important information from past studies risked being forgotten without digitalization and geocoding processes that can allow use of these results in future studies.

In our work, we acquired and digitalized all available documents and studies in the area of interest developed over the last 40 years. We created a geodatabase that identifies all the infrastructures and collects all the available information. The OM and the GIS database can be used to organize large and complex datasets that can be adopted to manage slope instability, and be used by experts or local authorities as a starting point for urban planning, to assess numerical models, or to study rockfall mitigation works. The proposed methodology is the first step toward a better definition of a long-term strategy to reduce the rockfall risk in urban areas that experts and local authorities must manage. We also created information sources for dissemination, such as a webGIS based on open source software and 3-D models aimed to increase preparedness among the population and simplify access to available information.

This paper is organized as follows. A description of the study area is provided in Section 2, followed by the materials and methods adopted in Section 3 and the results in Section 4. The results are divided into three parts: (i) archive digitalization and the history of rockfall works and events; (ii) remote sensing and LiDAR data, and (iii) a description of the operative monograph and results dissemination. The last two sections of the paper are the discussion (Section 5) and conclusions (Section 6).

2. Study Area

The town of the Lauria (Basilicata region, southern Italy) is located in the Apennine belt (Figure 1A).

From a geological point of view, the town is on the northern border of the Lauria Mountains structural unit [24], mainly made by Mesozoic calcareous formation. The lower part of the historical town (Lauria Inferiore) was built at the base of Sant'Elia ridge. According to the CARG Geological map [25], the slope affected by rockfall is located in the Jurassic unit "Alburno-Cevati-Pollino" (Figure 1B). The lithology is represented by dolomitic limestone, with interbedded layers of marl, conglomerate and calcareous sandstone (Figure 1B). The main structural lineament and sub-vertical faults are NNW-SSE, NW-SE, and N-S. The main dipping of the formation is to NW, and some karst processes enhance rock mass fracturation.

The high acclivity of the slope and the complex fracture systems isolate unstable blocks subject to frequent rockfall/toppling events of small-medium volumes. The slope affected by rockfall has a length of about 1 km, and reaches 200 m in height. The average gradient is about 60° in the sector just above the old part of Lauria town Figure 1C. Several buildings are located less than 20 m from the foot of the cliff.

In recent times, events such as severe rainfall (2002), wildfires (1996 and July 2017) and an earthquake (9 September 1998, the epicentre was located about 3 km southeast of Lauria and with a magnitude of Mw = 5.6) [23] have caused significant rockfalls that affected the closest buildings and the road. Fortunately, there have been no fatalities in recent years. In particular, in July 2017, several fires occurred in southern Italy [26], and a large one affected most of the Sant'Elia ridge. The event caused some concern in the local administration, which followed up with investigations to assess the maintenance state of the rockfall defence systems installed.

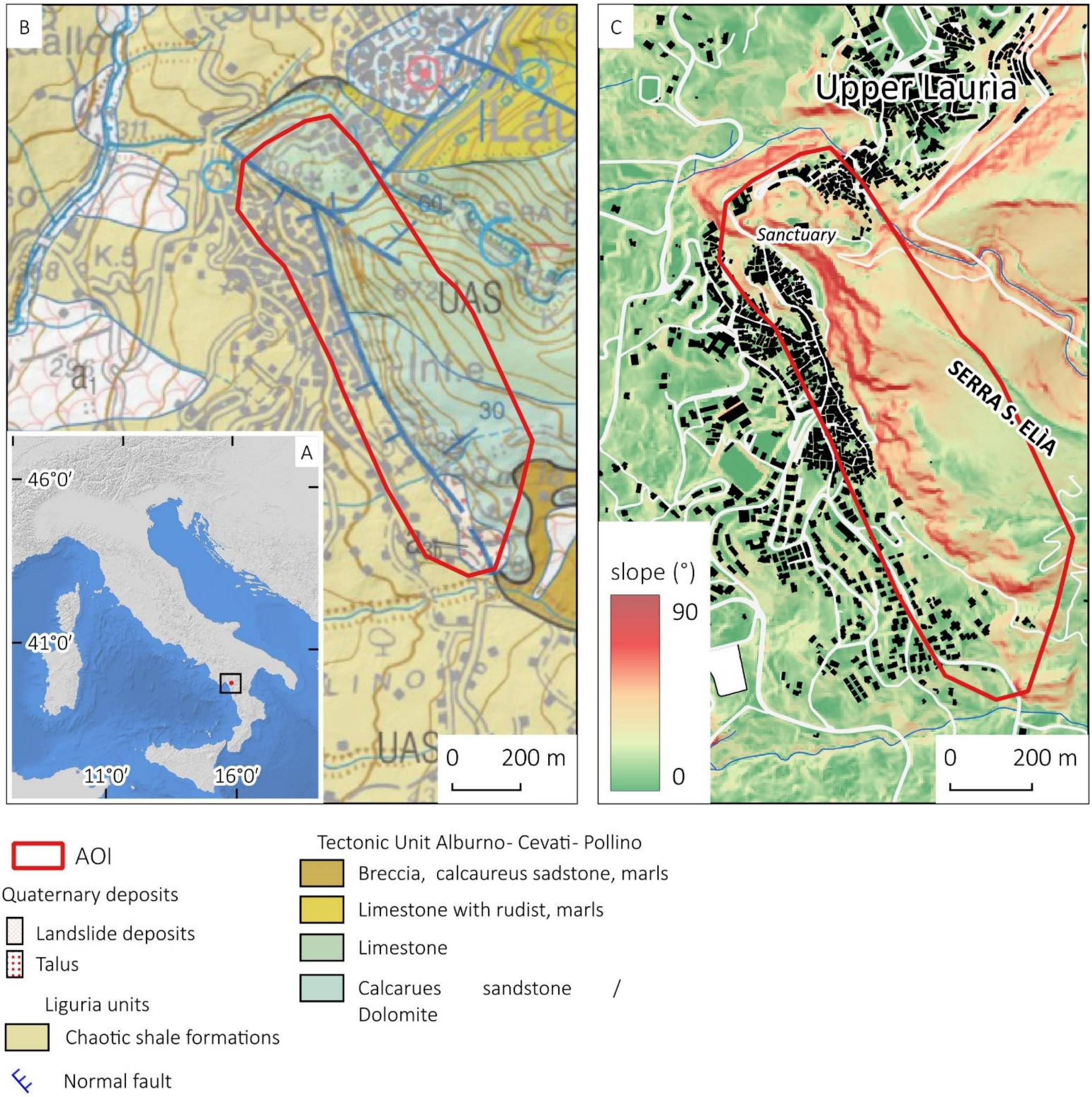


Figure 1. (**A**) Location of Lauria case study. (**B**) Geological settings of the study area, adapted with permission from [25] 2014, ISPRA Servizio Geologico d'Italia. (**C**) Acclivity maps of study area based on 5 m DTM of Regione Basilicata.

3. Materials and Methods

We created a methodological approach (Figure 2) to build a database of existing knowledge and data for future studies and dissemination to the population. The methodology comprised four steps: (i) data collection; (ii) an organized geodatabase setup; (iii) publication of the OM that collates all the available information on the case study, and (iv) results dissemination.

For data collection, there were four main input types: (i) Lauria municipal archive of mitigation works, (ii) rockfall events and other databases, (iii) creation of the 2017 wildfire map; (iv) DTM Lidar and orthophotos of the study area.

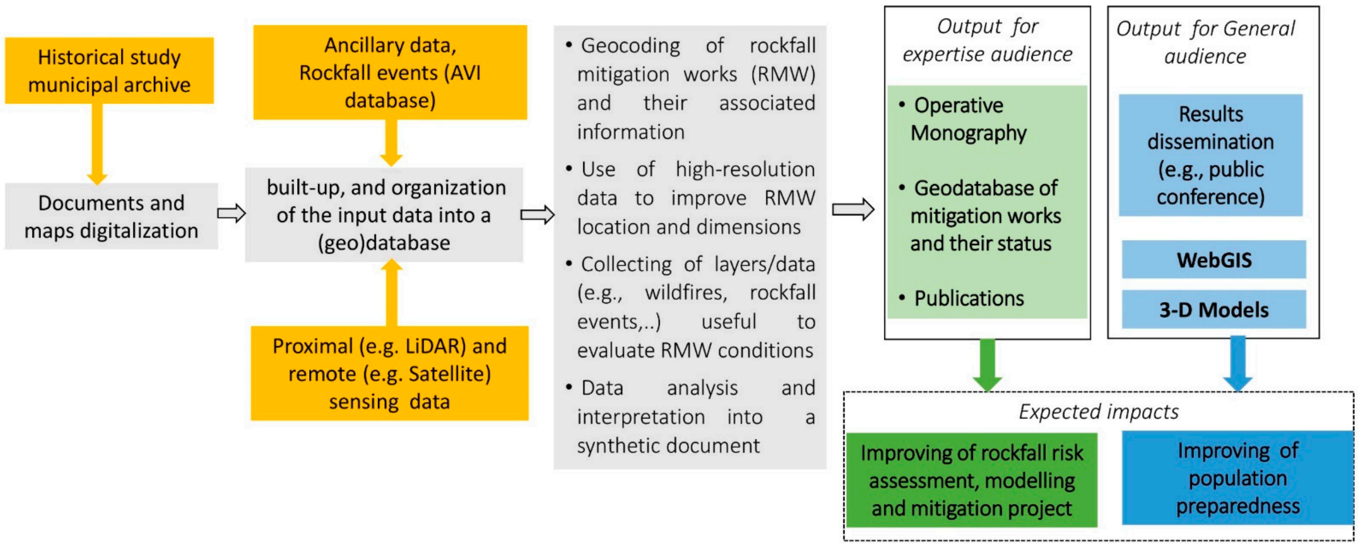


Figure 2. Flow chart of the proposed methodology.

The first input deals with the digitalization of old studies, maps and documents from the archive of Lauria municipality and the geocoding of maps on a GIS. We digitized about 70 documents and maps from the Lauria town hall archive (approximately 20 GB of data). Most of them were archived only in paper format in the Lauria town hall. We organized them in a hierarchical structure that follows the original archive's organization (Table 1).

Table 1. An example of the hierarchical structure of the database of digitalized documents (translated from an original document made for Lauria municipality).

Data/Documents Repository		Document Filename	Shorth Descriptions	Year
Parent	Child			
01_1997_ Draft projects	03_Normative	Tecnhichal_specifications.pdf	Rockfall mitigation works requirements	1999
		Barrier_req.pdf	Rockfall barriers requirements	1999
	04_Maps	Widespread_instability_map.tif	Preliminary maps of widespread rockfall instability	1999
		Punctual_instability_map.tif	Preliminary maps of punctual rockfall instability	1999
02_1998	01_geomechanicahl	Geomechanical_rel.pdf	Rock mass characterization relation and maps	1998
03_Final projects	03_Certificates	Rokfall_barrier_pr_1500kJ.tif	Rockfall barrier sketch	2001
		Rokfall_barrier_cert_1500kJ.pdf	Rockfall barrier certificate	2001
04_2002 Rockfall event	02_Maps	2002_barrier_maps.tif	Rockfall barriers maps	2002
		2002_restore_maps.tif	Maps of restoration of damaged mitigation works	2002

The second input involved collecting all the available information about rockfall events from historical archives of newspapers. In particular, we added to our project all the data from the "Aree Vulnerate Italiane" (AVI) project led by CNR-IRPI [15], a database of historical landslides and flood events that occurred in Italy until the early 2000s. Other sources of information and geo-data were the Regione Basilicata geoportal [27] and the national landslide inventory (IFFI project geoportal [28]) and other cartographic services [29].

The third input involved creating a burnt area map of the July 2017 wildfire using the variation of normalized burn ratio (NBR_{var}) or dNBR [30] obtained from NBR_{post}-NBR_{pre} fire. The NBR is based on the following equation: (NIR − SWIR)/(NIR + SWIR), where NIR is the near-infrared band, while SWIR is the short-wave infrared. This index is widely used in the literature [26,31,32]. We used Sentinel-2 images pre-wildfire and post-wildfire and validated the NBR_{var} map with post-event aerial photos of the Regione Basilicata.

The last input involved the acquisition of very high-resolution DTM and orthophotos based on LiDAR data of the study area. The LiDAR survey was made by an external enterprise and financed by Lauria municipality. The LiDAR used for the survey was a Riegl miniVUX-1 with Applanix APX-20 and Sony A7R Mk III loaded on a DJI MATRICE 600 UAV. The area covered was about 609,260 m^2, with an average point density of 176 pt/m^2. Using ground control points (GCPs) measured with real-time kinematic positioning of the global navigation satellite system (RTK GNSS) allowed validation of the cloud points, which have an accuracy of 2 cm on the vertical axis. The points cloud was processed to obtain DTM and DSM at 0.5 m of spatial resolution and orthophotos at 0.02 m. The LiDAR data were also managed directly on QGIS using the Whitebox plugin [33] for a detailed analysis of some rockfall barriers.

The second step was creating an organized database, in which the studies and project materials were sorted based on the year of production, works certification and typology. At the same time, through GIS software, we created a geodatabase of rockfall mitigation works, main rockfall events and other ancillary data. The mitigation structures were geolocated with the help of a high-resolution LiDAR orthophoto. We also did a ground survey to take photos of the most representative mitigation structures.

In the third step, we created the OM [16] that represents a practical (and standardized) organization of what we already know about the studied phenomenon.

The OM is a document for an expert audience and was delivered confidentially to Lauria municipality. The document contains six main chapters: (1) summary of available ancillary data; (2) geological/geomorphological and structural settings based on previous studies; (3) state of the art of the mitigation work, including the certificate and calibration; (4) description of LiDAR and orthophoto product; (5) webGIS and 3-D models metadata; (6) final consideration and suggestion for future studies. In particular, in the last section, essential information and data currently missing are suggested for implementing the geodatabase. In the conceptual scheme of OM, all the new information produced will be collected in the database and will update the OM in a positive feedback circle. In the case of rockfall mitigation work, these actions could, for example, include a new geomechanical survey or a deep investigation of the maintenance status of rockfall barriers.

The last considered step involves the dissemination of results. This phase aims to increase the population's awareness and knowledge about rockfall risk. The main products consist of a webGIS built on free software, and 3-D models for interactive visualization of the affected areas.

To create the webGIS of Lauria rockfall mitigation works, we used GeoServer and MapStore services. The GeoServer [34] is a web mapping software for geo-data dissemination. GeoServer is a Free and Open-Source Software (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 [35,36].

MapStore [37] is a professional FOSS cartography and geographical information platform based on a topological map model that allows creating webGIS services using the WMS obtained from, for example, GeoServer.

To create a 3-D interactive view of the mitigation works (that can be used with any browser without installing GIS or other software), we used the Qgis2threejs plugin for QGIS [38]. The LiDAR DTM was used as an elevation layer to create several high-resolution 3-D view models with different layers.

4. Results

Archive digitization, remote sensing and LiDAR data, and the dissemination of results allowed us to produce a detailed and updated state-of-the-art rockfall document. The result forms the basis for further works and decisions for experts and Lauria authorities. In the next section, the main outputs are discussed.

4.1. Archive Digitization and History of Rockfall Works and Events

The digitization of the archives and the search in all available databases allowed us to reconstruct the history of rockfall events and mitigation works, as summarised in Table 2.

Table 2. History of main rockfall events and mitigation work from historical archives.

Events/Action	Date	Source
Rockfall (generic report)	1970	AVI project [39]
Rockfall (report on mitigation strategy)	1983	AVI project [40]
Rockfall event	1996-11	parliamentary question [41]
Rockfall mitigation study start	1997	Lauria archive [42]
Rockfall triggered by an earthquake	1998-09	Lauria archive [43]
Rockfall mitigation works ends	2001	Lauria archive [44]
Rockfall damaged some mitigation structures	2002-01	Lauria archive [45]
Restoration of damaged structures	2002	Lauria archive [46]
Rockfall triggered by fires	2017	Local newspaper [47]
State of the art of mitigation work	2021	OM and webGIS of CNR-IRPI [48]
Start of the restoration of mitigation structures	2022	Lauria municipality [49]

For instance, in the AVI project archive it was possible to find the following information [40]: "The corps of Civil Engineers intervened in 1983 for the scaling of a stone volume. In 1983 the Prefecture assigned to the municipality of Lauria an amount of 50 million Italian lire necessary to cover the hospitality costs of the families temporarily evacuated. The recommended intervention methods are divided into two phases: (1) survey carried out by expert rock climbers aimed at carrying out scaling of completely detached boulders, cementing of the surface blocks in the process of detachment, nailing and application of electro-welded mesh; (2) implementation of active tie rods and simultaneous installation of monitoring instrumentation consisting of crackmeters, depth strain gauge bars, fixed inclinometer columns, and load cells".

Another source of documented rockfall events came from a parliamentary question of 1996 [41].

"In the night between 22 and 23 November 1996, during a violent storm, a rockfall of limestone rock occurred in Lauria (PZ), with an estimated volume of a few cubic meters. The detachment occurred from a pinnacle of the ridge overlooking the San Giacomo district. After a jump of about 100 m, the boulders reached the underlying collection basin, delimited by the rockfall wall. Large rock fragments overpassed the concrete barrier and reached the adjacent service road at 416 m, damaging two cars. Another large boulder hit a house breaking through the roof and the underlying brick floor. Fortunately, no people were involved in the rockfall".

After the 1998 earthquake [23], a technical report on rock mass characterization was commissioned through an utmost urgency procedure [43]. The geomechanical study detected several areas with critical potential instability related to discontinuities that isolate wedges and blocks prone to fall, even if they have small to moderate volumes. Some details of geomechanical station sm11 (Table S1) and a summary map (Figure S1), polar diagram of the fracture system (Figure S2), and table (Table S2) of the geomechanical survey are reported in the Supplementary Materials.

In January 2002, a few weeks after the conclusion of the remedial work, a rockfall located near an unstable sector detected in the 1998 report, partially destroyed the new barriers and nets. The defences were restored a few months later. These are the last documented works and studies on the unstable cliff of Sant'Elia Ridge.

In the last 20 years, no new risk mitigation projects have been done, and no maintenance work has been planned for the installed structure. In 2017, another wildfire that hit the area of Mount Sant'Elia caused new small rockfalls. In 2022 preliminary maintenance work commissioned by Lauria Municipality was started.

The results of digitization, geocoding, and database creation are shown in the following figures. The analogic maps (Figure 3A) of the ubication of the rockfall mitigation structures were digitized and geocoded in a geodatabase containing the most relevant information available in the report (Figure 3B). For instance, for each installation, it is possible to know the type and the number of anchors, eyebolt anchor and the mesh used (e.g., double-twisted hexagonal wire mesh). We also include a sketch of the rockfall barrier's design and other structures (Figure 3C). The sketch can be directly downloaded from a link in the vector database.

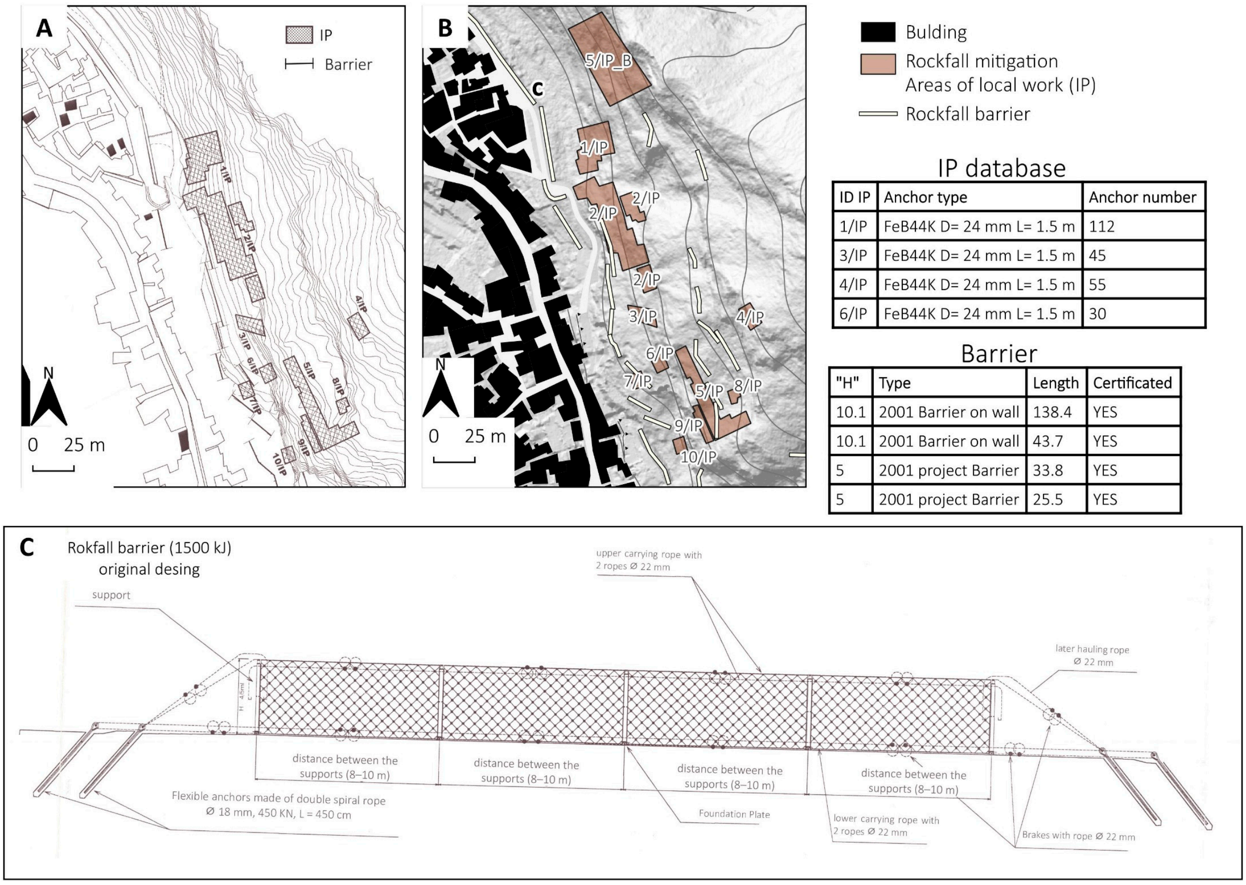


Figure 3. (**A**) Original map of local mitigation work (IP sectors) and rockfall barrier (Lauria municipal archive [44]). (**B**) Digitized map overlapped to hillshade LiDAR, with an example of tables database information. (**C**) Digitized sketch of 1500 kJ barrier (Lauria municipal archive [44]).

When feasible, we also classified rockfall barriers by their age of construction or design using available reports. We also included some photos taken on the ground (e.g., photos 1, 2 and 3 in Figure 4) to show their current condition. The LiDAR and the high-resolution orthophoto have been fundamental for detecting and accurately geocoding barriers located in the upper part of the slope and covered by vegetation (Figure 4B). The classification of the barrier is only qualitative, an accurate classification needs an expert survey (e.g., from a structural engineer) to assess the maintenance status of the barriers. This task was not within our competence and was suggested as a recommended action in the operative monograph.

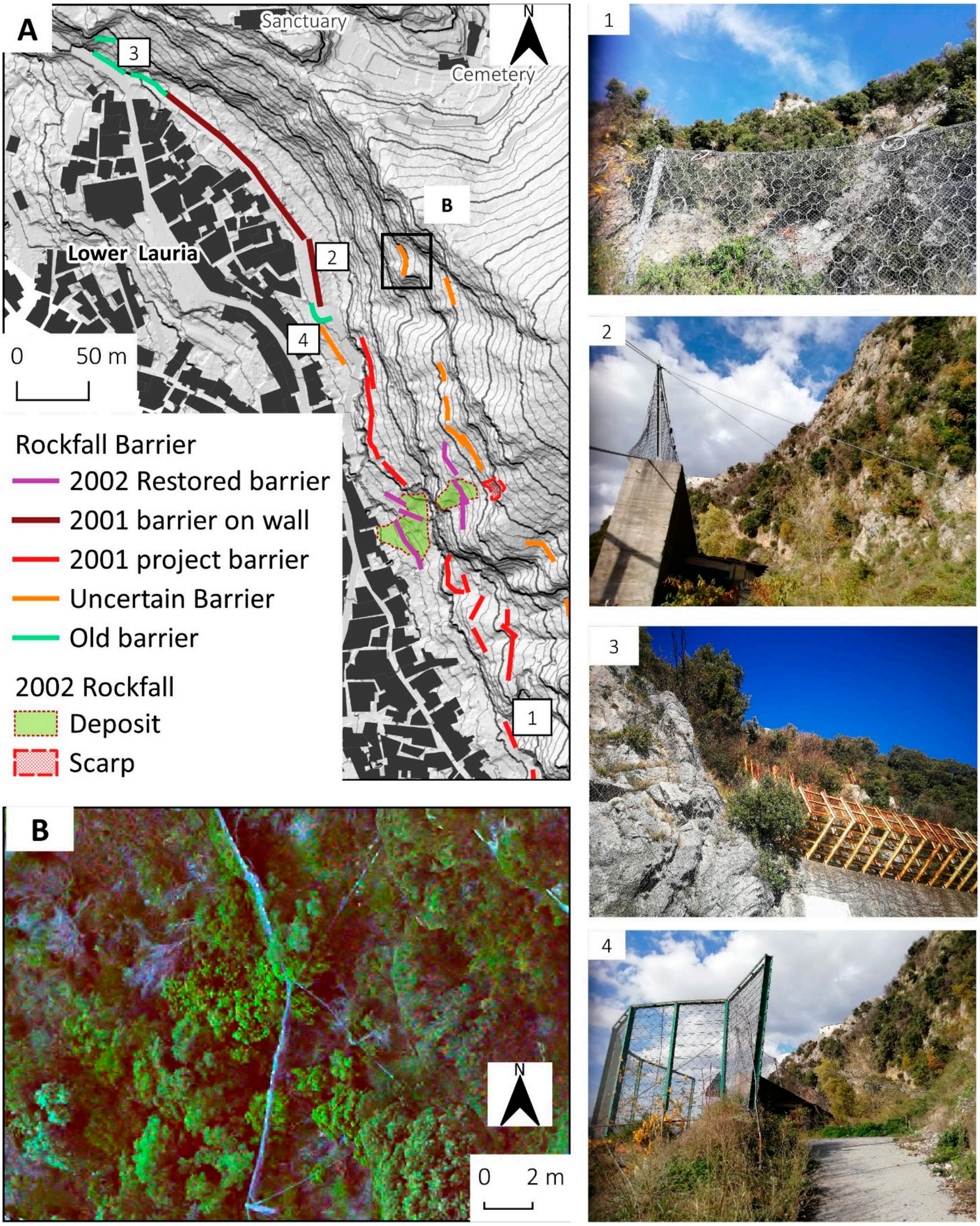
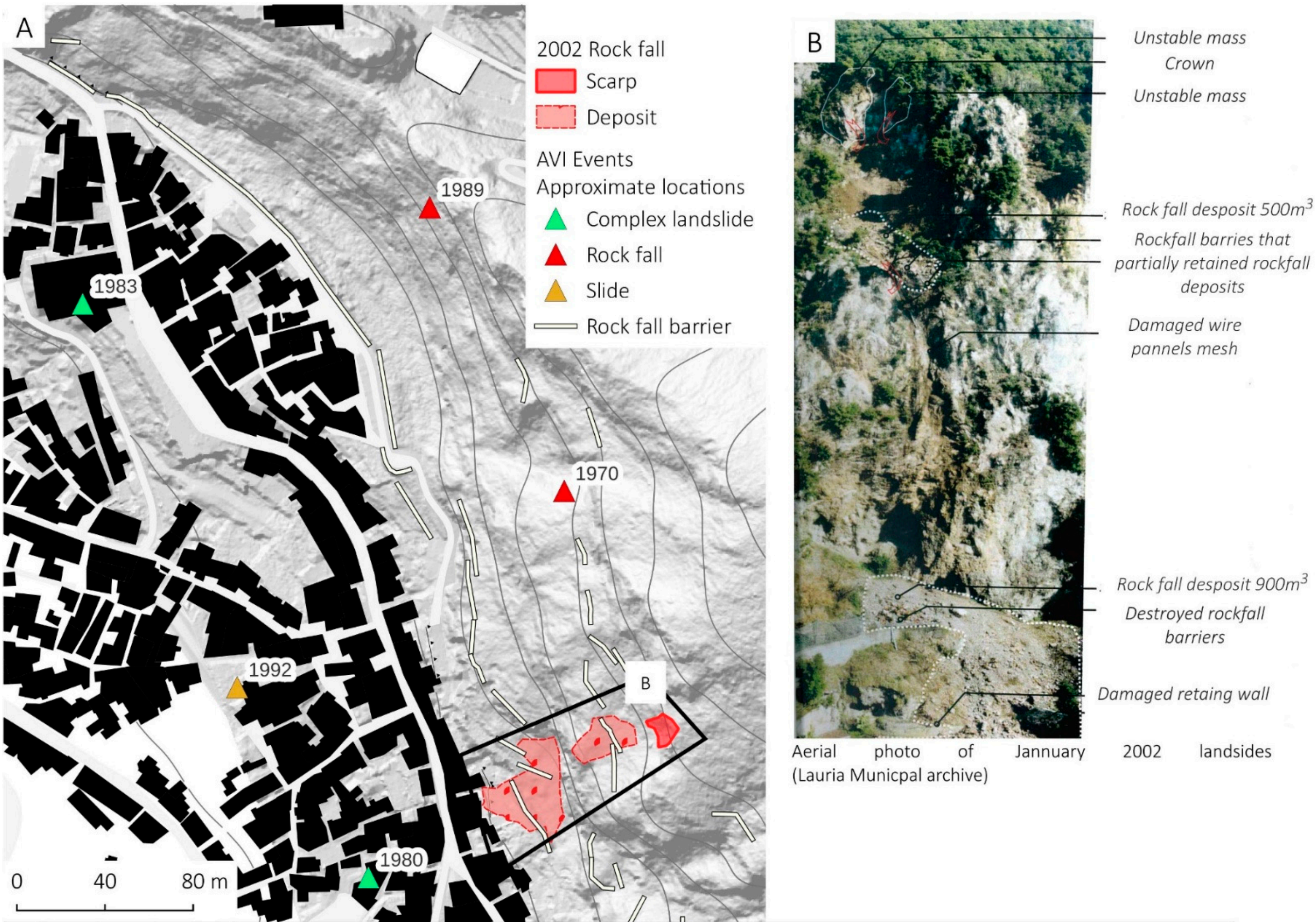


Figure 4. Example of digitized and geocoded rockfall barriers. (**A**) Classification of the barriers with the location of some representative photos (taken in February 2020 field survey). Photo 1 shows a certified rockfall barrier of 2001. Photo 2 shows a 1500 kJ barrier installed over a wall. Photos 3 and 4 show an old barrier (pre-2001) without documentation. (**B**) Barrier of uncertain age detected with UAV LiDAR and orthophoto (details in Figure 7).

Figure 5A show the location of events from the AVI database that occurred in the lower sector of Lauria town. Geolocation was improved from the original database using the text reference, but it is still approximate. The same map reports the location of the January 2002 rockfall event. The map and the aerial photo taken a few days after the rockfall (Figure 5B) comes from a report from the Lauria archive.



AVI_ID	year	type	Description
2,000,288	1,989	Rock fall	The Armo ridge is made up of carbonate rocks stratified in large banks crossed by numerous families of fractures and fissures. These isolate rock wedge, even of considerable size, especially between Punta San Giovanni and the Cerruti region
2,400,176	1,970	Rock fall	Rockfall from the collapse of fractured roc blocks, which occurred in very steep slope corresponding to fault lines, exposed to the action of atmospheric agents. They affected the inhabited area of Lauria Inferiore.

Figure 5. (**A**) Approximate location of AVI events and 2002 rockfall with related database information in the table. (**B**) Aerial images of rockfall available in the post-event report (source: Laura municipal archive [45]).

4.2. Remote Sensing and LiDAR

The creation of the 2017 wildfire map (Figure 6) was essential to estimate potential damage to rockfall works. The availability of pre-wildfire (Figure 6A), and post-wildfire (Figure 6B) Sentinel-2 images allowed us to calculate NBR_{var} (Figure 6C). We used the NBR_{var} with post-event aerial photos of Regione Basilicata [38] to map the area of the 2017 wildfires with reasonable accuracy. The map of NBR_{var} was used to estimate the potential damage to barriers (Figure 6D). The maps show that wildfires affected most of the study area. These results show that the fires could have damaged many fences, as documented in other sites [5]. After the wildfire, the reduction of vegetation protection (roots and dense shrubs) had unchained several meta-stable blocks and talus along the slope, causing an increase of small rockfalls with a similar process described by [12]. Fortunately, vegetation recovery was relatively rapid. During the 2019 surveys, evidence of the wildfire had almost disappeared, as confirmed by the LiDAR orthophoto of 2020, showing very dense active vegetation (Figure 7A).

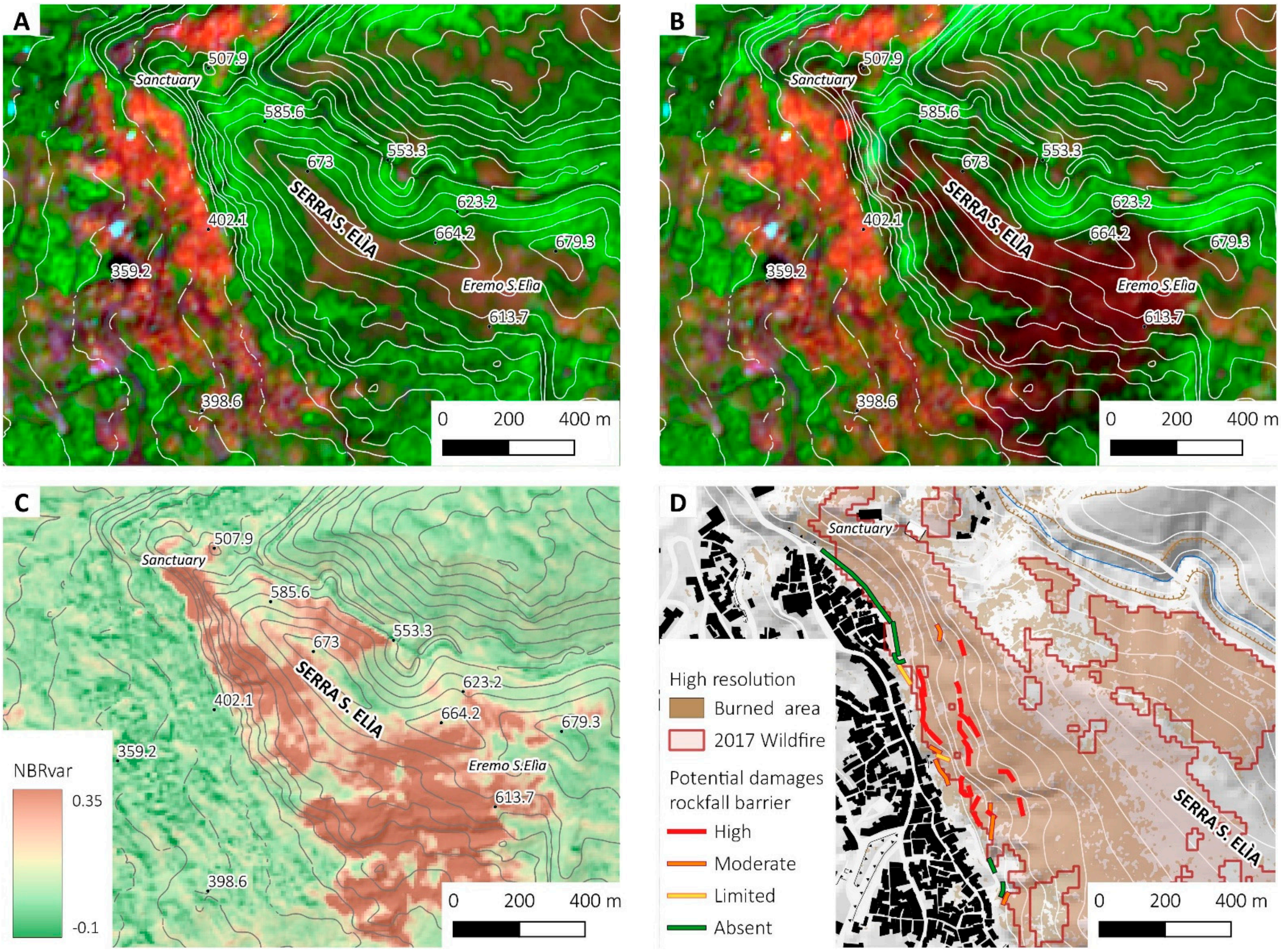


Figure 6. (**A**) Pre-event Sentinel-2 image (2017-07-02). (**B**) Post-event Sentinel-2 image (2017-07-12). (**C**) NBR_{var} index. (**D**) Map of burnt areas with estimated damages to rockfall barriers.

The UAV-LiDAR survey allowed us to obtain a very high-resolution orthophoto and DTM. The derived products, such as the slope gradient and the hill shade, have unprecedented details identifying the areas with high rockfall hazards. With a spatial resolution of 0.02 m, the orthophoto allowed us to detect some rockfall barriers surrounded by dense vegetation (Figure 7A). The combined use of LiDAR point cloud data classified by intensity allowed us to detect the shape and accurately geocode the barriers (Figure 7B,C). Moreover, the derived interpolated DSM allowed us to estimate the height of some fences (e.g., about 3 m in Figure 7D). The data show that their dimension agrees with a sketch of the 2001 project. The high-resolution DTM could also increase the accuracy of GIS-based rockfall runout models, such as the QPROTO plugin for QGIS [22].

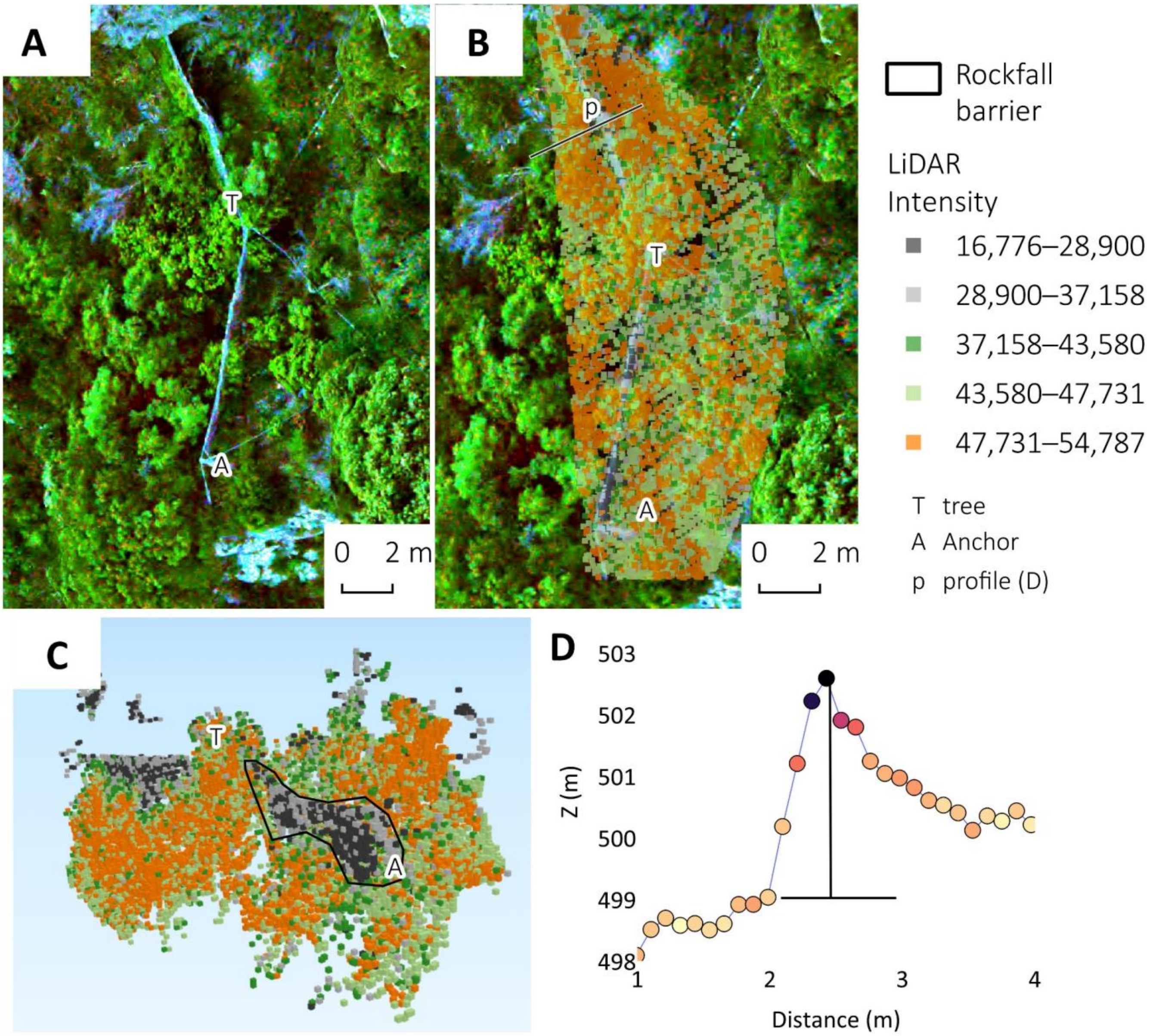


Figure 7. An example of a rockfall barrier in a steep slope detected on orthophoto and confirmed by LiDAR point cloud. (**A**) Orthophoto with 10 cm of spatial resolution. (**B**) Sampled LiDAR point cloud classified by intensity. (**C**) A 3-D view of the LiDAR point cloud. (**D**) Vertical barrier profile based on LiDAR data interpolated in 10 cm DSM.

4.3. Operative Monograph and Results Dissemination

The OM of the Lauria case study mainly focuses on (i) the structure of the database and GIS data; (ii) the available geological settings; (iii) a list of previous rockfall events; (iv) a report on rockfall mitigation work history and qualitative maintenance status, and (v) results of UAV-LiDAR survey. A document of about 40 pages was delivered confidentially to Lauria municipality at the end of 2020. In the OM, we highlighted some critical aspects, such as:

- the lack of data about the maintenance of rockfall works in the past few decades;
- the difficulty of collecting old certifications of the works;
- the need to update rock mass characterization and numerical modelling;
- the importance of constantly updating the digital database of mitigation and geocoding;

- the importance of planning rockfall mitigation strategies over a large scale (e.g., coordination with regional authorities) to optimise resources;
- the need for dissemination materials for the population of Lauria hamlet, in collaboration with an expert that worked on planning.

The dissemination phase aimed to produce simple-to-understand representations of results available to the general public which were provided as a demonstration during a meeting with public authorities. The webGIS contains a simplified version of the digitized GIS database with the most representative layers, the position of barriers, the 2002 rockfall, and the burnt areas.

The MapStore web application also allows adding widgets with a better explanation of the layer contents. A simplified English version of the webGIS is available at this link: http://irpi-geop.to.cnr.it:8080/mapstore/#/viewer/openlayers/12 (accessed on 14 September 2022).

The creation of some 3-D models (e.g., Figure 8A,B) allows an easy consultation of the database for non-experts. Several data can be overlapped into models, where single elements can be investigated directly on the browser, with a hyperlink to other information pages.

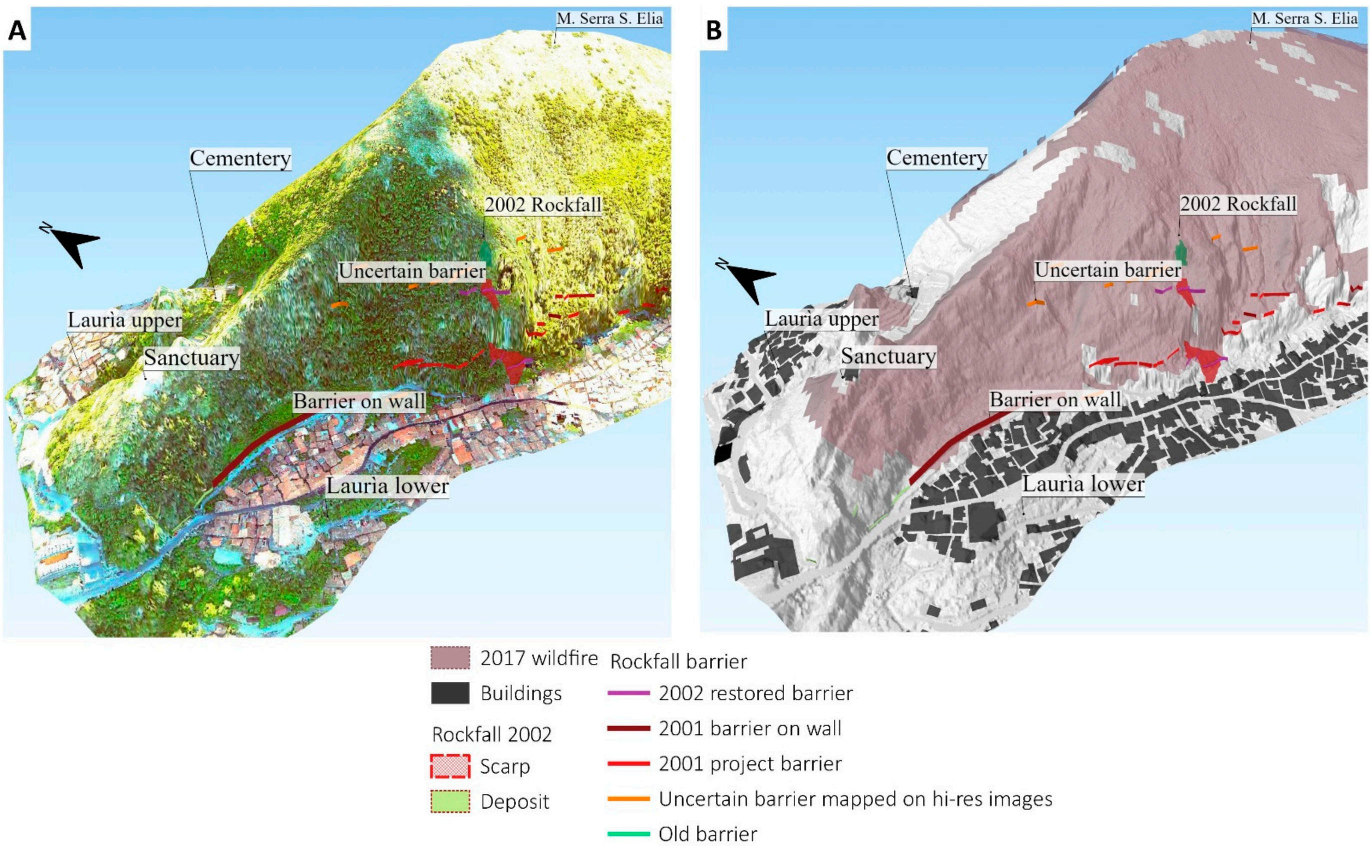


Figure 8. Exported 3-D view of the study area based on DTM LiDAR with rockfall barriers overlapped, obtained with the Qgis2threejs plugin [29]. (**A**) 3-D view with overlapped orthophoto. (**B**) 3-D view with overlapped shaded relief and burnt area. The 3-D views are available on the Zenodo platform [50].

5. Discussion

In the past few decades, in Italy and in many other parts of the world, vast numbers of rockfall mitigation structures (active and passive) have been installed but, for most of them, their state of maintenance, and the changes that occurred to the surrounding slope are not known.

A system that can manage and monitor the state of the structures and the slope is fundamental for detecting an increase of rockfall susceptibility, particularly if external events such as wildfires have damaged these structures. A geodatabase supported by OM can provide essential suggestions for implementing new studies and projects when the structures become inadequate. It is also necessary to highlight how many infrastructures were built with criteria that are not compliant with current regulations, e.g., Eurocode regulations [51]. An approach like the one we proposed can provide a complete picture of mitigation works and their characteristics to organize an ordinary/extraordinary maintenance plan to support progressive updating of older systems with modern and more functional structures.

In addition, a geodatabase of mitigation structures can be overlapped with all other ancillary data or model results that deal with rockfalls (e.g., the areas affected by wildfire or runout models).

The main difficulties that limit the creation of an updated database are the lack of resources, knowledge and personnel in small communities. Moreover, usually at a regional or national scale, there is no coordination and collection of small projects made locally.

One of the very few examples of a complete public inventory of rockfall mitigation works was made in South Tirol (Bolzano province) [52]. From their webGIS [53], it is possible to download the dataset that contains information about the type of rockfall mitigation, the vulnerable element (e.g., road) and the related contract. In the literature, there are no other clear examples of such databases.

For these reasons, we believe that our work has created an initial procedure to manage rockfall mitigation work and their state of conservation that can be integrated with other methodologies to manage rockfalls along the road network [3,54]. The test made at a local slope scale in Lauria Town can be used as starting point for regional application.

The OM, combined with a geodatabase, allows both authorities and experts to focus on the data and implement knowledge of mitigation works. In an updated version of OM, we will add to the "suggestion and comments" section a summary table with the current status of the data (e.g., Table 3). In a future update, other information could be related to priority, cost-benefit analysis [7,55] and the feasibility of the suggested action.

Table 3. Lauria case study. Summary of suggested actions aimed to implement the database of rockfall mitigation work. Current status legend P = partial or old data, X = missing data/information, V = complete and updated data.

Dataset/Study	Current Status	Notes
Geomechanical study	P	Only a technical report aged 1998 is available, a new study with more precise geocoding is suggested.
DTM	V	The new HR LiDAR DTM cover all the affected slope.
Numerical modelling	X	Runout modelling based on HR DTM could help design the restoration of mitigation structures.
Maintenance status information	X	An in-situ analysis, made by experts, is necessary to evaluate the structural condition of existing mitigation work.
Rockfall event database	P	A more systematic inventory of rock fall events is necessary.
Geodatabase/webGIS	V	They need to be updated when new data are available.
Dissemination	P	Public engagement on rockfall risk is necessary

For instance, in the municipal archive of Lauria, there is a geomechanical characterization of rock mass technical reports. However, this study was made under an urgent mandate, with imprecise geolocation of geomechanical stations. For this reason, in a dedicated section of the OM, we recommend making a new rock mass characterization with newly refined methods and rockfall simulations based on high-resolution LiDAR DTM.

Our study also describes the importance of updating and improving the landslide historical events database and related tools. This historical recording is one of the leading research fields in CNR-IRPI [15,56–58]. The associated remedial works should be part of a future database. In this sense, the future metadata repository will help data distribution. For example, at this link, there is a prototype of the CNR-IRPI data catalog: https://catalog.irpi.cnr.it/geonetwork/srv/eng/catalog.search#/home (accessed on 14 September 2022).

6. Conclusions

We present a methodological approach aimed at creating an affordable standardized, replicable approach to manage, catalogue and monitoring rockfall mitigation structures. The problem of correctly managing rockfall barriers and, more generally, all adopted solutions for rockfall risk mitigation has often been underestimated. There is a wide literature dedicated to rockfall risk reduction, but few studies have considered the importance of correct management and maintenance of adopted solutions. Much infrastructure was built more than thirty years ago, without a clear idea of the most challenging future events. Update of already installed infrastructures can involve extensive maintenance or replacement. This is a challenging activity in small municipalities, where the local authorities sometimes do not have sufficient technical knowledge to manage this effort. In this paper, we present a typical example of this situation. Lauria is a municipality that has invested many resources in the last decades to protect the town from rockfall risk. Nowadays, the most critical problems are assessing the effectiveness of the installed solutions and evaluating the need for new ones. The necessity of an effectiveness evaluation was amplified by the effect of wildfires that occurred in 2017 that involved areas in which rockfall barriers had been installed since early 1970. To support the municipality, we developed and proposed a procedure targeted at the needs of small communities. The method is based on creating a geodatabase, OM and in disseminating results. The approach also combines traditional archive digitization with remote sensing data from satellite images to high-resolution LiDAR surveys. We tested our methodology for the small town of Lauria (southern Italy). We obtained detailed state-of-the-art and qualitative maintenance conditions for mitigation works. The database shows that the most recent studies were made more than 20 years ago, and no significant maintenance works have been done on the structures. The documentation analysis pointed out the lack of an updated geomechanical study of the whole rockfall-prone area.

The LiDAR data with high-resolution orthophoto allowed precise geocoding of the barrier to estimate 3-D dimensions and an evaluation of vegetation cover. A future step could be integrating the geodatabase of mitigation works with high-resolution DTM LiDAR to produce detailed rockfall modelling to improve the estimation of impact energy on structures.

In addition, we mapped the area affected by the wildfire, and the resulting potential damage to structures, with Sentinel-2 satellite data. The combined use of Sentinel-2 and aerial images showed that the 2017 wildfire potentially damaged most rockfall barriers and other mitigation structures.

The acquired knowledge summarized in the OM is a starting point that experts may use to do more accurate modelling and design a more appropriate structure to mitigate rockfall risk. We also think that the local authorities should use this approach and our results as a reference for exhaustive studies and to plan mitigation work.

We also created products focused on the general public, such as the webGIS and interactive 3-D models, as we believe that population preparedness and knowledge about natural hazards and risk mitigation strategies are essential for choosing the best affordable and safe measures by decision-makers.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/land11111951/s1, Figure S1: Lauria, map of potential rockfall/topple instability for each geomechanical station; Table S1: sm11: main parameter of measured discontinuities; Table S2: Description of some significant rock mass characterization stations; Figure S2: Original polar diagram of the average orientation of the discontinuity systems of the slope affected by rockfall.

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