A heterogenous-source geoinformation system to manage climate-induced modifications on the landscape for sustainable development

Discover Sustainability

Research

A heterogenous-source geoinformation system to manage climate-induced modifications on the landscape for sustainable development

Lorenzo Serra Bellini[1,2] · Antonia Spanò[1,3] · Marcello Cittadini Bellini[1] · Fabio Giulio Tonolo[1]

Received: 21 March 2024 / Accepted: 19 September 2024
Published online: 27 September 2024

Abstract
Historical landscapes in Italy have been slowly changing over the centuries and this is because their features, once fixed into specific shapes, were perpetuated until new economic and social developments occurred. Yet, in the Alpine region, this territorial organisation underwent sudden changes after World War II (WW II), resulting in a loss in population and traditional agropastoral production in favour of skiing plants and holiday houses. Moreover, the loss of traditional knowledge pertaining to environmental behaviour has resulted in the urbanisation of lands that are vulnerable to extreme events. In turn, this has hindered sustainable urban development. Nowadays, modern mapping technologies enable the state of the landscape to be assessed before, during, and after extreme events, the increased frequency of which may be related to climate change. The case study examined in this paper is the flood that hit Limone Piemonte, Italy, between the 2nd and 3rd October 2020. On that occasion, an aerial survey of the affected areas was carried out using Uncrewed Aerial Vehicles (UAV) a few weeks after the event. Spatial analyses were also performed based on very high-resolution satellite imagery acquired a few days after the event in order to determine where to plan more detailed three-dimensional (3D) surveys. This has enabled assessments of damages at different map scales to be performed. Thanks to the availability of pre-event multitemporal cartographic reference datasets, it was possible to monitor the historical evolution of the affected areas. It was possible to assess the vulnerable areas before the event, as well as to evaluate the morphological and settlement changes after the disaster. Therefore, one of the goals of this manuscript is to demonstrate that geoinformation systems are among the primary technical tools used to analyse environmental and climatic alterations that impact landscapes. Finally, a 3D model of the affected areas was produced, fulfilling another goal of the research by providing the public administration with a sustainable and innovative tool for territorial and landscape management, in accordance with the 11th pillar of the United Nations Sustainable Development Goals (UN SDGs).

1 Introduction

The Alpine regions of Italy are among the areas most affected by climate change, mainly due to the fragility of their territories, which has worsened as a result of urban development over the last 80 years. Thus, the increasing incidence of catastrophic events associated with water, such as floods, landslides, and droughts, has been modifying

✉ Lorenzo Serra Bellini, lorenzo.serrabellini@uniroma1.it; lorenzo.serrabellini@polito.it; Antonia Spanò, antonia.spano@polito.it; Marcello Cittadini Bellini, marcello.cittadinibellini@polito.it; Fabio Giulio Tonolo, fabio.giuliotonolo@polito.it | [1]LabG4CH, Department of Architecture and Design (DAD) - Politecnico di Torino, Viale Mattioli 39, 10125 Turin, Italy. [2]Department of Science of Antiquities - Università La Sapienza, Piazzale Aldo Moro 5, 00185 Rome, Italy. [3]FULL – Future Urban Legacy Lab - Politecnico Di Torino, @OGR Tech, Corso Castelfidardo 22, 10128 Turin, Italy.

mountain landscapes faster than ever in recent decades [1]. In this context, Geomatics provide tools that can be used to study landscape modifications before, during, and after these events, not only to quantify the disaster but also to assess alterations, as the paper aims to demonstrate. The ultimate objective extended beyond merely producing a 3D model of the affected areas. Rather, it aimed to equip public administration with a sustainable and innovative tool for comprehensive territorial and landscape management. This initiative closely aligns with the 11th pillar of the United Nations Sustainable Development Goals, which emphasises the creation of inclusive, safe, resilient, and sustainable cities and communities. By integrating advanced geomatic technologies and 3D modelling, the project sought to enhance the capacity of local governments to monitor, plan, and manage urban and rural landscapes. This approach not only supports disaster risk reduction and recovery efforts but also promotes long-term sustainability, ensuring that the management of land and resources is both environmentally friendly and beneficial to the wellbeing of current and future generations.

Yet, it will only be possible to ensure sustainable development in the future if «disaster risk reduction (DRR) continues to be an integral part of social and economic development» [2]. In this sense, the United Nations Sustainable Development Goal 11 (UN SDG 11) states that urban areas have the highest risk of experiencing disasters since a high concentration of people live in such places. States are invited to implement SDG goals associated with expected outcomes in order to overcome these events. In particular, SDG targets 11.5 advocates for reducing deaths and losses in global gross domestic products due to disasters. In the Italian context, where landslides and floods are becoming more common, this means improving solid national and regional territory planning by avoiding building in dangerous areas. Even though human loss is not comparable with that of more affected countries, economic damages remain significant [3]. Yet, a robust planning capacity means protecting cultural and natural heritage against vandalism, wars, and, more generally, anthropic actions that reduce its value. SDG target 11.4 promotes «strengthening efforts to protect and safeguard the world's cultural and natural heritage» [4]. Thus, it recognises the protection of cultural landscapes as one of the most pressing challenges faced by cities and communities.

Furthermore, SDG 13 underscores the urgent need to take immediate action to mitigate climate change and adapt to its effects. This goal is crucial in ensuring a sustainable and resilient future for all. One component of this goal is to strengthen resilience and adaptive capacity. In order to enhance the ability of all countries to deal with climate-related hazards and natural disasters, especially in developing and rural areas, climate change strategies must be integrated into national policies, strategies, and planning. It is also important to improve education and awareness. Climate actions are mostly preventive. Geomatics, as will be shown in this article, makes it possible to develop actions for preventing climate-related disasters, and also facilitates the monitoring and predicting of severe changes in the territory.

The risk of natural hazards [5] is an urgent matter that has been addressed by the United Nations Educational, Scientific, and Cultural Organization (UNESCO) since 1978, and this developed further when the UN dedicated the decade between 1990–2000 to reducing natural disasters. UNESCO also set up the United Nations Disaster Relief Office (UNDRO). The first objective was to define the concepts associated with the evaluation parameters (i.e., the Risk (R, risk of losses of human lives, buildings, roads, and economic activities) resulting from a particular natural phenomenon; the Hazard (H, which refers to the probability that a given instability phenomenon—potentially destructive—will occur in a specific time interval and a particular area. It is expressed as a percentage) and the Vulnerability (V, the extent of loss produced in a specific element or group of elements at risk resulting from the occurrence of an instability phenomenon with a given intensity. It is expressed as a percentage). The parameters mentioned above are interrelated in the conventional formula $R = H \times V \times E$, with E corresponding to elements at risk (communities, properties, economic activities). Now, such concepts are consolidated and taken as a reference for many different types of disasters [6–9].

Since the 2000s, the Emergency Management Cycle (EMC) has been adopted as an essential awareness consequence of dealing with risk. This cycle is organised into a five-phase approach and is intended to serve as a cyclical process, The steps involved here are prevention (which guides government services, institutions, and non-profit bodies in coordinating prevention potential, reducing the impact of disasters on communities), mitigation (analysing disasters and related responses to support correct and efficient planning in order to provide for future events), preparedness (which involves the development of specific emergency plans that can be used in the event of disasters of different natures), response (which relates to the organisation of emergency operational centres which are entrusted with the task of coordinating the actions of all the services and institutions involved in dealing with emergencies) and recovery (activities aimed at restoring a normal situation for the affected populations, which are often established in disaster areas to speed up recovery and aid recovery efforts) [10].

In this context, researchers can refer to the second volume of the Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report [11], which focuses on the impacts, adaptations, and vulnerability to climate change. They can also consult SDG 13 and its undersections. This report states that climate change is already having widespread and irreversible impacts on natural and human systems, from melting ice caps to more frequent extreme weather events. Certain regions, populations, and ecosystems are particularly vulnerable to climate change, including mountain communities and those reliant on agriculture. Therefore, adaptations are crucial in managing the current and future impacts. These may include building resilient infrastructure, enhancing cognitive resilience, and implementing early warning systems for extreme weather events.

The incidence of disasters, their impacts and the destructiveness associated with climate change have also led to the adoption of the Sendai Framework for Disaster Risk Reduction (2015–2030) [12]. This framework constitutes a guideline for institutions and governments to help them protect their territories and human communities. In Fig. 1, a diagram is presented that offers a precise reference representing the complex economic and social processes and interconnections between the SDGs and the Sendai Framework.

This research refers to this international framework which concerns principles at the base of action. The case study under investigation occurred on 1st October 2020, when weather parameters between Italy, France, and the United Kingdom (UK) produced perfect conditions for an extra-tropical storm. The following day, in the higher part of Tanaro Valley, the weather station recorded nearly 600 mm of precipitation, which is more than 50% of the average annual rainfall [13]. It can legitimately be said that this quantity of water involved equal or much more energy along shores than events that had occurred in previous years (1993, 1994, 2000, and 2016). In the present case, it was so fast that the water was not able to penetrate and percolate the soil due to landslides and rapid streams, and water dragged a quantity of wooden material through riverbeds. The effects of the storm included shore erosion, building foundation erosion along shores that resulted in their overturning, and a deposit of mud, stones, and wood in urban areas (Fig. 2). After the disaster that took place in November 2020 and later in 2021, a three-dimensional (3D) survey campaign was carried out by the Geomatics group of the Polytechnic of Turin. The survey covered affected areas close to Limone Piemonte, from Vernante to the entrance of the Colle di Tenda tunnel on one side, and the skiing plants of Limonetto on the other side. The Vermenagna torrent and some of its tributaries overflowed, causing damage to buildings and infrastructures along the water courses for approximately 15 km. This area has been mapped and analysed using satellite data and Uncrewed Aerial Vehicle (UAV) photogrammetry techniques (Fig. 3a, b).

The final objective of this research is to identify and validate tools to support effective urban and territory planning and decrease disaster risk whilst also improving the quality of the alpine cultural landscape. The following section discusses the significance of understanding the history, culture, and tools to describe landscapes, focusing on Italy's unique

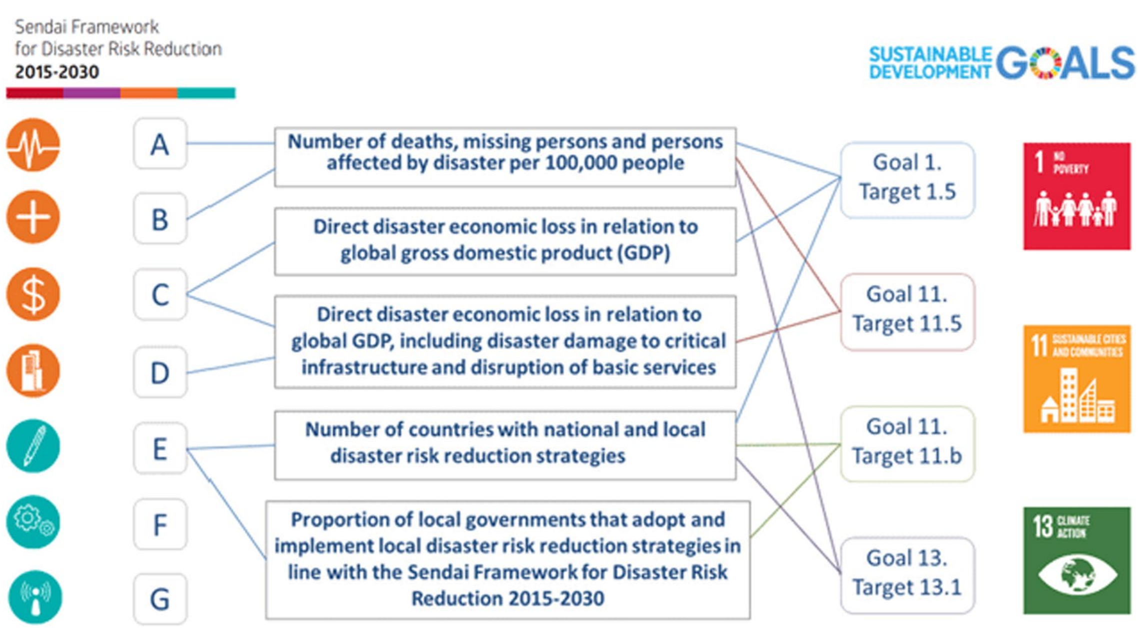

Fig. 1 The scheme shows the relations among SDG targets referred to goal 1, 11, and 13 and Sendai Framework indicators [12]

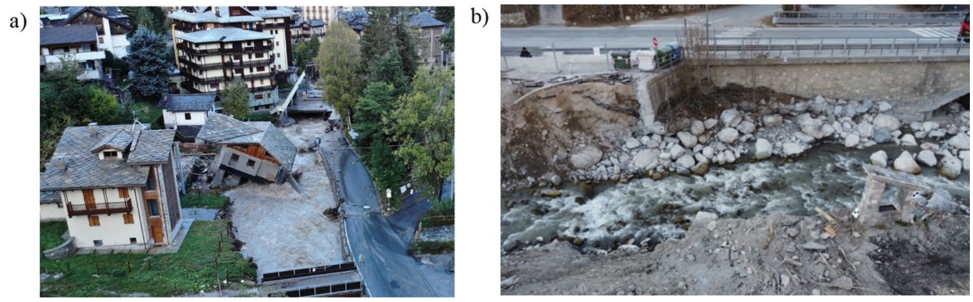

Fig. 2 **a** Image of a flooded building that has become a symbol of the Limone Piemonte 2020 flood [70]. **b** Collapsed bridge in Limone Piemonte from a low-altitude drone image (by authors)

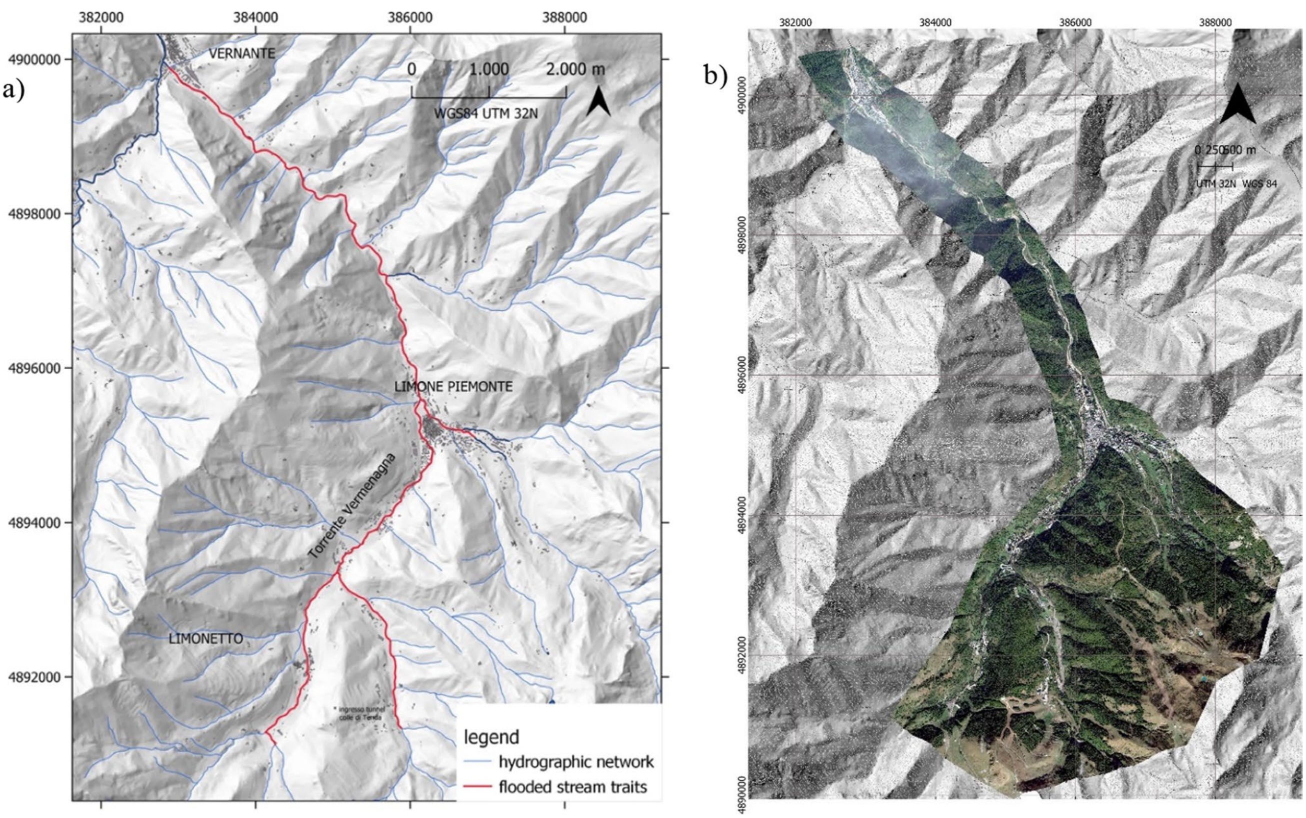

Fig. 3 **a** Map of the area hit from the event in a map derived from regional topographical datasets. The red lines represent the flooded sections of the Vermenagna stream and its tributaries. **b** Coverage of the orthophoto derived from GeoEye-1 satellite image acquired immediately afterwards the event (catalogue ID 10500500B7DD8400)

landscape challenges. It covers the historical debate, the impacts of urbanisation post-World War II (WWII), and modern geomatics techniques that help to assess landscapes following a disaster. Integrating technologies such as satellite remote sensing, UAV photogrammetry, and multi-sensor mapping contributes to rapid and detailed disaster responses and recovery efforts. The third section emphasises the importance of spatial analysis in promoting sustainable development and disaster mitigation using techniques such as satellite remote sensing and UAV photogrammetry. It discusses how geomatics helps to implement and carry out pre-emptive measures through historical analysis and the detection of landscape changes. Multi-sensor surveys that are tailored to specific needs can facilitate post-disaster recovery efforts by providing detailed 3D datasets for damage assessment. The integration of 2D and 3D data allows for both qualitative and quantitative insights to be obtained, aiding in recovery planning by detecting changes in landscape morphology. The fourth section outlines the application of geomatics tools designed to support the EMC phases, focusing on prevention and preparedness, emergency response, and recovery. It utilises historical cartographic data and flood hazard scenarios to identify vulnerable buildings. Satellite and UAV data are employed for damage assessment, with ortho-projection and classification techniques used for image analysis. The recovery phase involves change detection strategies, comparing pre- and post-event elevation models to assess damage extent. This is supported by 3D geometric modelling for detailed analysis of landscape changes and infrastructure damage. The "Results" section describes the historical development of settlements in the Limone Valley, noting their positioning away from rivers and valleys prone to flooding. It highlights the significant increase in the number of built-up areas since the 1960s, particularly in high flood hazard zones. The impact of this urban expansion is evident in the extensive flooding of the Vermenagna stream and its tributaries, leading to repeated damage to buildings and infrastructure, especially those located near riverbanks. The "Discussion" section emphasises the importance of 3D surveying and historical map analysis in identifying flood-prone areas, aligning with existing operational services such as the European Union Copernicus Emergency Management Service (EU CEMS). It highlights the significance of 3D models and orthophotos in improving both the emergency response and recovery phases, advocating for user-friendly geographical information systems (GIS) tools for data utilisation. The "Conclusion" section highlights challenges in terrain morphology and the need for expertise in field operations. It also emphasises the importance of sustainable landscape planning and effective disaster risk reduction efforts.

2 Background

It is only possible to analyse a landscape when its history is known, as well as its peculiarity and how it is viewed by the culture that built it. The first section provides insights into the landscape from the perspective of Italian culture. Then, it is possible to assess a landscape by knowing which tools can be used to describe it. The second section reviews how geomatics can help to assess such risks and survey a post-disaster territory.

2.1 The Alpine border: the Italian development of a transnational landscape

In Italy, the concept of landscape is much different than those of other countries. For example, part of the debate is still linked to the concept of wilderness, expressed in the early essays on the subject written by Ralph Waldo Emerson and Henry David Thoreau [14]. In the Italian national context, this category of interpretation is slightly applicable since «this is the third great work of the ancients that I have seen, and still the same grandeur of conception. A second nature made to work for social objects», as Goethe wrote in his journal ([15], p. 218). In other words, the territory has undergone centuries-long development and collaboration between man and nature, meaning that unspoilt wild places (such as that described in [16]) cannot be found.

The Italian landscape is so peculiar that it has a long history of debate between scholars, designers, and lawmakers [17]. Yet, under the pressure of the overwhelming economic development that occurred during the 1960s, territorial planning tools resulted in weaker-than-normal urban modifications [18]. This resulted in differences between outstanding studies in the academic world (e.g., [19, 20]), anachronistic urban laws by legislators [21–23], and urbanisation by speculators [24].

One bias concerned three different laws regulating landscape [25–27] and one for urban [28] planning that set unintegrated speeches on the same legislative object. They became a legacy of Benedetto Croce's idealistic conception of nature and culture, and this distinction did not allow for the integrated planning and protection of landscapes. Moreover, the new democratic organisation of Italy, the horror of WWII, allowed the private market to build new urban areas to accommodate people who lost their houses during the war and improve economic growth. The issue was an undiscriminated and undisciplined urban sprawl and destruction of natural landscape features [29].

After World War II, the alpine valleys underwent a double alternative process: either the population declined or there was a shift from an agropastoral economy to a loisir economy. Still, their primary income emanated from winter and/or summer tourism [30]. The construction of new infrastructures in many valleys, such as railways or highways to ease connections with France, Switzerland, and Austria, caused significant changes to the landscape. To facilitate the installation, excavations were carried out, and the earth of the tunnels was used to create new terraces. They also facilitated this new urbanisation, exacerbating the phenomenon that was already underway. Landscape can be defined as the shape of the territory produced by a social organisation [31]. Thus, after the decline of traditional organisation, the urban economy succeeded and took on a different landscape shape [32]. On the one hand, settlement shape and typologies changed, and new residential areas invaded river shores. On the other hand, new mobility infrastructures were oversized for valleys.

On the contrary, the historical landscape has a spatial relationship with the shape of the territory, which has allowed human settlements to have great inertia concerning changes [33]. Regarding the relationship between settlements, urban morphology and their location in the territory, extensive literature has shown that it is possible to identify systematic logics for homogeneous areas. In other words, settlements would always be at the intersection of a specific geomorphological condition of the territory and terrestrial or water routes [34, 35], which is one of the key assumptions of landscape archaeology [36].

Rather, traditional knowledge made it possible to integrate agriculture and land practices (i.e., production and care of the landscape). The construction of terraces on the slopes, dams on the rivers, and the planting of forests in areas prone to landslides progressed in that direction [37]. Furthermore, the construction of canals controlled excess water and made the fields fertile. This resulted in a completely waste-free land use. From a contemporary point of view, this territory could have been more productive, but at least it was efficient.

2.2 Geomatics' tools for emergency survey and risk assessment. A brief review

The development of social, economic, cultural, and technological aspects over the last 80 years has changed the organisation of the territory, making it more fragile. From the perspective of sustainable development and the prevention of the disastrous impacts of potentially calamitous events, it is necessary to specialise the processes so that both qualitative and quantitative information regarding the shape of the landscape can be obtained. The most modern combined aerial and terrestrial survey techniques, such as satellite remote sensing, UAV photogrammetry, and focused range-based scanning, enable us to interpret the territory in a complex way. This will enable us to combine and cross-reference data from heterogeneous sources whilst also conducting geoinformation data management.

In the early 2000s, innovations in the geomatics and geoinformation sectors were shared. This introduced many relevant novelties relating to data acquisition technologies, particularly platforms and sensors (ranging from very high-resolution optical sensors installed on satellites to image and range-based terrestrial sensors), and data processing and management procedures. Among other things, multi-scale, multi-platform, and multi-sensor mapping technologies can effectively support the EMC.

The first satellites to use extremely high-resolution geometric sensors were Ikonos (Ground Sampling Distance—GSD = 1 m) and Quickbird (GSD = 0.6 m). These were launched in the early 2000s and aroused great interest from the institutions responsible for the protection and management of emergencies. This is because these very high spatial resolutions have been able to transform the photointerpretation and classification of satellite images, allowing levels of detail to be obtained that were previously impossible. Furthermore, the spectral sensitivity of the sensors outside the visible spectrum made them suitable for semi-automatic processing aimed at deriving information that would otherwise be undetectable and within a quick time frame, which is ideal for emergency response purposes [38].

The consequent evolution has involved the consistent use of satellites with remotely sensed data and this is thanks to the rapidity with which data covering areas affected by disasters can be made available to end users, up to the structuring of infrastructure data services. A relevant example to mention here is the European emergency service of the Copernicus program, with its satellite component represented by the Copernicus Sentinels. With the CEMS service [39], the Copernicus program disseminates and makes geospatial data available in the form of maps and data regarding the impacts of the disaster in a few hours/days after the service activation request (Rapid Mapping component) and also information that supports the risk prevention and assessment phases (Risk and Recovery Mapping component).

Although the Copernicus service has adopted the term rapid mapping for activities conducted using satellite remote sensing, this meaning has been extended to many technologies that adopt rapid data acquisition systems and that use sensors closer to the affected areas. This includes UAV photogrammetry and terrestrial mobile mapping systems (MMS). The combined use of different technologies has been confirmed to contribute significantly to enhanced documenting of the damage, compared to just the nadiral satellite point of view [40, 41].

The integration of different technologies is considered to be effective and advantageous, both in emergency responses, immediately after the disaster, and in the emergency recovery phase. The latter requires more information refinements than the first response and substantially corresponds to the research described in this paper. UAV photogrammetry is now being increasingly adopted to address the critical issues associated with timeliness and high spatial resolution requirements, to add oblique images to the nadiral perspective, and ultimately to limit the permanence of operators in risk areas as much as possible [42, 43]. Photogrammetric data processing workflows that are based on structure-from-motion (SfM) and multi-view stereo (MVS) algorithms are being refined to provide effective support to requests for rapid damage documentation, risk assessments, and usability in sites affected by disasters, as well as the rapid processing and sharing of operational data [44, 45]. UAVs that are equipped with on-board Global Navigation Satellite System (GNSS) sensors have increasingly demonstrated their crucial role in facilitating remote observations of the site, planning rescue operations, collecting qualitative data, and generating metric products such as orthophotos and digital surface models (DSMs) at a very large scale. These DSMs can be used to derive 3D models that possess high-resolution textures and accuracy, even down to a few centimetres [46]. The impacts of a better GSD in better-discriminating damage levels to affected buildings have also been demonstrated since the separation between minor and significant damage grades is only possible when images containing a GSD of approximately 0.1 m are available [47].

Moreover, to reduce the need for topographic measurements on the ground, which lengthens the time needed to acquire the data required to control the final results (which can be critical in rapid mapping emergency scenarios), studies examining the possibility of improving the performance of inertial measurement unit (IMU) platforms and on-board GNSS receivers typically adopt direct photogrammetry approaches [48, 49]. An example here is the real-time estimation (RTK—Real Time Kinematik) of the position of images or adopting a post-processing approach (PPK, Post Processing Kinematik) [50].

It is important to highlight that it is not only optical sensors in the visible part of the spectrum that can be effectively used in the emergency mapping domain but also multispectral sensors that are sensitive to the infrared sections of the spectrum. UAV multispectral sensors [51] are generally limited to the Near-InfraRed (NIR) section of the electromagnetic spectrum. By contrast, satellite sensors cover a more comprehensive range (including short-wave infrared bands), providing a higher spectral resolution. Multispectral imagery increases the capability of discriminating different spectral signatures and, consequently, the thematic accuracy of the derived information. More specifically, it is possible to (semi) automatically classify optical images to assign a cluster of pixels to a specific information class (e.g., flooded areas [52], burnt areas [53], affected buildings) and, in emergency response applications, to estimate damage levels whenever possible. Pixel-oriented, object-based, and unsupervised or supervised classification algorithms can be applied, depending primarily on the images' spatial resolution. Nevertheless, deep-learning classification algorithms based on convolutional neural networks (CNN) are being increasingly employed in emergency mapping to perform semantic segmentation on both satellite images [54] and UAV photogrammetric datasets (in the latter case, possibly exploiting the related point cloud [55]).

Active radar sensors can also be exploited in the emergency mapping domain, especially to overcome the intrinsic limitations of passive optical sensors (i.e., the non-usability of images in the presence of cloud coverage), which is especially relevant to flood events in tropical areas. Synthetic Aperture Radar (SAR) sensors can automatically and effectively identify flooded areas and monitor the evolution of flooding events [56].

Regardless of the sensors, platform, and scale employed, the identification of the main affected areas and damage to infrastructures is based on multitemporal analyses in most response applications. This typically involves comparing the situation before and after the event. For example, in the case of flooding, the availability of the pre-event data enables authorities to clearly distinguish between flooded areas and average water areas [57]. Generally speaking, change detection algorithms can be applied to identify changes that have occurred between two epochs and at global and local scales, which supports different phases of the EMC. Furthermore, different algorithms can be applied to different types of geospatial data, exploiting consolidated approaches and cutting-edge solutions based on artificial intelligence methods [58]. When high-density and high-precision DSMs (in the form of point clouds) are available, multi-temporal change detection can be conducted to detect even millimetre-level changes, which is extremely beneficial in evaluating post-event damages (e.g., for structural building analyses in case of earthquakes) [59, 60]. Moreover, the pre-event dataset also plays a critical role in ensuring preparedness and response activities. Guidelines, best practices, and regulations are also important in supporting and encouraging these pre-event mapping activities, prioritising areas at higher risk, protected areas and cultural heritage sites. A number of emergency mapping applications based on the geospatial data mentioned above are now being operationally adopted around the world. This is evident in the recommended practices shared in the Knowledge Portal of the United Nations Office for Outer Space Affairs (UN-SPIDER) [61].

3 Material and methodology

When pursuing sustainable development and mitigating potential calamities, it is imperative to spatially analyse relevant processes in order to yield qualitative and quantitative insights into landscape morphology. Leveraging contemporary techniques such as satellite remote sensing, UAV photogrammetry, and focused range-based scanning facilitates the acquisition of a nuanced interpretation of the terrain by integrating diverse data sources, thereby encompassing geo-information data management (Fig. 4).

According to the EMC, the first step in responding to an emergency is to prevent the emergency or prepare for it in advance. Geomatics can enable researchers to collect and analyse previous surveys and maps in order to make comparisons and detect changes over time. The first approach highlights the historical depth of the landscape. Meanwhile, the first step in studying landscape is to assign dates and signs and establish meaningful historical thresholds [62]. From a semiology perspective, signs can be defined as any objects from which clues, inferences, or knowledge that is conventionally assumed to represent something can be drawn, and traces refer to visible or even intangible signs that serve as documents, testimonies, echoes, or memories of a fact, situation, or condition. For example, the presence of ancient country chapels and paths in now inaccessible areas—objects that are difficult to interpret in the context of contemporary territorial organisations—reveal a history that needs to be reconstructed. The meaningful historical delimitation is not arbitrary but rather derives from the research questions and themes. Spatial analyses and related analytical comparisons (Sect. 4) of data obtained from cartographic sources related to the threshold made it possible to determine when today's buildings were constructed. The use of photos, paintings, engravings, and other similar media when depicting landscape features adds tangible meaning to the signs found on historical maps. As an intermediate product, a multi-temporal map depicting the evolution of the urban fabric can be created. Using this as a starting point, a first qualitative analysis allows us to establish constants in settlement patterns by describing urban morphologies. Once georeferenced data are obtained, quantitative information can be acquired, which is necessary to identify any buildings that are possibly involved or vulnerable to damages from the flood event.

To support the emergency recovery phase, multi-sensor and multi-scale geomatics surveys have been carried out. This is because the choice of the sensors and nominal map scale was tailored to suit the specific needs of each area of interest. The planned workflow aligned with consolidated approaches from experiences and literature, the references of which are presented in Sect. 2.2. Firstly, a small-scale analysis based on satellite images was used to identify hot spots. Secondly, more accurate UAV photogrammetric flights that facilitate very high spatial resolutions (GSD up to a few centimetres) of the main affected areas can be used to assess damages to buildings and infrastructures. Subsequently, a series of high-resolution terrestrial range surveys can be performed to provide a more detailed 3D dataset pertaining to the network infrastructure. In turn, this increases the thematic accuracy of the damage assessment.

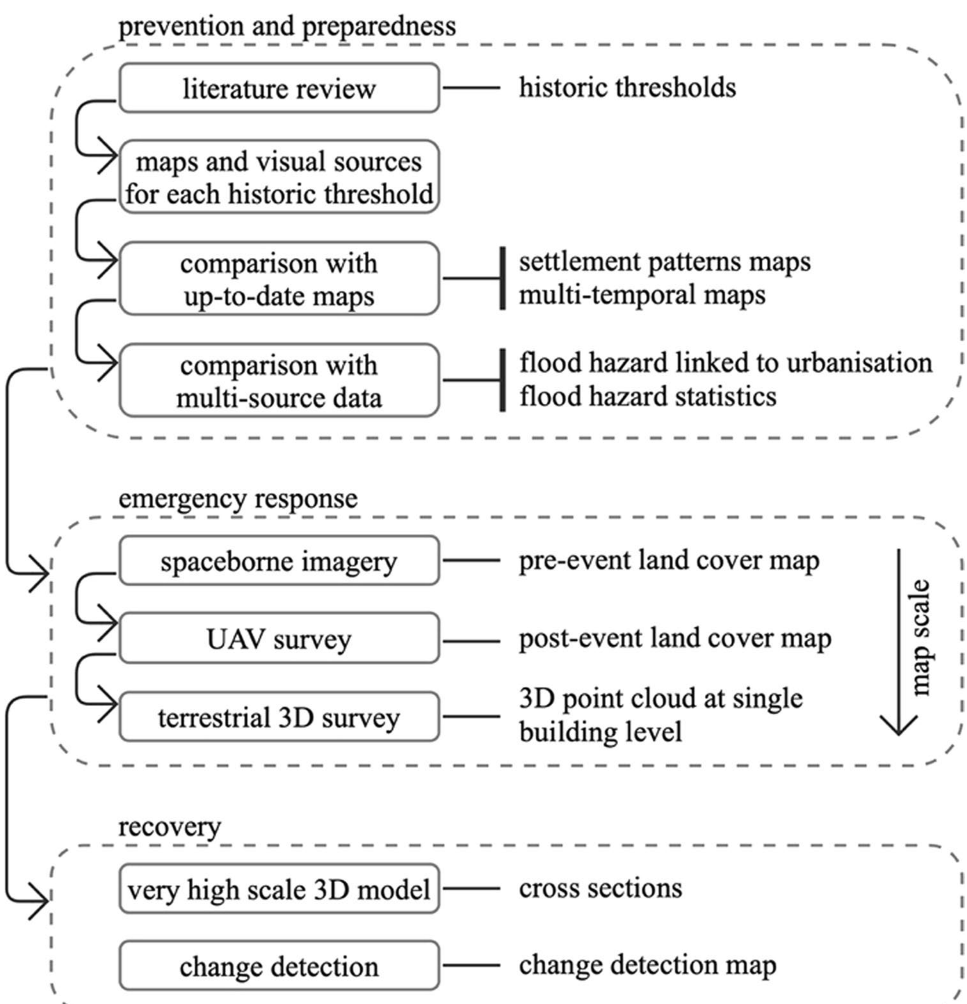

Fig. 4 Flowchart of the methodology: geospatial data supporting the different phases of the EMergency Management Cycle

While the first analysis and processing of satellite data were designed to identify the areas most affected by the flood event based on 2D products (e.g., image classification and visual interpretation), the following analyses are primarily based on 3D data (or 2.5D derivative products), since UAV photogrammetry facilitates the extraction of 3D information in the form of point clouds. Therefore, it is possible to gain insights into the damaged areas and conduct an impact assessment of the landscape. The first emergency mapping effort was qualitatively based on operator skills and experience in recognising soil classes. At the same time, the latter, with a better ground resolution, is helpful for developing a recovery plan.

Detecting changes is crucial for the EMC recovery phase. Firstly, differences in elevation can be analysed to identify areas that suffered damage during the flood event. Secondly, a series of sections along the valley can better represent differences between pre-and post-event conditions.

4 Case study: flood events in north-western Italy

Surveys and analyses were carried out after the disastrous flood event that occurred on 2nd October 2020. The following section attempts to concretely apply support to the EMC using geomatics tools, providing the research with a robust structure.

4.1 Prevention and preparedness

The literature review identifies three significant historical phases when studying the relationship between settlements and natural hazards in the Limone Valley. It is also important to highlight the relationship to the Sect. 2.1. The time frame identified for Limone Piemonte also applies to many other valleys in the Alpine arc and the Italian Apennines. The first phase corresponds to the years up to the post-WW II period. Reference Cartography was identified as a reference map produced by the Istituto Geografico Militare (Military Geographical Institute) in 1960. This was presented in raster format at a map scale of 1:25000 (Geoportale Nazionale). The contemporary period was divided into two phases from the 1960s to the present day. For the period between 1960 and 1990, the Carta Tecnica Regionale Numerica (CTRN) updated to vector format in 1991 at a scale of 1:10000 (Geoportale Piemonte, 2020) was used, while the Base Dati Territoriale di Riferimento degli Enti 2019 (BDTRE) was the topographical multiscale dataset archive used to study development over the last 30 years [63]. The BDTRE was used as the reference data, to which a semantic attribute was added to indicate the year of the source and, thus, the presence of the buildings in the area on that date. By managing the reprojection of the reference systems used in the different epochs for the different cartographic products, it was possible to highlight the buildings already present in 1960 and 1995 using the most recent dataset (Fig. 5a) [64].

In Fig. 5a, the built-up areas have been divided according to the period of occurrence in the cartographic sources. Additionally, some data from the Flood Risk Management Plan, established by the European Directive 2007/60/EC [65], was used to map and identify buildings vulnerable to experiencing a possible flood event. In particular, datasets of flood event hazard scenarios were used to create the map presented in Fig. 6. Furthermore, a GIS environment could be established using the slope raster dataset as a base map. These portions of land could be affected by flooding and have been labelled as having a high, medium, or low probability of water disaster events. According to which built-up surfaces in Limone Piemonte insist on areas of known flood hazard, a series of graphs (see Fig. 7a–f) presents information pertaining to the surfaces and percentages of buildings classified according to the construction period, which is compared to the cross-reference probability of being exposed to flooding (NULL probability is presented in grey, medium probability in orange, and high probability in red).

4.2 Emergency response

4.2.1 Analysis of spaceborne images classification

The multi-spectral satellite image used was acquired by the GeoEye-1 satellite at an off-nadir angle of 23.3°, consisting of three spectral bands in the visible range of the electromagnetic spectrum (red, green, blue) and one in the NIR

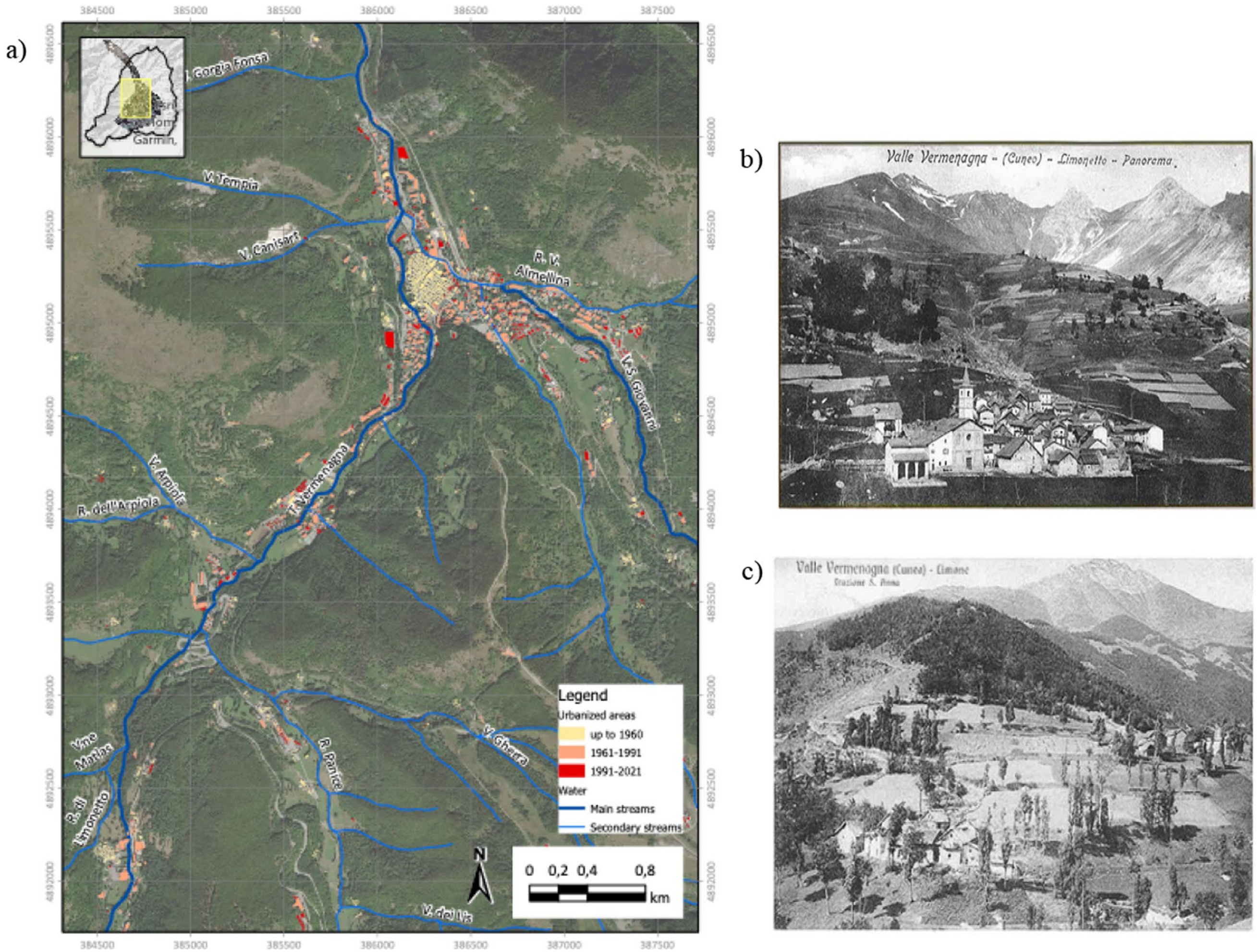

Fig. 5 **a** Excerpt map showing the evolution of the built environment according to the triple time frame (before 1960, building development between 1961 and 1991, building development and sprawl between 1991 and 2019), original scale datasets 1:10,000 and 1:25,000 [64]; **b** The top photo shows the village of Limonetto in 1920, in a concentrated core along a ridge, with a small valley with alluvial deposit material behind it, consolidated with a forest. Above the hamlet and on the other side of the valley are cultivated fields ([68], p. 42). **c** In the photo below, the southern slope is cultivated with terraced fields. Trees between the fields help consolidate the land, as well as mark the property line. On the northern slope are white spruce trees ([68], p. 43)

part, with a nominal GSD of 0.5 m. This acquisition was made on 5th October, 2020 at 10:27 Coordinated Universal Time (UTC), three days after the flood event. This is because there were better atmospheric conditions (minimal cloud cover over the affected area). The satellite data were a second-level product, thus already radiometrically corrected. However, further geometric corrections, such as ortho-projection, needed to be properly georeferenced.

To carry out this operation, the 2011 Digital Elevation Model (DEM) made available by the Piedmont Region geoportal was employed as the terrain model. This model is characterised by a geometric resolution of 5 m and an altimetric accuracy that varies from 0.3 m to 0.6 m, depending on the characteristics of the territory (flat and regular areas have a better accuracy). As for the Ground Control Points (GCPs) and Check points (CPs), these were acquired with about 5 cm accuracy during a survey campaign through a network real time kinematic (NRTK) approach. Thus, GNSS receivers were connected to the national network of permanent GNSS stations. Image ortho-projection was performed using ArcGIS Pro software via a non-parametric method, namely rational polynomial coefficients.

The next step was a value-added information extraction process that resulted from three primary operations, namely image segmentation, analytical clustering, and supervised classification. The output of each operation is the input for subsequent operations, where the goal is to produce a map that represents the different thematic information classes. Training forests, buildings, riverbeds, meadows, buildings, and breakdowns, which are the most sensitive areas for distress assessment. By checking the preliminary results, multiple classes representing a single entity (i.e., the same category of

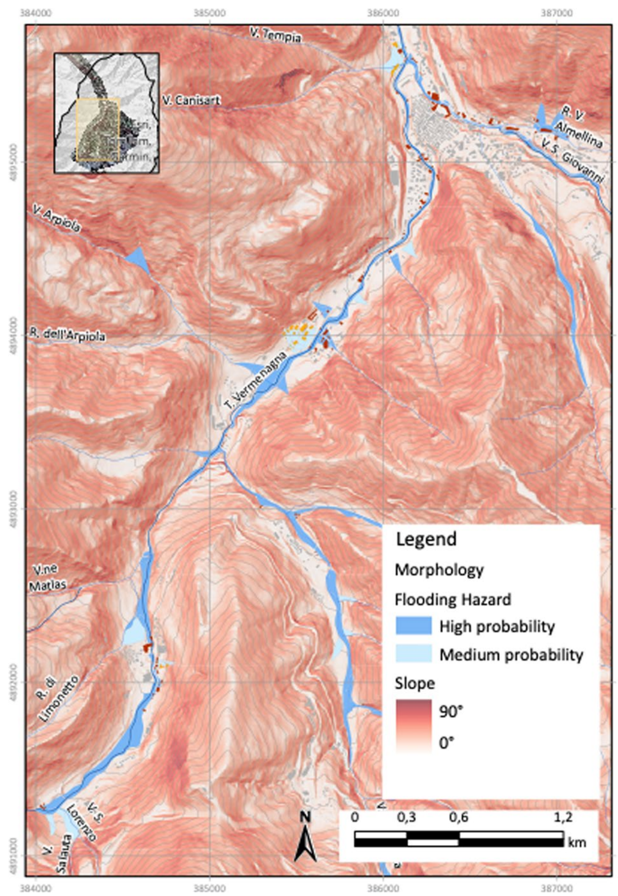

Fig. 6 Excerpt of the flooding hazard map in the municipality of Limone Piemonte; buildings not affected by flood are in gray while building in red and orange refer to hazard degree, rivers are blue polylines, while for flood areas, dark blue ones have high probability of being flooded, light blue ones have medium probability (original datasets 1:10,000 and 1:25,000) [63]

shaded and unshaded surface) were merged. Subsequently, the classification results were further refined. First, the edges of the class boundaries were smoothed (since the classification is based on raster data). Then the image was filtered using tools that assign isolated regions consisting of a few (or single) pixels) to the spatially adjacent thematic class.

Figure 8 presents the results of the semi-automatic classification. It is evident from this figure that photointerpretations have a considerable advantage when it comes to estimating damage (potentially by comparison with pre-event data), which is considerably more time-consuming and must be carried out manually by image analysts. With regard to thematic accuracy, a manual classification (considered as ground truth) of the buildings and breakdown classes was compared with the automatic classification in two test areas. The result was positive for the breakdown class and the non-densely built-up test area (correspondence of correctly classified damaged surface around 80%, false positives approximately 20%). The automatic classification for the building class proved to be less satisfactory, particularly in the more densely built test area, which is affected by shaded areas (although the correspondence of correctly classified surfaces stood at 89%, and false positives were 45% in one case and 60% in the other).

4.2.2 Integrated 3D survey from UAV photogrammetry

Starting in November 2020, UAV photogrammetric surveys were conducted to promote damage documentation and related water supply restoration activities in the Limone Piemonte and Vernante municipalities located along the Vermenagna River. The flights were thus designed to cover the entire area shown in Fig. 3a and the sectors presented in Figs. 9 and 10, with a buffer strip of on average 80 m along the river and State Road No. 20, in order to produce ortho-imagery and DSM products with accuracy suitable for a 1:500 nominal map scale (expected precision of final products below 10 cm and accuracy lower than 20 cm (at 95% probability). A DJI Phantom 4 RTK UAV platform was employed. This platform is equipped with a 20-Mpixel resolution complementary metal–oxide–semiconductor (CMOS) sensor and a multi-frequency and multi-constellation RTK GNSS receiver. An in-depth examination of the positional accuracies of the 3D was also conducted based on different image orientation strategies. The findings confirm that, if an RTK-enabled platform and an appropriate workflow are followed, the use of ground control

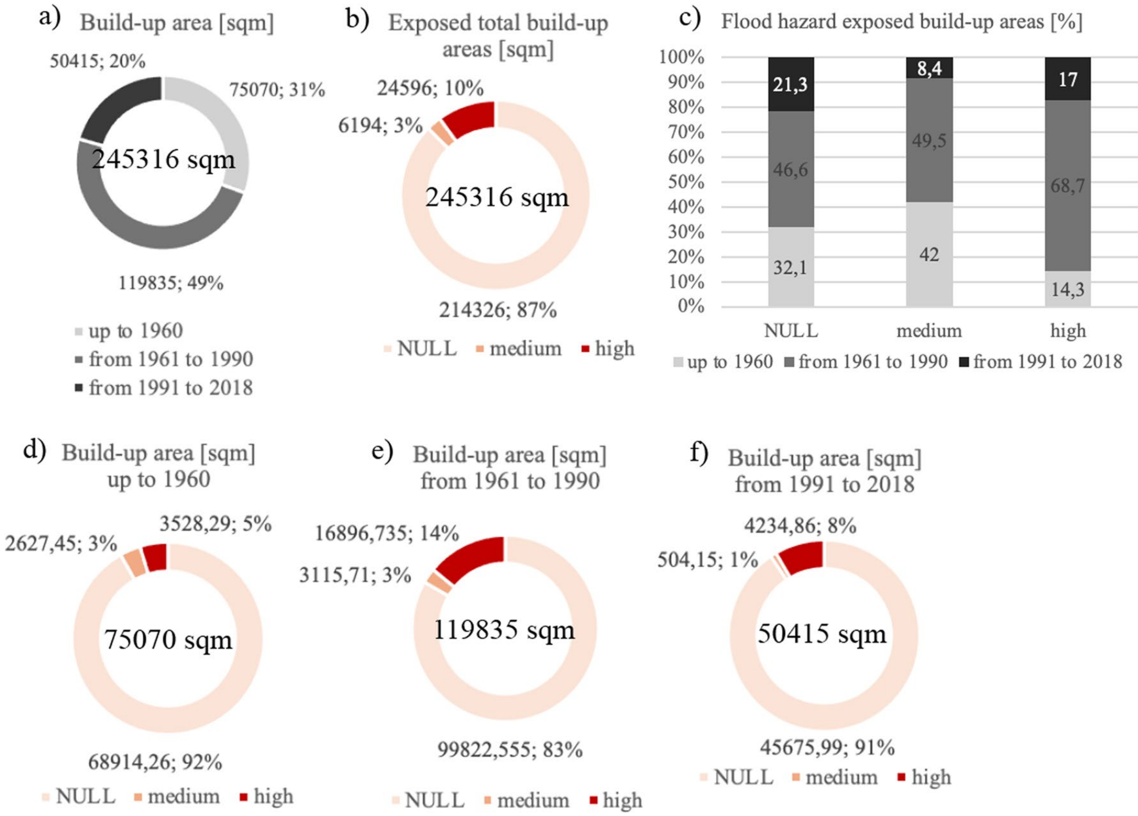

Fig. 7 **a** Summary graph of the built-up area on the ground for the periods considered (percentages of the total built-up area as at 2019). **b** Summary graphs of built-up areas exposed to different hazard level of flooding events for the time periods considered. **c** Built-up areas exposed to different classes of probability of a flood event compared to the total. **D**—**f** Periods of built-up area development for each exposure class to a flood even (graphs created by the authors)

points (GCPs) does not significantly improve the overall positional accuracy [23]. This is also due to the integrated use of nadiral and oblique poses, which make the bundle adjustment of the photogrammetric process more robust [67]. The process ultimately reduced the time required to ensure acquisition compliance using the rapid mapping approach (Figs. 9 and 10). To conclude the topic of mapping via UAV photogrammetry, Table 1 compares the quality parameters of flights processed in standard mode (i.e., with the aid of GCPs) and a flight oriented via direct georeferencing.

The UAV image acquisitions were combined with higher-resolution terrestrial surveys of hotspots to monitor infrastructures that are as important as they are fragile (an example of a comparison between different resolution aerial products can be seen in Fig. 11). In order to facilitate more accurate documentation of damages, an articulated series of laser scans using a Cam2 Focus3D Terrestrial Laser Scanner was acquired in the area of the collapsed parking lot and bridge in Limone Piemonte (via Cuneo). A photogrammetric flight at the altitude of about 20 m above the ground from DJI Mini Mavic micro-drone was also planned in this area to obtain orthophotos and DSMs with very high accuracy and resolution using a multiscale survey strategy (Fig. 12). These data were employed after the event in the Limone Piemonte Municipality to restore destroyed bridges and roads.

4.3 Recovery

4.3.1 3D Models and change detection analysis

After this process has been performed, information regarding the extent of the disaster is clear. Firstly, to assess the damage that occurred during the event in more depth, a change detection strategy can be employed, which involves

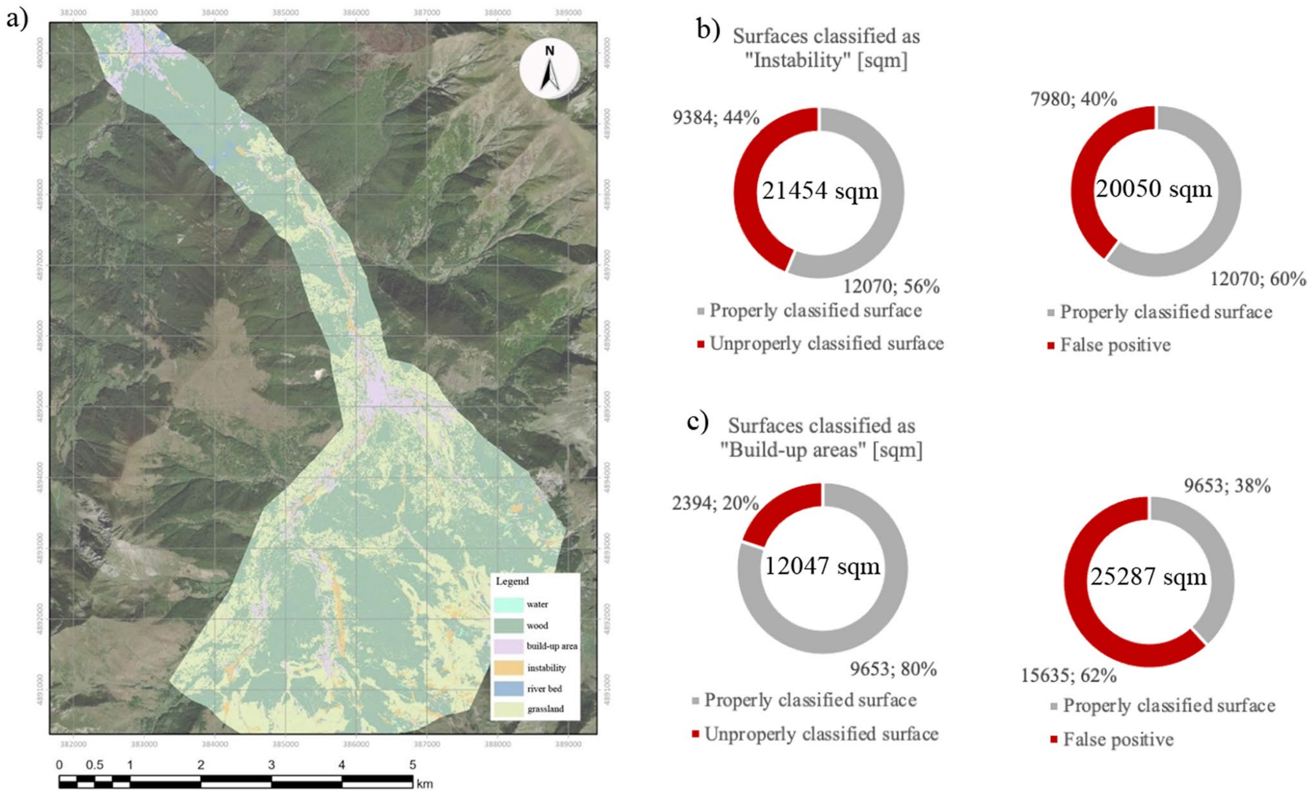

Fig. 8 **a** Land use classes have been derived from an automatic classification of satellite orthoimages, with an estimated scale close to 1:1000. In the resulting map, rivers are depicted in blue, forests in dark green, meadows in light green, buildings in purple, and flood and landslide disruptions in orange. The estimated planimetric accuracy is approximately 1 m. ([59], p. 65). **b**, **c** The graphs show the accuracy of the classification for the "instability" and "build-up areas" classes (graphs created by the authors)

identifying changes that occur on the land or built heritage using automatic approaches. In this case, the analysis was based on 2.5 D surfaces. Therefore, comparing the pre-event DEM by the Piedmont Region with the DSM generated by the UAV photogrammetric process is helpful. As mentioned above, they have different features (i.e., resolution and accuracy) due to different final scales and primary purposes.

The elevation comparison was performed in the GIS environment through a subtraction operation between the two elevation models. In other words, the DEM was subtracted from the DSM (Fig. 13a, b). This operation results in positive values for buildings and vegetation, and negative values for eroded surfaces. The final product is a map on which areas with lower elevations than the conditions recorded before the event are represented in gradations from yellow to red. These represent part of the territory where damage has occurred.

After analysing the textured 3D geometric mode derived from the photogrammetric process, creating architectural scale section profiles, and projecting representations on vertical planes, this change in the landscape becomes even more evident. A textured 3D geometric model was derived from the photogrammetric process using a drone to acquire images and a survey of GCP. Sections at a scale of 1:100 (Fig. 14a, b, and c; and Fig. 15a, b, c) were created on the post-event DSM (accuracy 0.05m) and the DTM (accuracy 0.60m), representing the pre-event conditions. Subsequently, they were combined so that comparisons could be made between the two investigated cases. These products, characterised by geometric resolution and centimetre accuracy, quantify the significant changes suffered by the land and the extensive damage caused to the built environment.

5 Results

Before 1960, buildings were clustered in well-defined cores, and routes were halfway from the river. From Vernante to Limone Piemonte, the borgate (an Italian name for hamlets) are located at the intersection between this route and small streams: Tetti Salet, Tetti Mariné, and Tetti Mezzavia. Going in a southerly direction from Limone Piemonte

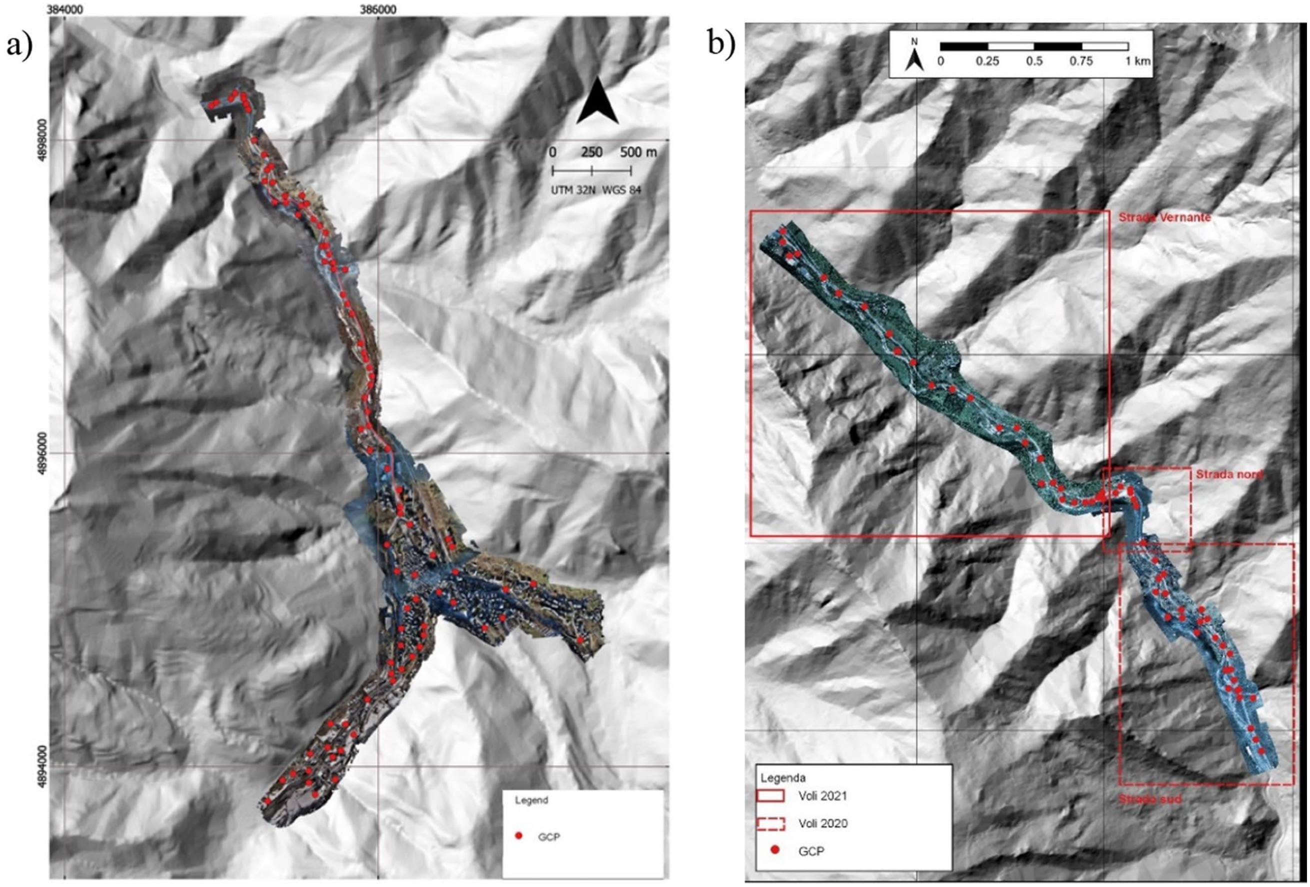

Fig. 9 **a** The area of the center of Limone Piemonte and the area directly downstream have been mapped through 7 different flights, mosaicked in the orthophoto shown. The map also highlights the measurement of GCPs which were observed with the ground-based GNSS RTK technique to validate the on-board RTK strategy (map created by the authors). **b** the map representing the tiled orthophotos of the municipality of Vernante demonstrates how the flights coverage was planned both based on the flight time ability of the UAV, but also, and in some cases above all, based on the morphology of the valley (map created by the authors)

to the highest borgata in the valley, all cores are located at the intersection between the halfway route and the ridge line, starting with Limone Piemonte itself, Tetti Mecci, and Limonetto. All of these cores are distant from the river and also from the base of the small valleys, which are loaded with snow in winter, and rain in spring and fall. As documented in some historical photos (Fig. 5b, and c [68]), incoherent deposit materials accumulated in these valleys, but were consolidated through planting and managing forests. After World War II, new settlements were built in the Paleoalveum of the Vermegnana River (Fig. 16), which is now partially lithified with control works (such as levees and barriers) when not silting watercourses in tunnels. This development also has changed the soil type in the area: there are no longer meadows but rather artificial impermeable materials.

As presented in Fig. 7, there was a significant increase in land area between the 1960s and 2019, indicating that the land area occupied by built-up areas has more than tripled during this timeframe. This fig. is quite interesting, even considering the ground surface area alone. Between the 80s and 90s, new buildings (including hotels and residences) settled on a multi-store building typology of up to 8 -10 floors above ground. Thus, the fig. is quite impressive.

The graph for Fig. 7 shows the percentages of built-up areas on grounds exposed to flood hazard in comparison to the total. Moreover, it shows that 2.5% of the built-up area is exposed to a medium flood probability, while 10% is exposed to a high flood probability. In the graph of Fig. 7, the built-up areas have been separated based on the period of occurrence in the cartographic sources. This graph also shows the probabilities (in percentages) of being exposed to flooding (low, medium, high). It is evident that the city has developed a number of high flood-hazard areas since the 1960s. Interestingly, more than 58% of the medium probability zones (representing 2.5% of the entire ground area) were constructed after 1961 (49.5% + 8.4%). The built-up areas exposed to high probability turned out to be 10% of the total, and, of those, more than 85% were occupied after 1961.

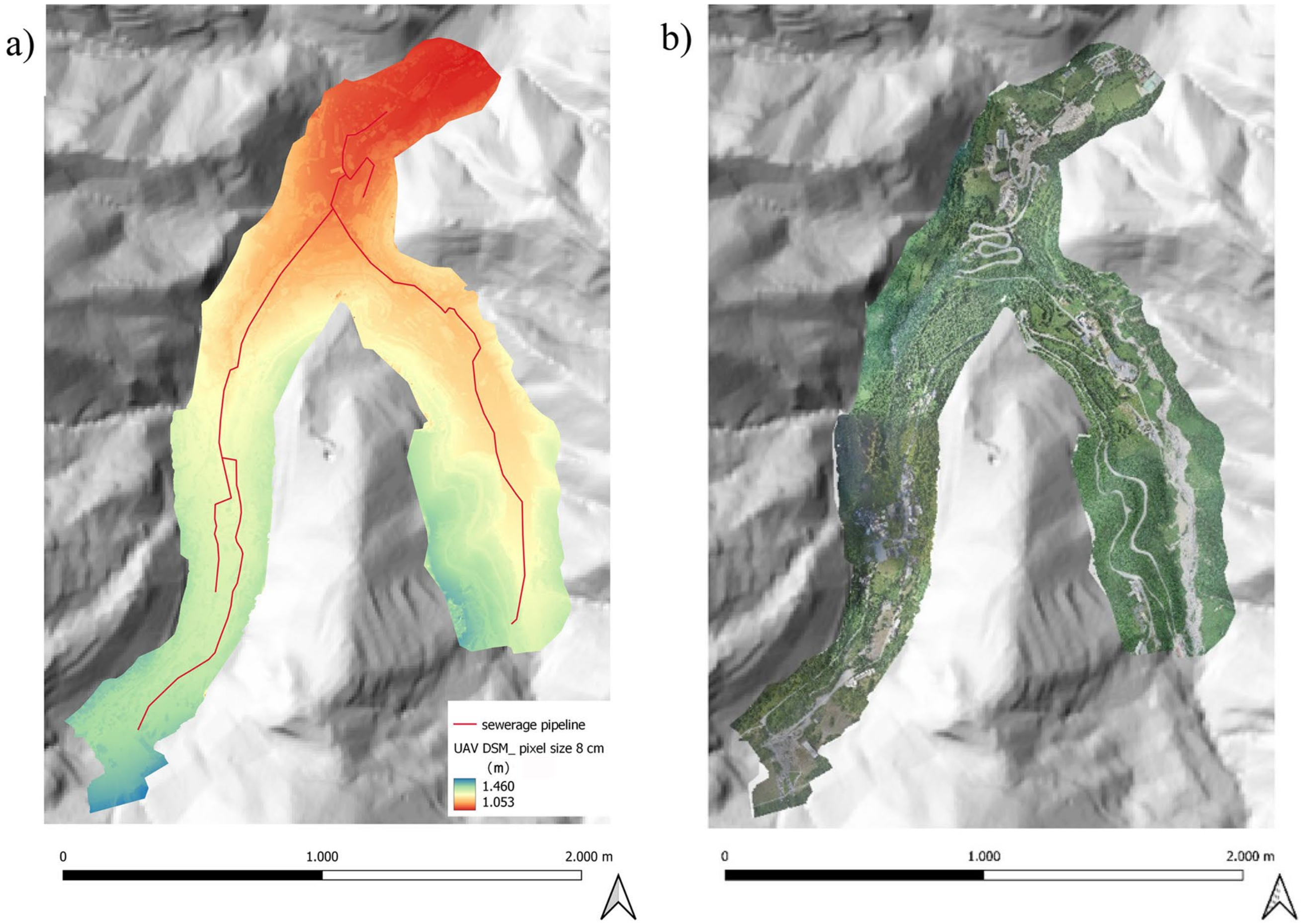

Fig. 10 **a** DSM of the same area, showing also the sewer pipeline whose path has been derived from the cadastral map in order to contribute to the correct plan of UAV flights (map created by the authors). **b** Mosaic of UAV orthophotos in the area reaching 1400m a.s.l. Here, the valley is divided into two parts: to the west, the Limonetto valley with the ski plants largely damaged, and to the east the Rio Panice valley, also with a village damaged by the flooding of the same name stream (map created by the authors)

Table 1 Comparison among accuracy values represented by RMSE in flights processed using a standard approach and direct georeferencing, enabling to save time acquisition

	Flying altitude (m)	GSD (cm/pixel)	GCPs RMSE (cm)	Cps RMSE (cm)
Area 1	87	4.40	1.53	4.00
Area 2	95	2.37	1.60	2.49
Area 3	117	2.91	2.98	6.60
Ares 4	120	3.04	3.51	7.36
Area limone centre (direct georeferencing)	108	2.97	2.53	4.69

A quick visual inspection of the satellite classifications in Fig. 8 highlights the extensive areas of flooding around the Vermenagna stream and its tributaries, confirming that the damage to buildings and infrastructures was concentrated on extremely vulnerable areas, exactly as predicted on the flood hazard map. The roads abutting the river are located in a highly vulnerable area, and repeated damage over time has rendered its recovery unsustainable. The entire road network is at a high risk of experiencing disruption, while the most damaged or wholly destroyed buildings are located near the riverbanks. This results in different soil and a widening of the riverbed.

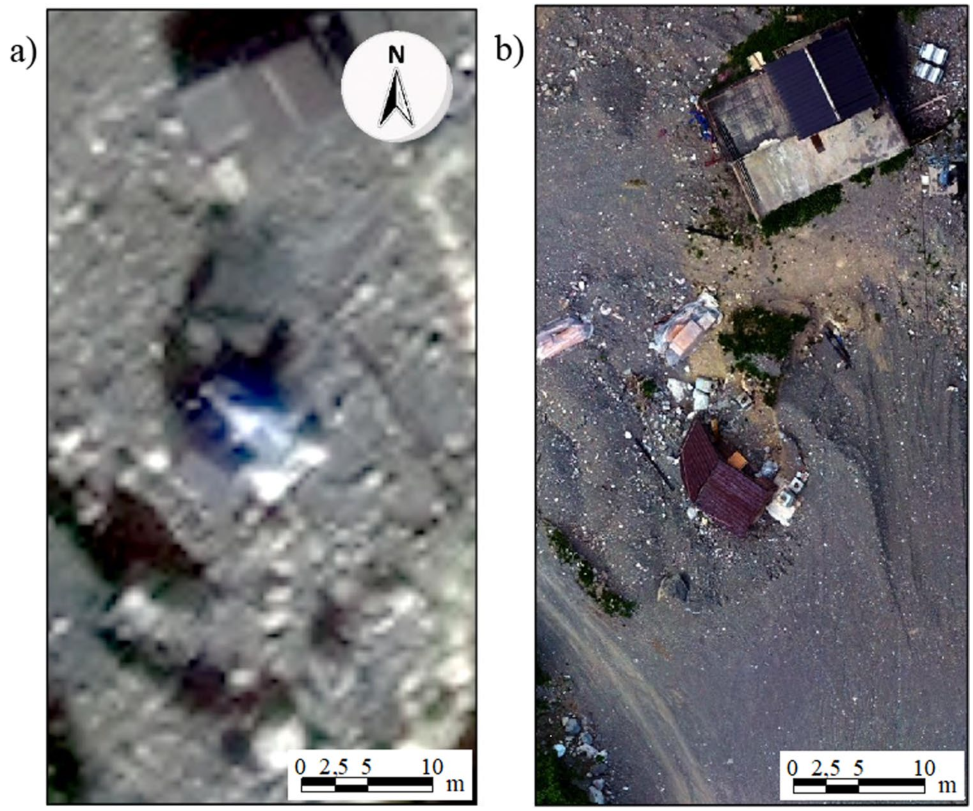

Fig. 11 Qualitative comparison between GeoEye-1 satellite orthophotos (**a**) and drone orthophotos (created by the authors). **b** over a damaged Limonetto area

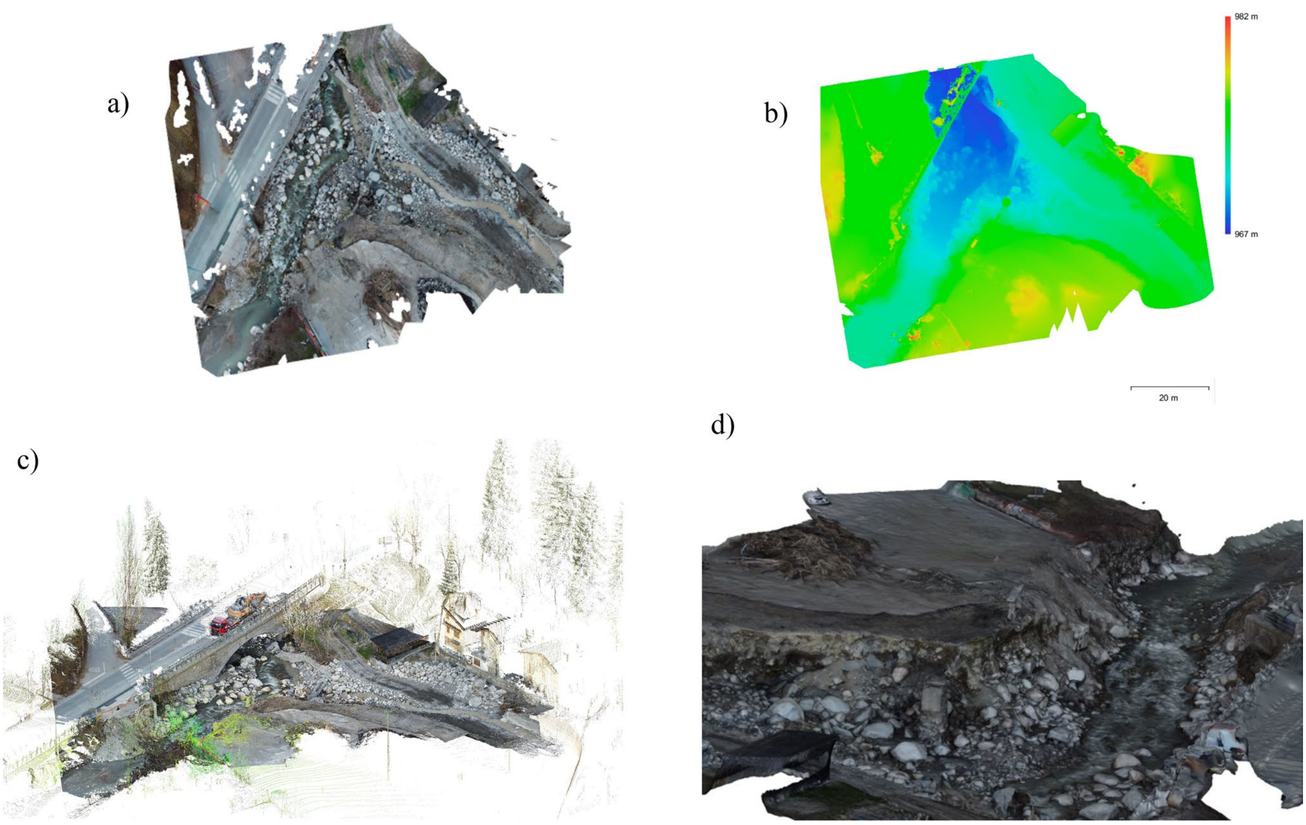

Fig. 12 **a** and **b** respectively orthophoto and DSM derived from a very low altitude UAV photogrammetric flight (resolution 2.6 cm/pixel, points density: 0.148 points /cm.^{2}); **c** and **d** respectively LiDAR point cloud and textured 3D (created by the authors)

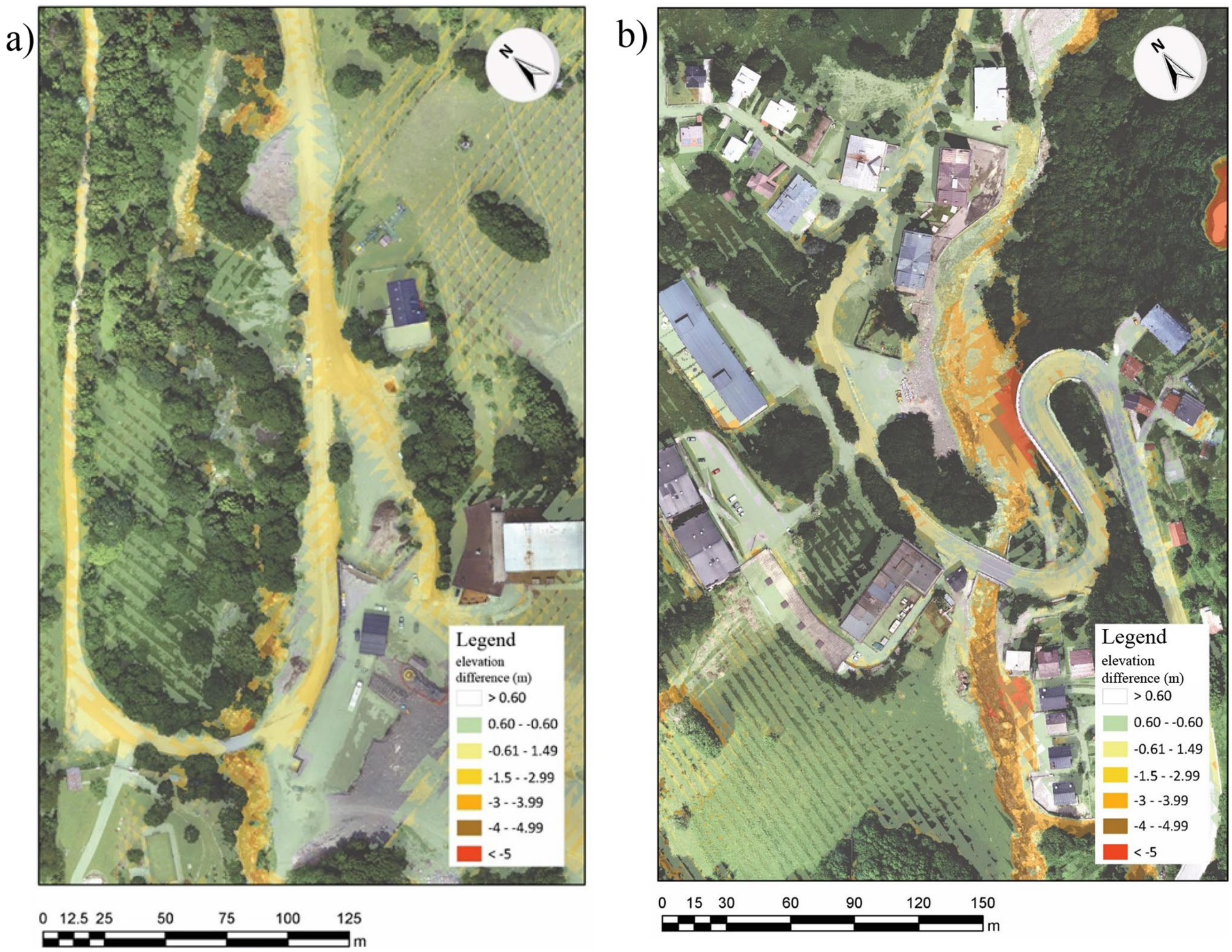

Fig. 13 **a** Elevation difference between elevation models: Post-event—pre-event (Limonetto); **b** Elevation difference between elevation models: Post-event—pre-event (Tetti Mecci) [59]

6 Discussion

The 3D surveying activities carried out to document and map the post-flood situation in the area of Limone Piemonte, combined with the analysis of the evolution of built-up area based on historical technical maps, highlight areas of recent urban development (in the 1960s-1990s, especially after the 1990s) that have a high risk of damage in the case of flooding. This outcome highlights the importance of the preparedness phase, enabling us to predict the areas that are at risk for specific hazards and facilitating more sustainable development of Alpine territories in accordance with the 11th pillar of SDGs.

The proposed methodology aligns with the one adopted by existing operational services (such as the Mapping component of the EU CEMS), with one module specifically focusing on the response phase after the event and one focusing on risk and recovery mapping before the event. With regard to the response phase, CEMS is now adopting a multi-platform and multi-scale approach, as highlighted in this paper. In other words, a wide-area, satellite-based damage analysis was performed to identify and map hotspots in more detail using UAV photogrammetric acquisitions. Both techniques have been found to be suitable for delineating the damages in affected areas during the first response phase and for performing in-depth analyses that are necessary for evaluating the extent of the damage. In turn, this enhances efforts to protect and preserve cultural and natural heritage in alpine areas (SDG target 11.4).

Moreover, 3D models (in the form of point clouds or DSMs) and orthophotos are vital products in the emergency response and recovery phases, demonstrating their intrinsic sustainability and usefulness for different applications.

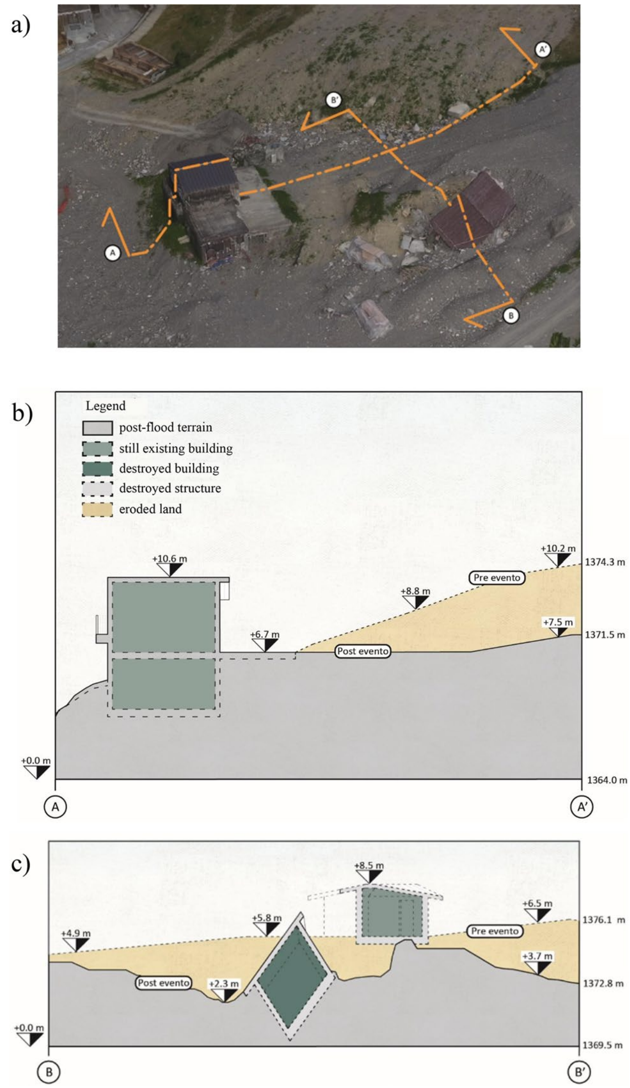

Fig. 14 **a** 3D textured geometric model of the Limonetto area (21/06/2021) and section lines; **b** Section AA′, original scale 1:200; in gray is the post-flood land in section, the still existing volumes are in light green while the destroyed volumes are in dark green and light gray, the eroded land is in yellow; **c** Section BB′, original scale 1:200 [59]

The availability of dense geospatial information that represents the new configuration of the post-disaster landscape can be critical for effectively managing the landscape itself. In fact, it is both a crucial knowledge source for the new arrangement of natural and anthropic elements related to landscape and a key tool in feeding operational tools for the public administration bodies. This process is conducted in accordance with SDG 13, as this goal focuses on combatting climate change and its impacts by promoting mechanisms that raise the capacity for effective climate change-related planning and management.

Data usability is one of the most significant issues related to the products derived from geomatic acquisition techniques and connected geoinformation processing. This is both due to the weight of the files and the need for users to have the software and skills required for visualisation and management at their disposal. This reasoning also pushes researchers to develop adequate and readily available tools that can be used to increase the diffusion and correct use of data in the direction of user-oriented webGIS solutions, or even a digital AMS (asset management system) platform [69]. In the post-emergency documentation case of Limone Piemonte, the recipients were the province water management society (ACDA—Azienda Cuneese dell'Acqua) and the municipality. Here, the archive of documents delivered included the orthophotos and DSMs of all areas, which were created using different resolutions to ensure that the corresponding products were used in a more versatile way. The orthophotos were designed with resolutions (GSD) equal to 3, 6, and 12 cm, while the DSMs had resolutions equal to 6, 12, and 24 cm.

In 2020 (and the first months of 2021), when local authorities were busy restoring the usability of roads and infrastructures, the COVID-19 pandemic made free mobility incredibly difficult (in fact, this mountain area remained free

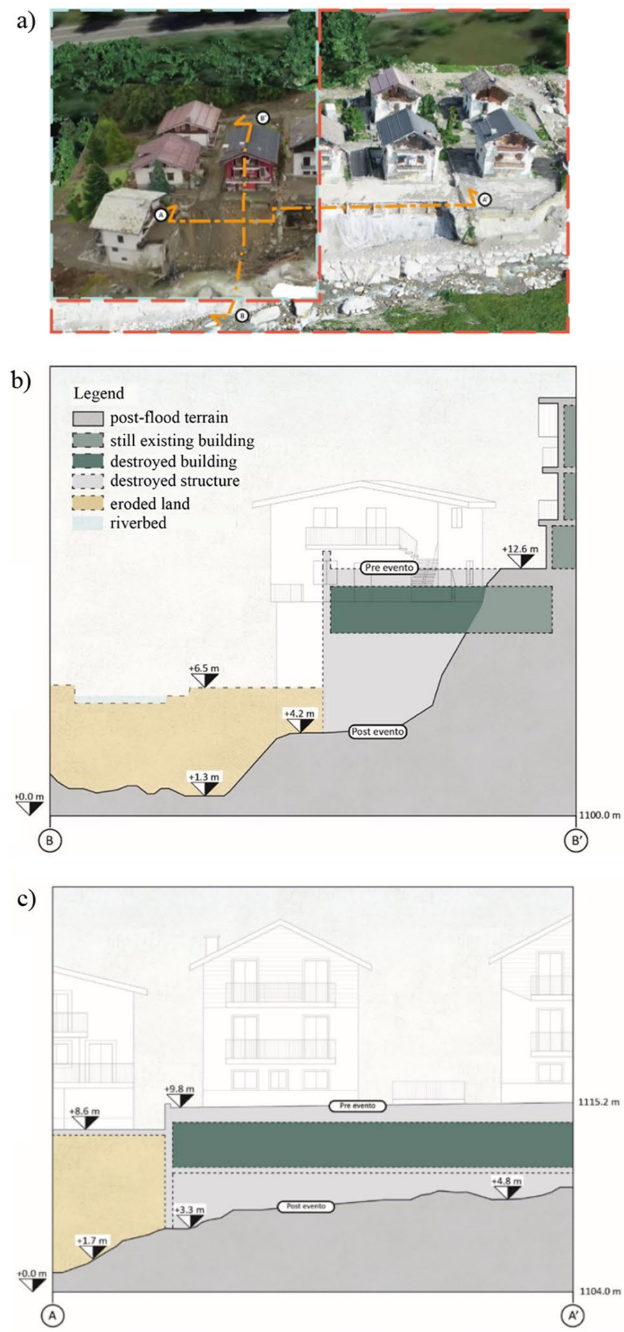

Fig. 15 **a** Comparison of textured 3D model derived from images acquired during the event (05/10/2020) on the left with post-event 3D model (21/06/2021) on the right; **b** Section BB', original scale 1:200; in gray is the post-flood land in section, the still existing volumes are in light green while the destroyed volumes are in dark green and light gray, the eroded land is in yellow; **c** Section AA', original scale 1:200 [59]

from the contagion until before the flood, which brought many rescue and civil protection teams to these areas, which brought in the COVID-19 virus). When displayed in a GIS environment, the availability of orthophotos and DSM archives can allow new sewer pipe routes to be designed without further inspections or, at most, reducing them to a minimum. This opportunity has been facilitated through online sharing with ACDA technicians.

GIS tools enable us to evaluate the exact positioning of the pipeline for excavation, allowing us to check both the planimetric position on orthophotos and the trend of the section profile produced on the DSM, both of which are derived by processing from UAV data. The images presented in Fig. 17 a, b, c, and d illustrate the phases involved in extracting a section profile operated on the DSM once the exact planimetric position has been identified under the control of the high-resolution orthophoto (3 cm).

The road section profiles that are enriched by retaining walls, small walls, bridges, buildings, road crossings, and maintenance holes are combined with many elevation points. The usual technical preparations that the construction

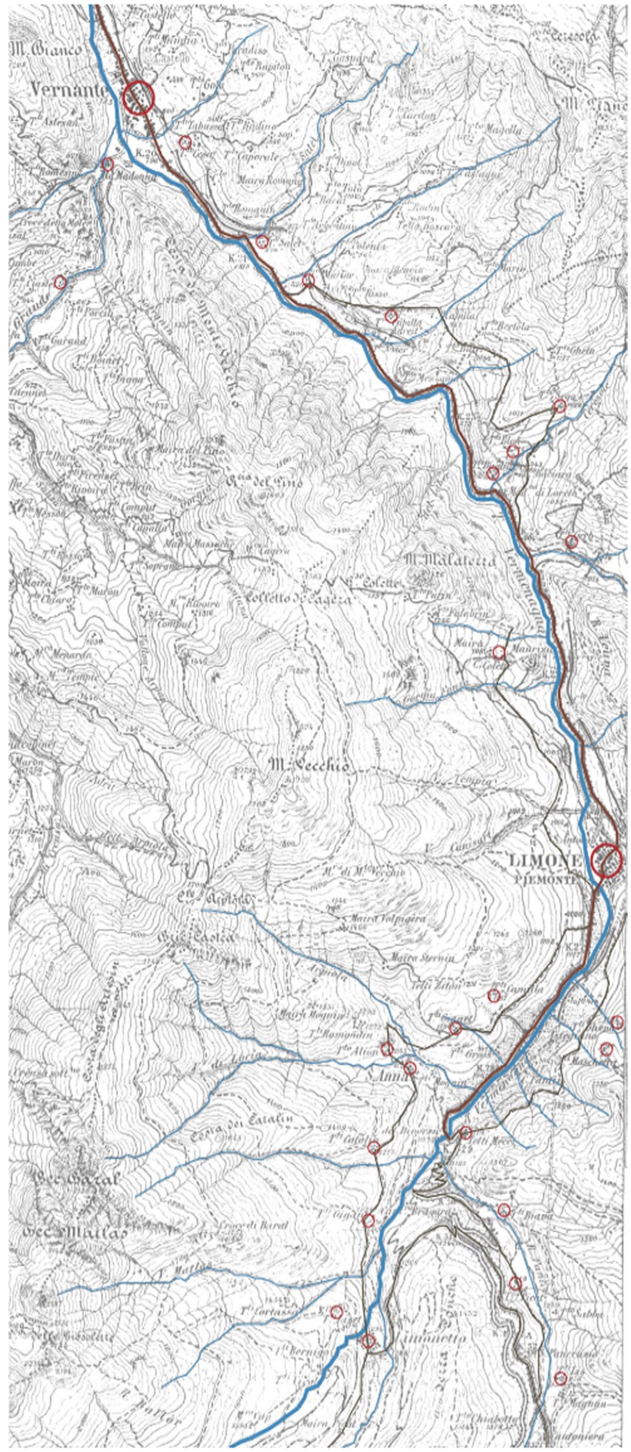

Fig. 16 Limone Piemonte Municipality in 1901 (Istituto Geografico Militare, scale 1:25000). By isolating some elements of settlement form, it is possible to identify the historical logic of spatial construction. In dark blue the Vermegnana River, in light blue the minor streams, in dark brown the valley route, in light brown the halfway route, in dark red the major cores, in light red the minor cores (map compiled by the authors)

company carrying out the restoration must have at its disposal. The availability of DSMs and orthophotos with an accuracy and resolution from which the drawings can be derived is undoubtedly an innovation because it reduces (or sometimes even eliminates) the need to carry out additional surveys in the field. Thus, it certainly proves to be a sustainable aspect of recovery.

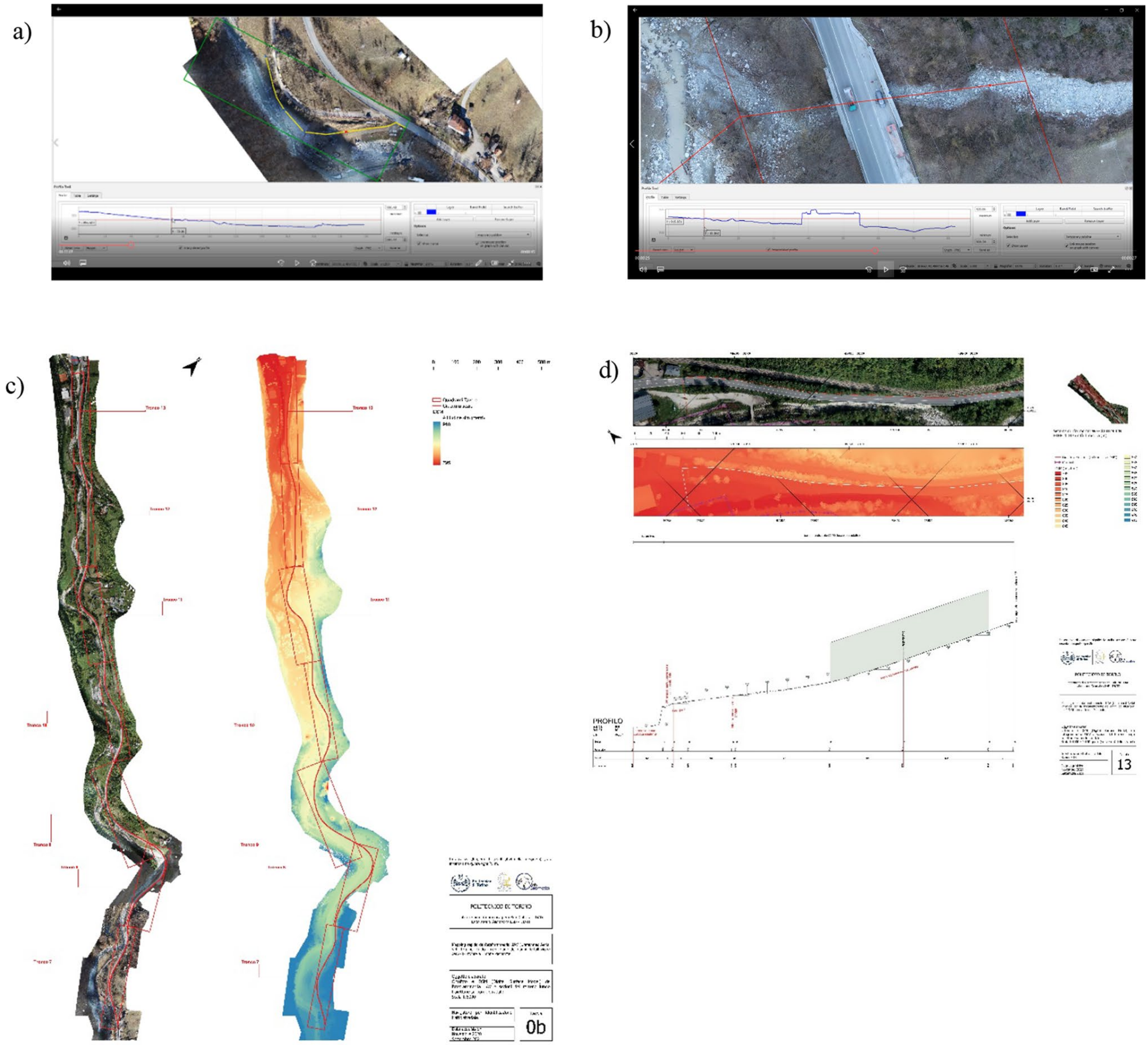

Fig. 17 **a** Generation of the section profiles operated on the DSM by UAV photogrammetry and displayed on the screen in relation to the orthophotos **b**) Generation of additional section profiles, drawn in a direction perpendicular to the road to evaluate the possible burial of the pipeline near the crossing of secondary watercourses **c**) Overview of the section profiles developed along a section of the main road no. 20. **d** Contents of a typical table: planimetric layout overlapped on orthophotos and DSM, section extracted in a GIS environment and edited in Autocad (created by the authors)

7 Conclusion

With regard to the transferability of the methodology employed in this work (primarily in terms of different landscapes and geographical areas), the terrain morphology is the most significant factor that needs to be considered. It can be difficult to perform some activities in the area (e.g., UAV flight planning and the availability (and quality) of mobile phone signal coverage to receive RTK GNSS corrections required for direct georeferencing strategies) due to steep mountain areas and narrow valleys. Despite the existence of numerous technical solutions for such critical areas (vertical take-off and landing fixed-wing UAVs, and the use of PPK GNSS post-processing algorithms rather than RTK positioning), the expertise required by the operators in the field is higher and requires an additional investment in training and hardware solutions. This may be considered a limitation associated with the employed technologies.

Added-value products can be produced with different technical specifications (i.e., level of detail, positional accuracy, 2D, 3D or 4D (multi-temporal)). Depending on the specifications, they can be exploited for different purposes and to support different phases of the EMC.

Focusing on assessing the flood impact on the landscape, the post-event products show specific patterns in the deterioration of the landscape, ranging from water bodies to a territorial organisation incapable of absorbing and recovering from traumatic events in a short time. Citizens must realise that creating ideal landscape conditions is a gradual process that requires thorough planning. In other words, this helps to promote inclusive and sustainable urbanisation whilst also strengthening the capacity for participatory, integrated, and sustainable human settlement planning and management in all countries, as stipulated in SDG 11.

The recovery phase often takes a long time due to the time needed to maintain or regenerate the urban fabric after experiencing damaged infrastructures, pipelines and/or sewer systems. Thus, the possibility to sustainably document and map the affected areas is an effective tool that can be used by the public bodies in charge of the recovery activities.

From the broader perspective of disaster risk reduction at this point in history, numerous tools are available. These include conceptual tools designed through landscape history and theory to facilitate landscape protection, regional governance tools (i.e., the Regional Landscape Plan, in Italian Piano Paesaggistico Regionale), and monitoring and assessment tools (i.e., the tools presented in this paper). The fragility of the territory highlights the need to adhere strictly to established protection measures (SDG target 13.2). However, the synergistic potential of the aforementioned tools is not being further exploited at present, which results in less effective disaster risk reduction efforts.

Acknowledgements The work was also carried out within the PhD programme in Heritage Science at the University of Sapienza (Italy)—38th cycle, with the support of a scholarship co-financed by the Italian Ministerial Decree no. 351- 2022, based on the NRRP—funded by the European Union—NextGenerationEU—Mission 4 "Education and Research".

Author contributions L.S.B., A.S., F.G.T. contributed to the manuscript writing. A.S. supervisioned the UAV and terrestrial section of the research, including the GIS data for the public bodies; F.G.T. supervisioned the satellite remote sensing activities. M.C.B. developed a Master's Degree thesis (supervised by F.G.T. and A.S.), from which part of the figures of the manuscript are derived. Manuscript editing and supervised by L.S.B. and A. S. All authors have read and agreed to the published version of the manuscript.

Funding The research activities of satellite and UAV rapid mapping have been funded by ACDA (Azienda Cuneese dell'Acqua), resp. A. Spanò. The overall experience has also been used as a training activity and has been offered to students enrolled in the DIRECT team (Disaster Recovery team) of Politecnico di Torino, who have also been tutored by some of the authors. The survey activities were carried out by the Laboratory of Geomatics for Cultural Heritage (Department of Architecture and Design) team and the Laboratory of Photogrammetry, Geomatics, and GIS (Department of Environment, Land and Infrastructures Engineering) team of Politecnico di Torino.

Data availability All the data and maps produced by the research and described in the paper are available to the public administrations (ACDA and Municipality of Limone Piemonte).

Declarations

Competing interests The authors declare no competing interests.

References

1. ISPRA, "Gli indicatori del clima in Italia nel 2021," Roma, 2022.
2. U. Department of Economic and Social Affairs, "Disaster risk reduction." https://sdgs.un.org/topics/disaster-risk-reduction#description Accessed 18 Jan 2024.
3. Weinkle J, et al. Normalized hurricane damage in the continental United States 1900–2017. Nat Sustain. 2018;1(12):808–13. https://doi.org/10.1038/s41893-018-0165-2.
4. UN, "SUSTAINABLE DEVELOPMENT GOAL 11 Make Cities and Human Settlements Inclusive, Safe, Resilient And Sustainable A GUIDE TO ASSIST NATIONAL AND LOCAL GOVERNMENTS TO MONITOR AND REPORT ON SDG GOAL 11+ INDICATORS," New York. https://

www.local2030.org/library/60/SDG-Goal-11-Monitoring-Framework-A-guide-to-assist-national-and-local-governments-to-monitor-and-report-on-SDG-goal-11-indicators.pdf Accessed 08 Jan 2024.
5. FEMA, "National Risk Index. Technical Documentation," Jan. 2023.
6. Office of the United Nations Disaster Relief, Natural disasters and vulnerability analysis : report of Expert Group Meeting, 9–12 July 1979, UN, Geneva, 1980. https://digitallibrary.un.org/record/95986. Accessed 12 Feb 2024.
7. ICCROM, *A guide to risk management of cultural heritage*. ICCROM, 2016.
8. UNESCO / ICCROM / ICOMOS / IUCN, Managing disaster risks for world heritage. Paris: United Nations Educational, Scientific and Cultural Organization, 2010
9. O. for O. S. A. UN and UN-SPIDER Knowledge Portal, "Disaster Risk Management," https://www.un-spider.org/risks-and-disasters/disaster-risk-management.
10. Wisner B, Adams J. Environmental health in emergencies and disasters: a practical guide. Geneva: World Health Organization; 2002.
11. Intergovernmental Panel on Climate Change (IPCC). Climate change 2022 – impacts adaptation and vulnerability. Cambridge University Press. 2023. https://doi.org/10.1017/9781009325844.
12. United Nations Office for Disaster Risk Reduction. Sendai framework for disaster risk reduction 2015–2030. Geneva: United Nations Office for Disaster Risk Reduction; 2015.
13. ARPA. Eventi alluvionali in Piemonte Evento del 2–3 ottobre 2020. Torino: ARPA; 2020.
14. Iovino S. Filosofie dell'ambiente Natura, etica, società. Carocci editore: Rom; 2008.
15. J. W. von Goethe, *Letters from Italy*, vol. 12. London: Francis A. Niccolls & Co., 1901. https://en.wikisource.org/wiki/The_Works_of_J._W._von_Goethe. Accessed 08 Jan 2024
16. Thoreau HD. Walden or life in the woods. Boston: Ticknor and Fields; 1854.
17. Colantonio Venturelli R, Tobias K. La cultura del paesaggio : le sue origini, la situazione attuale e le prospettive future. L.S. Olschki: Firenze; 2004.
18. Di Biagi P, editor. La grande ricostruzione: il piano Ina-Casa e l'Italia degli anni Cinquanta. Roma: Donzelli; 2010.
19. Sereni E. Storia del paesaggio agrario italiano. 20th ed. Laterza: Roma - Bari; 2018.
20. Assunto R. Il paesaggio e l' estetica. Napoli: Giannini; 1973.
21. Di Giorgio G. L'alloggio ai tempi dell'edilizia sociale Dall'INA-Casa ai PEEPD. Edil Stampa: Roma; 2011.
22. Di Biagi P, editor. La grande ricostruzione il piano INA-Casa e l'Italia degli anni 50. ROma: Donzelli; 2012.
23. P. Chicco, M. Garelli, and Sirchia G., *Sviluppo urbano ed edilizia residenziale pubblica*. Celid: Torino. 1980
24. Cederna A. I vandali in casa. Laterza Editore: Roma - Bari; 1956.
25. *Per la tutela delle bellezze naturali e degli immobili di particolare interesse storico*. Roma, 1922.
26. *Tutela delle cose d'interesse Artistico o Storico*. Roma, 1939.
27. *Protezione delle bellezze naturali*. Roma, 1939.
28. *Legge urbanistica*. Roma, 1942.
29. Cederna A, Insolera I, Pratesi F. La difesa del territorio Testi per ITALIA NOSTRA di Antonio Cederna, Italo Insolera, Fulco Pratesi. Mondadori: Milano; 1976.
30. De Rossi A. La costruzione delle Alpi. Immagini e scenari del pittoresco alpino. Donzelli: Roma; 2014.
31. Sereni E. Il capitale nelle campagne (1869–1900). Torino: Einaudi; 1947.
32. Secchi B. La città del ventesimo secolo. Laterza Editore: Roma - Bari; 2005.
33. Comoli Mandracci V, Very F, Fasoli V. Le Alpi storia e prospettive di un territorio di frontiera les Alpes histoire et perspectives d'un territoire transfontalier. Torino: Celid; 1997.
34. Ellis EC. Land use and ecological change: a 12,000-year history. Annu Rev Environ Resour. 2021. https://doi.org/10.1146/ANNUREV-ENVIRON-012220-010822.
35. Ellis EC, et al. People have shaped most of terrestrial nature for at least 12,000 years. Proc Natl Acad Sci U S A. 2021. https://doi.org/10.1073/PNAS.2023483118/-/DCSUPPLEMENTAL.
36. Chapman H. Landscape archaeology and GIS. Brimscombe Port: The History Press; 2006.
37. Ferro-Vázquez C, Lang C, Kaal J, Stump D. When is a terrace not a terrace? the importance of understanding landscape evolution in studies of terraced agriculture. J Environ Manage. 2017;202:500–13. https://doi.org/10.1016/J.JENVMAN.2017.01.036.
38. Voigt S, et al. "Global trends in satellite-based emergency mapping." Science 1979. 2016. https://doi.org/10.1126/SCIENCE.AAD8728/SUPPL_FILE/VOIGT-SM.PDF.
39. Copernicus emergency management service - mapping | COPERNICUS EMERGENCY MANAGEMENT SERVICE.https://emergency.copernicus.eu/mapping/#zoom=2&lat=13.56036&lon=33.82273&layers=0BT00. Accessed 12 Feb 2024.
40. Kerle N. Satellite-based damage mapping following the 2006 Indonesia earthquake—how accurate was it? Int J Appl Earth Obs Geoinf. 2010;12(6):466–76. https://doi.org/10.1016/J.JAG.2010.07.004.
41. Ajmar A, Balbo S, Boccardo P, Giulio Tonolo F, Piras M, Princic J. A low-cost mobile mapping system (LCMMS) for field data acquisition: a potential use to validate aerial/satellite building damage assessment. Int J Digit Earth. 2013. https://doi.org/10.1080/17538947.2011.638991.
42. Joint Research Centre, "Drones and planes: unprecedented imagery resolution for disaster assessment."https://joint-research-centre.ec.europa.eu/jrc-news-and-updates/drones-and-planes-unprecedented-imagery-resolution-disaster-assessment-2023-09-25_en. Accessed 20 Feb 2024
43. C. E. M. Copernicus, "introducing the aerial component to improve CEMS mapping products," *EMS Information Bulletin*. 2023.
44. Fernandez Galarreta J, Kerle N, Gerke M. UAV-based urban structural damage assessment using object-based image analysis and semantic reasoning. 2015. Nat Hazard Earth Syst Sci. https://doi.org/10.5194/NHESS-15-1087-2015.
45. Crommelinck S, Bennett R, Gerke M, Nex F, Yang MY, Vosselman G. Review of automatic feature extraction from high-resolution optical sensor data for UAV-based cadastral mapping. Remote Sensing. 2016. https://doi.org/10.3390/RS8080689.

46. Calantropio A, Chiabrando F, Sammartano G, Spanò A, Losè LT. Uav strategies validation and remote sensing data for damage assessment in post-disaster scenarios. 2018. Int Arch Photogramm Remote Sens Spatial Inf Sci. https://doi.org/10.5194/ISPRS-ARCHIVES-XLII-3-W4-121-2018.
47. Cotrufo S, Sandu C, Giulio Tonolo F, Boccardo P. Building damage assessment scale tailored to remote sensing vertical imagery. Eur J Remote Sens. 2018. https://doi.org/10.1080/22797254.2018.1527662.
48. Ekaso D, Nex F, Kerle N. Accuracy assessment of real-time kinematics (RTK) measurements on unmanned aerial vehicles (UAV) for direct geo-referencing. Geo-spatial Inf Sci. 2020;23(2):165–81. https://doi.org/10.1080/10095020.2019.1710437.
49. Chiabrando F, Giulio Tonolo F, Lingua A. UAV direct georeferencing approach in an emergency mapping context. the 2016 central italy earthquake case study". 2019. Int Arch Photogramm Remote Sens Spatial Inf Sci. https://doi.org/10.5194/ISPRS-ARCHIVES-XLII-2-W13-247-2019.
50. Tomaštík J, Mokroš M, Surový P, Grznárová A, Merganič J. UAV RTK/PPK method—an optimal solution for mapping inaccessible forested areas? Remote Sens. 2019. https://doi.org/10.3390/RS11060721.
51. Santoro V, Patrucco G, Lingua A, Spanò A. "Multispectral UAV data enhancing the knowledge of landscape heritage", the international archives of the photogrammetry. 2023. Remote Sens Spatial Inf Sci. https://doi.org/10.5194/ISPRS-ARCHIVES-XLVIII-M-2-2023-1419-2023.
52. Albertini C, Gioia A, Iacobellis V, Manfreda S. Detection of surface water and floods with multispectral satellites. Remote Sens. 2022. https://doi.org/10.3390/RS14236005.
53. Hu X, Ban Y, Nascetti A. Uni-temporal multispectral imagery for burned area mapping with deep learning. Remote Sens. 2021. https://doi.org/10.3390/RS13081509.
54. Ghassemi S, et al. Satellite image segmentation with deep residual architectures for time-critical applications. Euro Signal Proc Conf. 2018. https://doi.org/10.23919/EUSIPCO.2018.8553545.
55. Vetrivel A, Gerke M, Kerle N, Nex F, Vosselman G. Disaster damage detection through synergistic use of deep learning and 3D point cloud features derived from very high resolution oblique aerial images, and multiple-kernel-learning. ISPRS J Photogramm Remote Sens. 2018;140:45–59. https://doi.org/10.1016/J.ISPRSJPRS.2017.03.001.
56. Notti D, Giordan D, Caló F, Pepe A, Zucca F, Galve JP. Potential and limitations of open satellite data for flood mapping. Remote Sens. 2018. https://doi.org/10.3390/RS10111673.
57. International working group on satellite-based emergency mapping (IWG-SEM), *Emergency Mapping Guidelines. Working Paper*. IWG-SEM, 2000.
58. R. Gens and J. C. Rossellò Eds., Advances in Geospatial Data Analysis for Change Detection. Remote Sensing, 2022.
59. Zhou Z, Gong J, Hu X. Community-scale multi-level post-hurricane damage assessment of residential buildings using multi-temporal airborne LiDAR data. Autom Constr. 2019;98:30–45. https://doi.org/10.1016/J.AUTCON.2018.10.018.
60. Chiabrando F, Di Lolli A, Patrucco G, Spanò A, Sammartano G, Losè LT. Multitemporal 3d modelling for cultural heritage emergency during seismic events: damage assesment of s. agostino church in amatrice (RI). 2017. Int Arch Photogramm Remote Sens Spatial Inf Sci. https://doi.org/10.5194/ISPRS-ARCHIVES-XLII-5-W1-69-2017.
61. "Recommended Practices | UN-SPIDER Knowledge Portal." https://www.un-spider.org/advisory-support/recommended-practices. Accessed 07 May 2024.
62. Longhi A. La storia del territorio per il progetto del paesaggio. Artistica Piemontese: Savigliano; 2004.
63. "Home - Geoportale Piemonte. https://geoportale.igr.piemonte.it/cms/. Accessed 13 Feb 2024.
64. Cittadini Bellini M. Il ruolo della Geomatica a supporto della valutazione dei danni al territorio a seguito di eventi alluvionali Il caso dell'alluvione di Ottobre 2020 a Limone Piemonte (CN). Torino: Politecnico di Torino; 2022.
65. D. S. S. P. C. e S. A. B. (A. I. B) Regione piemonte - direzione opere pubbliche, "piano per la valutazione e la gestione del rischio di alluvioni. Relazione Regione Piemonte," Torino, Jan. 2016.
66. Teppati Losè L, Chiabrando F, Giulio Tonolo F, Lingua A. UAV photogrammetry and vhr satellite imagery for emergency mapping. the october 2020 flood in limone piemonte (ITALY)". 2021. Int Arch Photogramm Remote Sens Spatial Inf Sci. https://doi.org/10.5194/isprs-archives-XLIII-B3-2021-727-2021.
67. Lingua A, Noardo F, Spanò A, Sanna S, Matrone F. "3D model generation using oblique images acquired by uav", the international archives of the photogrammetry. 2017. Remote Sens Spatial Inf Sci. https://doi.org/10.5194/ISPRS-ARCHIVES-XLII-4-W2-107-2017.
68. Fiandra R, editor. Limun d'in bot Limone Piemonte in cartoline d'epoca. Vignolo: MG Servizi Tipografici; 2013.
69. Sammartano G, Avena M, Fillia E, Spanò A. Integrated HBIM-GIS models for multi-scale seismic vulnerability assessment of historical buildings. Remote Sens. 2023. https://doi.org/10.3390/RS15030833.
70. "Limone Piemonte ricorda i tragici eventi dell'alluvione 2020 con la 2ª edizione di 'Inondazione,'" lavocedialba.it. [https://www.lavocedialba.it/2022/09/28/leggi-notizia/argomenti/attualita-14/articolo/limone-ricorda-i-tragici-eventi-dellalluvione-2020-con-la-2a-edizione-di-inondazione.html. Accessed 12 May 2024.