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First national inventory of high-elevation mass movements in the Italian Alps

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ABSTRACT

Climate change in the European Alps, in particular in the high-elevation environments, is causing an increase in mass movements and hazards. To learn more about relationships between mass movements and climate drivers, the location of the starting zone and date of the instability events need to be known. Nevertheless, not all existing inventories of mass movements are suitable for the purpose. For these reasons, we have implemented a specific inventory of mass movements which occurred in the Italian sector of the Alps at an elevation >1500 m.

Currently, the inventory contains information relating to 772 mass movements. The most frequent types of processes documented are rockfall and debris/mud flows, with 279 and 191 cases respectively. The highest number of events occurred in 2022 (71 events), and an evident trend towards an increase over the years and during summer was found.

This inventory is an excellent support tool for many activities that take place in and for the mountains, its consultation, both online and offline, makes the inventory suitable for use with different types of devices and can be used not only as a consultation tool on mass movements occurred in the past, but also to insert new events. This use can be particularly suitable for monitoring activities, managed by civil protection structures, municipalities, natural parks, environmental agencies, researchers, freelancers and so on.

1. Introduction

Climate change in the Alps, in particular in the high-elevation environments, is causing an increase in mass movements and hazards. Air temperature and precipitation changes, in terms of values and regimes, with associated environmental changes (e.g. deglaciation and permafrost degradation), seem to be the main preparatory and triggering factors for mass movements: an extensive analysis on this topic is reported in Gariano and Guzzetti (2016) and in Chiarle et al. (2021). There is a general agreement that the impact of temperature and precipitation changes on slope stability is remarkable: however, the understanding of these processes, in the context of climate change and the forecasting of future scenarios, needs to be deepened. For this reason, it is important to collect, catalogue and make available information on mass movements occurred at high elevation. To learn more about the relationship between mass movements and climate drivers (and change), the location of the starting zone and date of the instability events need to be known (Coviello et al., 2015; Wood et al., 2020). Nevertheless, not all inventories of mass movements are suitable for this purpose. For example, the most complete landslide inventory for Italy is the “Inventario dei Fenomeni Franosi in Italia (IFFI)” realized by the Istituto Superiore per la Protezione e la Ricerca Ambientale (ISPRA) and by the administrative Regions and Autonomous Provinces (https://www.isprambiente.gov.it). IFFI collected 620,808 landslide events, affecting an area of about 23, 700 km^2 (7.9 % of the Italian territory). The IFFI dataset includes updates from 2007 to 2017. However, the inventory is mainly based on the recognition of evidences of past events and unstable area from aerial photo interpretation, as the inventory was intended for land use purposes. For this reason, in most cases the identified landslides are not dated. Moreover, not all types of mass movements are inventoried, and in some part of Italy high elevation environments have been excluded from the analysis. The IFFI inventory should be continuously fed by regional/provincial inventories, such as the “Catasto Dissesti della Regione Autonoma Valle d’Aosta”, updated to 2022 (https://catastod

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issesti.partout.it/) and the “Sistema Informativo delle Frane in Piemonte”, updated to 2019 (https://tinyurl.com/sifrap). Other inventories have been created to document specific slope instability events or have been made for a specific alpine sector and/or a specific type of process (Corò et al., 2015; Lucchesi et al., 2019; Blondeau et al., 2021; Savi et al., 2021; Chiarle et al., 2022; Peruccacci et al., 2023). It is therefore possible to note that, for Italy, there is not an inventory that responds to all the following characteristics.

i) It collects mass movement events that occurred throughout the Italian Alps, at an elevation above 1500 m;
ii) It considers all types of processes;
iii) It includes accurate information on hour/date of occurrence;
iv) It is updated to 2022;
v) It is available online for free;
vi) It can be used online and offline;
vii) It is not only consultable but also editable.

For these reasons, we have implemented an inventory of mass movements which occurred in the Italian Alps at an elevation >1500 m (hereinafter MIA).

In this paper, Section 2 gives a brief description of the Alps and its landslides. At this point it is necessary to underline that the MIA collects data relating to different types of mass movements but, in order to facilitate their dissemination, we have decided to combine them in a single term: “mass movement”. An extensive description of mass movements and their typologies can be found in Eisbacher and Clague (1984). Section 3 describes the methodology applied for the construction of the MIA and the different ways of use, both online and offline. Subsequently, in the results and the discussion section (Section 4), we will present some of the main outcomes of the analyses of the events included in the MIA. The paper ends with the conclusions (Section 5), which include some suggestions for future developments.

2. The Alps and its landslides

Our study focuses on the Italian sector of the European Alps, stretching 1200 km from East to West and covering about 5200 km^2, (27.3 % of the entire Alpine area). The amazing geodiversity of the Alps arises from its complex geological history, a double-vergence collisional belt including litho-structural domains from different plates and geological environments. In the classic alpine literature, three main sectors show-case different paleogeographic region and crustal levels (Dal Piaz et al., 2003).

i) the “internal” (southern and eastern) sector of the Italian Alps includes south-verging structural units from the upper plate of the collisional system (“Southalpine” domain); a complex of Hercynian and pre-Hercynian basement rocks, their Mesozoic sedimentary cover and later magmatic bodies, bounded to the north by the Periadriatic lineament, also named Insubric line;
ii) the “external” (western and northern) sector, belongs to the lower plate of the collisional system (“European” foreland area: Helvetic–Dauphinois domains of literature) made by Hercynian intrusive massifs (e.g. Mont Blanc), Mesozoic sedimentary covers and detrital deposits (flysch);
iii) the “axial sector” is bounded by two crustal scale discontinuities: the Insubric line to the south and the Pennidic front thrust to the North. It includes Hercynian and pre-Hercynian continental crustal rocks, their metasedimentary covers, oceanic lithosphere with cover units from the ocean facing continental edges and orogenic flysch units.

The complex kinematic framework of the whole chain involves extensional, contractional and strike-slip tectonics, dominating in the internal zones, whereas a coeval contractional kinematics mainly affects the external zones; late, intense uplift and exhumation of the western side culminated with the onset of Mont Blanc Massif (4810 m a.s.l.), top summit of whole European Alps.

As a collisional belt, the Alps have been modelled as a mountain chain by several geomorphic processes interacting with tectonic ones, as shown by the main physiographic features at the regional scale: e.g. the arch-shaped western mountain sector following main thrusts, and the network of major valleys at the core of Central and Eastern Alps, aligned to continental Insubric shear zone. Nevertheless, the repeated Pleistocene glacial pulsations modelled the alpine valleys (Giardino et al., 2017), Holocene gravitational and fluvial/torrential processes deeply modified glacial landforms and deposits, causing widespread mass movements (Soldati et al., 2006).

The numerous interactions between the general atmospheric circulation and the mountain range make the climate of the Alps particularly complex and diversified (Wanner et al., 1997). The several climate regimes that are present are influenced by air masses from south (warm wet, Mediterranean), from east (cold dry, Continental), from northwest (warm or cold wet, Atlantic) and from north (cold dry, Polar). The Köppen-Geiger climates present are: Arid, Warm temperate, Boreal and Alpine (Barry, 2008; Rubel et al., 2016).

In the Italian Alps, the climate is cold and dry in winters and warm and wet in summers (Fratianni et al., 2017): the hottest months are July and/or August and the coldest months are January and/or February: this climate can be considered as a cold temperate type, with a transition to a nival type at altitudes above 2700 m. Differences in temperature values are present, due to the elevation gradient and to the slope aspect. The cold air masses coming from the arctic region and the hot air masses coming from Africa can cause high amount of rainfall, in particular in the more exposed sectors, with peaks of 3000 mm per year (Fratianni et al., 2017). The total annual precipitation shows a significant variability, that depends by the local climate conditions and by the different Alpine sectors (Barry, 2008).

Air temperature in the Alps are increasing at an average rate of 0.3 °C/decade (global warming rate 0.2 °C/decade), and this is mainly observed in summer and spring (Hock et al., 2019). A recent study has highlighted that in the Alps, during the 1991–2020 climate normal, minimum and maximum annual temperature are −2.4 °C and 4.4 °C, respectively, with a warming rate of 0.5 °C/10 years (Nigrelli et al., 2023). In particular, the periglacial environment shows the highest warming rate of the Alps: up to 0.6 °C/10 years and 0.8 °C/10 years for the maximum and minimum temperatures respectively (observation period 1999–2019, Nigrelli and Chiarle, 2021). Annual precipitation shows no clear trends in recent decades (Hock et al., 2019).

The geo-structural and topographic setting, the morphological evolution due to the action of exogenous agents (in particular glaciers), the diversity of climates and the ongoing climate change make the Alps prone to natural instability or, more specifically, mass movements (Fig. 1). The Alps share some types of instability with other physiographic environments: block falls, rock falls, landslides, slow ground deformation, soil slips, debris/mud flows. In high-altitude areas, especially where glacial cover vanished over the decades, extensive and widespread debris bodies are exposed to reworking by transport processes, mainly by gravitational, avalanche, and debris flow activities (Lucchesi et al., 2019). These dynamics are often interconnected and prepare for debris mobilization. Debris flows usually occur in summer, as a result of short and intense precipitation (rainfall amount in mm/h vary greatly from area to area), and more rarely in autumn, due to the type of rainfall events (generally low in intensity and lasting only a few days). Other processes, on the other hand, are specific to alpine environments, due to the necessary relief energy, or because they involve glaciers (e.g. Glacial Lake Outburst Floods, so-called GLOF, ice falls/avalanches).

Under current climate change, rock falls/avalanches, debris/mud flows and ice falls/avalanches seem to occur more frequently (Chiarle et al., 2022), but the lack of systematic documentation of such events

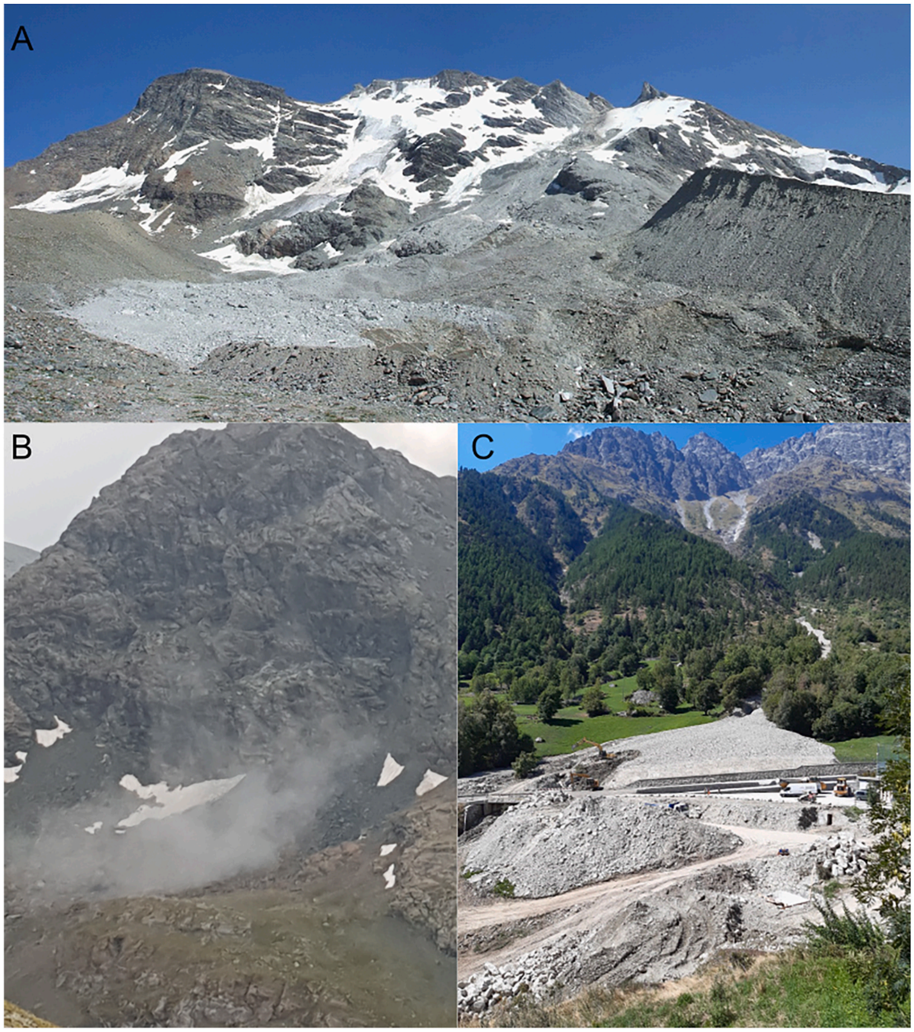

Fig. 1. Typical mass movements that occur in the Italian Alps. A, rock avalanche (in this picture rockfall occurred on 2014.11.20, Id 304 in the MIA); B, blockfall (occurred on 2019.08.23, Id 473 in the MIA); C, debris/mud flow (occurred on 2022.08.05, Id 547 in the MIA).

does not allow solid and statistically based conclusions. Certainly, global warming and related environmental changes are causing an upward shift of instability processes towards higher altitudes and an extension of the seasonality. In this context, particularly insidious are process chains, in which glaciers (and, more in general, the cryosphere) play a key role (Walter et al., 2020).

There is a long history of mournful events that have involved anthropic areas, causing victims and serious damage (Luino, 2005). Not only landslides are included among these well identifiable phenomena, but also other extremely rapid and dangerous processes that are almost always classified as landslides by the uninitiated. For this reason, media reports need to be carefully analyzed by experts in the field when susceptibility studies and interventions are needed.

In recent years a higher frequency of climate anomalies and extreme events has been argued as possibly responsible for the increased of mass movements at high-elevation sites (Gariano et al., 2016; Hock et al., 2019). In the scientific literature, most part of studies focus on the development of landslide forecasting systems use in-situ observations and in particular precipitation data at both regional and slope-scale. The most common use of precipitation data is to derive rainfall thresholds (Guzzetti et al., 2008). More recently, in the light of the ongoing climate change, the role of extreme high temperatures on rock wall stability has been widely analyzed and especially in the alpine region in terms of high temperature-related effects on different mass-wasting processes (Gruber and Haeberli, 2007; Schlögel et al., 2020; Viani et al., 2020). Statistical approaches were proposed to detect possible relations between climate variables at multiple scales and the triggering of different mass-wasting processes (Huggel et al., 2010; Allen and Huggel, 2013). To identify anomalies in climate variables associated with the initiation or preparation phase of geo-hydrological hazards, Paranunzio et al. (2015, 2016, 2019b, 2024) proposed a method for recognizing possible links between temperature/precipitation and the trigger of different mass-wasting processes, pointing out the potential role of meteorological anomalies (i.e., values above or below a specific threshold in percentile) in the initiation/preparatory phase of such events. More recent studies aimed to better characterize the interplay among different climate variables in relation to different slope failure events by performing multivariate analysis, deriving indices and critical empirical thresholds or exploiting more sophisticated predictive models based on machine learnings techniques (Jomelli et al., 2019; Bajni et al., 2021; Ponziani et al., 2023). The role of temperature was investigated further also in the case of typically rainfall-induced processes like debris flow or shallow landslides (Rebetez et al., 1997; Pavlova et al., 2014; Mostbauer et al., 2018; Prenner et al., 2018; Jomelli et al., 2019). These studies agree that, in the Alpine region, most parts of the considered events are correlated to the occurrence of unusual climate conditions in the lead up of the event. Late-spring/summer time and higher elevation rockfalls are mainly associated with the occurrence of high temperatures. Such positive temperature anomalies potentially affect the cryosphere at short time-scale by acting on near-surface dynamics and at longer-scales at depth or enhancing the active layer thickening. Short-term precipitations are the main driver of debris flows and initiation of landslides while long-term precipitation may have a major role on the enhanced soil moisture and thus on the preparation phase. A contribution of long-lasting periods of high temperature may increase the probability of such events indeed.

3. Methodology applied and types of use

The MIA was made taking as a reference a procedure already widely applied by the authors for the construction of some relational databases related to geo-hydrological resources (Nigrelli et al., 2012; Sacco et al., 2012; Nigrelli et al., 2013; Turconi et al., 2014) and two previous datasets on landslide events (Paranunzio et al., 2019a; Guerini et al., 2021). However, the relational databases cited above are now obsolete and therefore no longer available online.

The methodology applied for the construction of the MIA consists of 4 steps that are described below and are reported in Fig. 2.

3.1. Step 1: data collection

Data collection of mass movements which occurred in the Alps (>1500 m a.s.l.). We made this choice because above this elevation threshold, the alpine environments: i) are responding quickly to climate change, due to the presence of cryosphere (permafrost, snow, glaciers); and ii) are the ones where landslides are increasing, as a consequence of temperature increase (Allen and Huggel, 2013; Gobiet et al., 2014).

We used six main data sources: 1) Online and offline archive documents; 2) Survey data; 3) National/regional agencies datasets; 4) Scientific papers; 5) Web alerts; 6) Newspapers and social media.

The different types of data sources are essential in order to acquire as much information as possible on the mass movements occurred. Nevertheless, the heterogeneity of the data acquired from different sources does not allow a direct use of these data: thus, an in-depth quality control and an accurate validation are necessary.

3.2. Step 2: data processing

Data processing consists of four consecutive stages: 1) Quality control; 2) Validation; 3) Dataset construction; 4) realization of a QGIS project. In order to perform this procedure in the best possible way, guaranteeing reproducibility and avoiding bias, a multidisciplinary and systematic approach is strongly recommended, as also reported in Piacentini et al. (2020) and in Poratelli et al. (2020). Quality control and data validation are closely connected. Quality control and validation are performed by a skilled human analyst who checks and validates (or discards) the acquired data in relation to the attributes necessary for the implementation of the dataset and, subsequently, of the shapefile. In this process, the analyst makes use of various resources (e.g. spreadsheets, maps, online geoportals, satellite and orthophoto images, web resources). The procedure is not very complex, but requires a good level of knowledge in both geoscientific and IT fields.

After quality control and validation procedures, a dataset containing all the necessary information relating to the single mass movement was realized. The dataset is then imported into a QGIS project as a ".csv" file, thanks to Lat/Lon fields, and saved as a point shapefile. The list of attributes that are present in the shapefile with their description is shown in Table 1.

Regarding the "S_acc" attribute, a value from 1 to 3 is assigned in relation to the accuracy of the geolocation of the point in the shapefile with respect to the place of event initiation: 1, exact and punctual geolocation; 2, areal geolocation, close to the event site or the toponym (less than 500 m); 3, indicative geolocation in relation to the event site or the toponym (more than 500 m). Regarding the "T_acc" attribute, a value from 1 to 3 is assigned in relation to the accuracy of the mass movement occurrence date: 1, exact date of occurrence (yyy-mm-dd, with knowledge of the time of occurrence, in some cases); 2, year and month of occurrence known, day not know (yyy-mm-00); 3, year of occurrence known, month and day not know (yyy-00-00); Regarding the "Process" attribute, we have identified thirteen different types of mass

Table 1
List of attributes included in the web map of the mass movements inventory in the Italian Alps. In the display order, * are shown in the POI file.

Attribute	Description
S_acc*	Spatial accuracy
T_acc*	Time accuracy
Adm_reg	Administrative region
Source	Data source
Event	Name of the event
Date*	Date expressed in yyyy-mm-dd
Elev*	Meters above sea level
Latitude	°N (EPSG: 4326 – WGS 84)
Longitude	°E (EPSG: 4326 – WGS 84)
Process*	Name of the type of process
Owner*	The owner of the data
Id*	Identification number

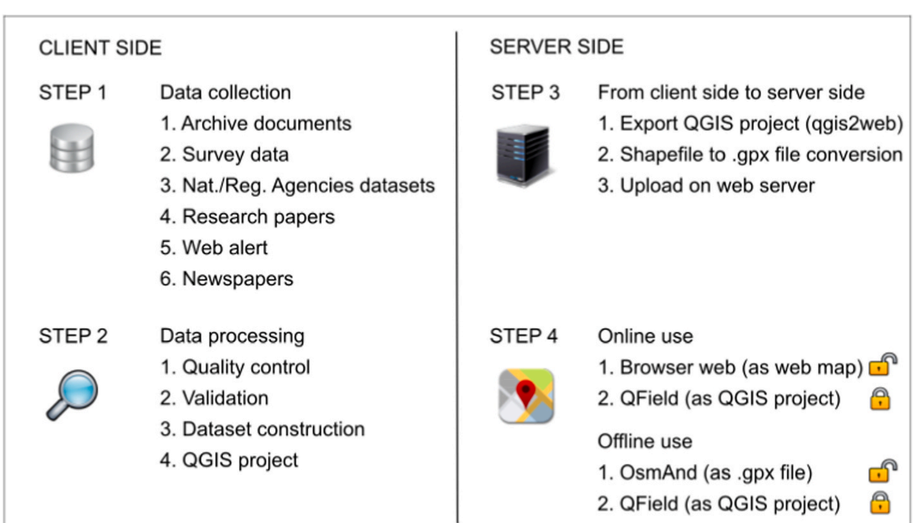

Fig. 2. Flowchart of the methodology applied, illustrating the different steps of the mass movements inventory in the Italian Alps.

movements: blockfall, complex, debris/mud flow, GLOF (glacial lake outburst flood), ice and snow avalanche, ice avalanche, ice fall, landslide, rock avalanche, rockfall, rockfall/ice avalanche, slow deformation, and soil slip. The other attributes are easy to understand and need no explanation. The term "landslide' has been used to include cases where the exact process type cannot be identified.

From now on, the MIA update is done directly on the shapefile in QGIS.

3.3. Step 3: from client side to server side

This step consists of three consecutive stages: 1) Export of the QGIS project; 2) Shapefile conversion; 3) Upload of files on the web server.

In the QGIS project, the MIA shapefile is exported as web map folder with qgis2web plugin. Qgis2web generates a web map folder directly in QGIS project that can be exported and uploaded in the website. No server-side software is required. The web maps created with this plugin can be inserted into responsive websites. With the dialog box of this plugin, it is possible to set the type of web map, the type of visualization and define the attributes of each layer that you want to query through the web map.

In addition, the web map comprises the Google Maps WMS (Web Map Service) and the OpenStreetMap WMS as base maps, alongside the MIA shapefile.

Moreover, the MIA shapefile has been converted to ".gpx" file, in order to use it as a POI (Points of Interest) on tablets or smartphones.

The web map folder of the MIA is uploaded in a web server via internet. A RAID 5 server configuration with 3 hard drives ensures data integrity. Periodic backups to external NAS unit are performed after each MIA update (usually every year).

3.4. Step 4: online and offline use

The MIA can be consulted both online and offline. Online, MIA can be consulted with a web browser, by connecting at http://geoclimalp.to.cnr.it/landslide-inventory, or with QField. In order to have the shortest internet address, the URL and the. zip file of the "inventory of high-altitude mass movements in the Italian Alps" was converted to "landslide-inventory".

Consultation via web browser is simple and intuitive. The web map shows the 772 points relating to the mass movements (red circles). By clicking on each point, the web map returns the attribute list of the associated process (Fig. 3). The web page includes four dialog boxes useful for querying the MIA. Mass movements queries can be done as follows (from top to bottom of the web page).

i) On the process type (Process);
ii) On the Italian administrative region in which the processes occurred (Adm_reg);
iii) On the elevation of the detachment or trigger zone (Elev);
iv) On the year in which the mass movement occurred (Date).

Offline consultation of the MIA is mainly necessary during field survey, during rescue and civil protection activities, or during mountain hiking or climbing, using tablet or smartphone devices. This is necessary because in various sectors of the Italian Alps, especially in high-altitude environments, there is not GSM signal. In this way, it is possible to consult the MIA even in the absence of an internet network, simply using the offline maps and the GPS signal of the tablet/smartphone.

MIA can be consulted offline with OsmAnd and with QField. OsmAnd (OpenStreetMap Automated Navigation Directions) is a navigation map/app for Android and iOS. The application is free of charge (110 MB) and data can be stored for offline use. Map files are downloaded to your device by selecting the desired countries or administrative regions. To use the MIA offline with OsmAnd is necessary to download the following maps: Liguria (69 MB), Piemonte (207 MB), Valle d'Aosta (22 MB), Lombardia (286 MB), Trentino Alto Adige (127 MB), Veneto (217 MB), Friuli Venezia Giulia 93 (MB). After downloading the maps directly in OsmAnd, it is necessary to download the MIA in ".gpx" file format (355 KB, 29 KB in compressed ".zip" file), available at https://geoclimalp.irpi.cnr.it/wp-content/uploads/2023/03/POI-landslide-inventory.zip. The ".gpx" file must be uploaded to OsmAnd as "My Places". This file is a light version of the web map shapefile. In fact, due to the small size of the screen and the type of file that OsmAnd manages (.gpx), the number of attributes relating to each point had to be reduced and it had to be displayed using a special string format. The string format is as follows (for the description of attributes see Table 1): "Id|Date|Elev|Process|S_acc|T_acc|Owner". An example of the OsmAnd screenshot is shown in Fig. 4A. With OsmAnd it is possible to query only one point at a time, but it is also possible to insert new points and modify those already present.

Online and offline consultation of the MIA are possible by using

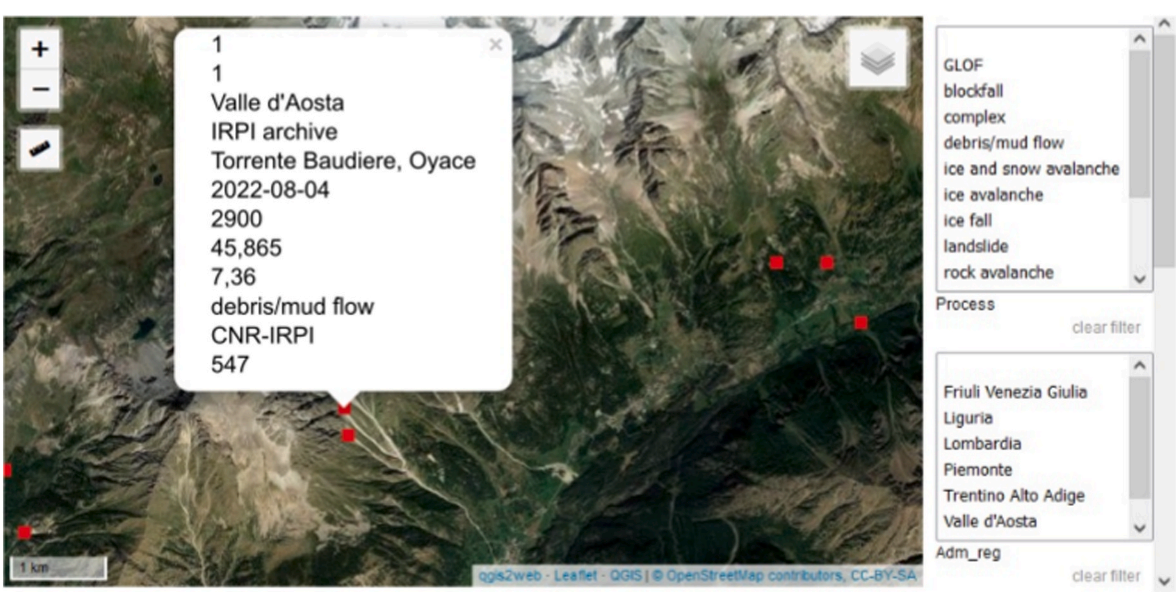

Fig. 3. Screenshot of the online consultation of the mass movements inventory in the Italian Alps with a common web browser. In this screenshot the point Id 547 is highlighted (base map Google Maps). For the attribute list and the display order see Table 1.

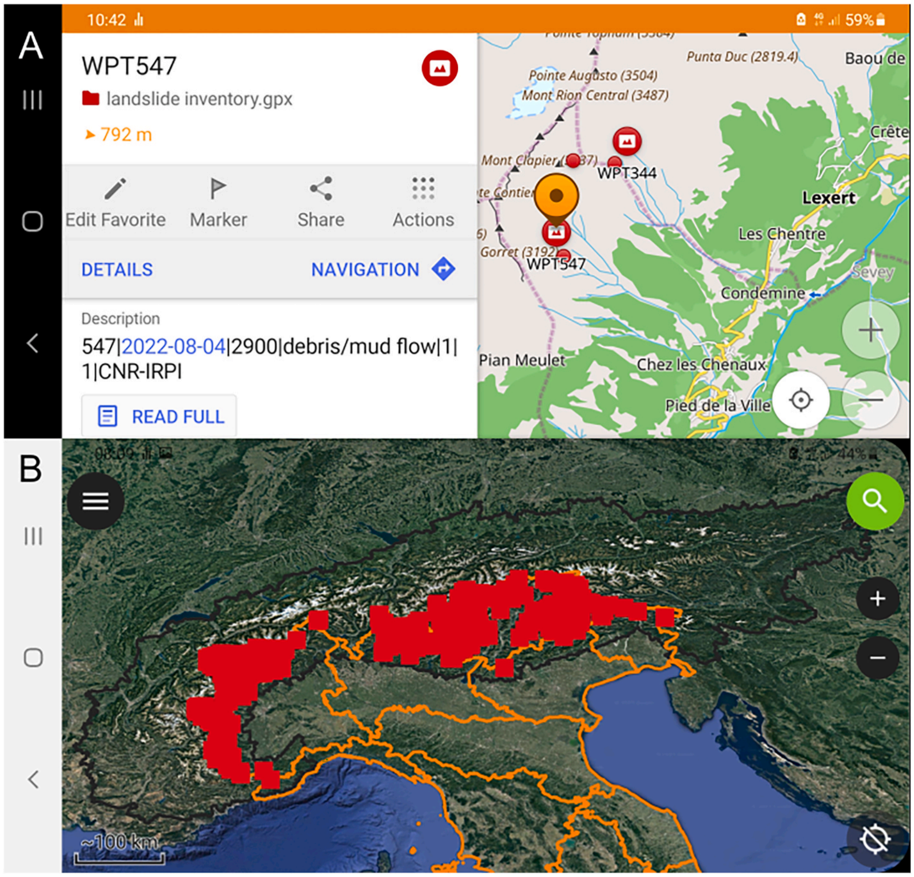

Fig. 4. Offline consultation of the mass movements inventory in the Italian Alps by smartphone. A, in this OsmAnd screenshot the point Id 547 is highlighted (base map OpenStreetMap). B, screenshot of an overview of the 772 points (red squares) of the mass movements inventory in the Italian Alps as appear in QField (base map Google Maps). The regional administrative boundaries (orange lines) and the alpine area boundary (black line), have been identified by the Alpine Convention (https://www.alpconv.org).

QField, an app supported by both Android and iOS. The QGIS projects can be loaded directly into QField. QField is based on QGIS and can be used on the field, with tablet or smartphone (version newer than Android 5.0). The application is free of charge (65 MB). The requirements on field are different from the desktop ones. The screen is smaller and this limits human-peripheral interaction. To fix this problem, several operations (e. g. layer styling setup, downloading offline maps, project setup) should be done on a desktop/laptop PC with QGIS installed first. Also in this case it is possible to query one point at a time, insert new points and modify those already present.

Using QField online, the WMSs that are present in the QGIS project are directly imported as base map. Using QField offline, the maps that are present in the QGIS project are directly imported as base map. An example of the QField screenshot is shown in Fig. 4B. In order to promote and extend this type of investigation, the use of the MIA through QField is released within specific collaboration agreements.

4. Results and discussion

Currently, the MIA contains information relating to 772 mass movements occurred in the Italian Alps at an elevation above 1500 m, during the period 2000–2022.

The most frequent types of processes are rockfall (279 processes, 36 % of the total) and debris/mud flows (191 processes, 25 % of the total). The most affected administrative regions are Valle d'Aosta (311 events, 40.3 % of the total), Lombardia (147 events, 19.1 % of the total), Piemonte (126 events, 16.3 % of the total) and Trentino Alto Adige (121 events, 15.7 % of the total). The greatest number of events occurred in 2022 (71 events), and out of these 71, 60 events (85 %) occurred in the summer (June, July, August). Another analysis has highlighted an evident trend towards an increase in mass movements over the years and during summer (Fig. 5). Among the main causes of this increase we can mention permafrost degradation, poor snowfall in winter and spring seasons (Nigrelli et al., 2018, 2022; Biskaborn et al., 2019; Masson-Delmotte et al., 2021).

Observing geographical position of the 772 mass movements in the Italian Alps, it can be seen that some alpine sectors have a higher concentration of events than others (Fig. 6). This uneven geographical distribution of the mass movements is due to various factors, and in particular to.

i) Different geological and geomorphological features: for example, the western Alpine sector is the one in which the highest mountain massifs are present, consequently there are many steep slopes and more prone to instability;
ii) Different meteo-climatic conditions: in the Alps, climate can differ greatly from one alpine sector to another.
iii) Presence/absence of cryosphere: cryosphere distribution varies considerably, depending on the specific climatic, geographical and geomorphological features. Over the last thirty years, temperature increase caused melting of part of the cryosphere and, as a consequence, the permafrost degradation, with the increase in slope instability.
iv) Different degree of knowledge about mass movements: there are many mass movements that take place in remote alpine areas and, for this reason, are unfortunately not identified and documented;

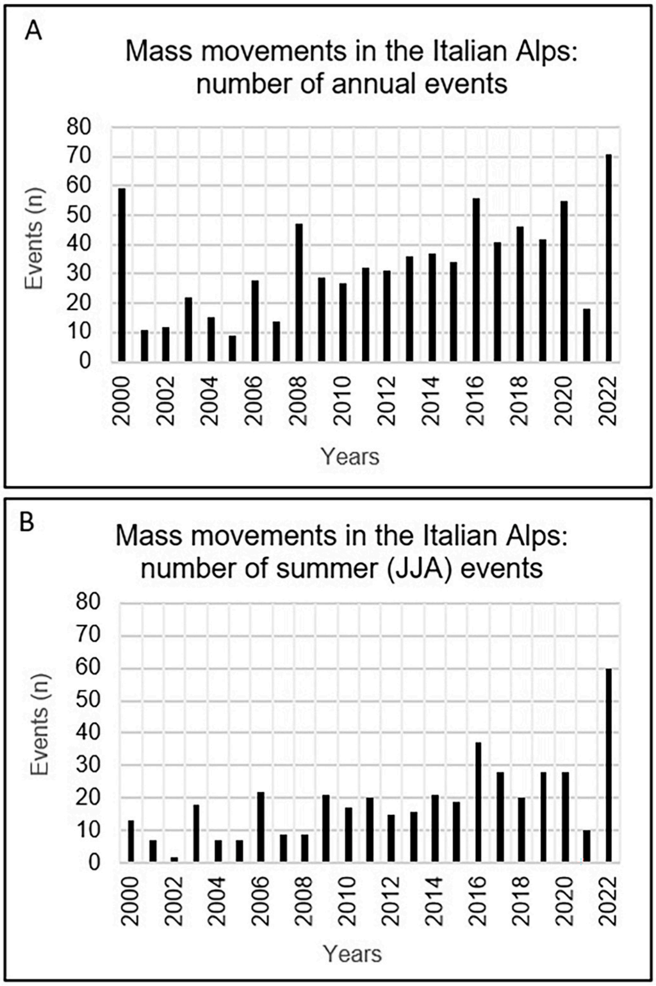

Fig. 5. Mass movements inventory in the Italian Alps. A, number of annual events; B, number of summer events (JJA: June, July and August).

v) Different regional policies for collection and publication of data on mass movements.

MIA is an excellent support tool for many activities that take place in and for the mountains. Its consultation, both online and offline, makes MIA suitable for use with different types of devices. For example, with desktop and laptop devices, the MIA can be used indoors and the main users can be local government bodies, decision makers, researchers, journalists, or anyone who wants to plan different types of mountain activities. With tablet and smartphones devices, the MIA can be used outdoors, during rescue and survey activities, training and environmental education activities, hiking or climbing. In this mode, the main users can be researchers, professors and teachers, hikers, climbers, tourists, citizens, or those who want to carry out on-site training activities on the natural hazards in the mountains. On this regard, it is worth reiterating that the MIA can be used not only as a consultation tool but also to enter new mass movements. This use can be particularly suitable for land-use planning, disaster prevention, risk mitigation and monitoring activities, managed by government bodies, municipalities, natural parks and environmental agencies. The damages caused by mass movements on infrastructures and human activities in the Alps are growing and the socio-economic losses are remarkable (Gariano et al., 2016; Luino et al., 2020; Huang and Zhang, 2022). To reduce these damages and, more generally, to apply correct risk mitigation strategies, some solutions based on historical data or monitoring systems or ecological approaches can also be adopted. As regards solutions based on historical data, it is necessary to underline its importance, since this is often ignored or considered of little importance by the scientific community. Historical data can contain key information about events, their impacts and social and cultural adaptation (Luino et al., 2023). As regards solutions based on monitoring systems, it is possible to say that these systems are very effective for some types of mass movements but not for all. For example, the monitoring systems used to prevent and mitigate risks arising from debris flows have now reached a high level of reliability and are used in many cases in the Alps (Marchi et al., 2021; Arattano et al., 2023). Regarding solutions based on ecological approaches, we can mention the role that forests have. Existing methods and models for assessing the effects of forests on natural risks are now sufficient to integrate forests into quantitative risk assessment (Moos et al., 2018).

Currently, the understanding of future scenarios still shows large uncertainty and, in this context, MIA can be an effective tool in promoting new risk mitigation strategies in scenarios of uncertainty.

5. Future developments and conclusions

Because of the fact that there is a clear trend towards an increase in mass movements over the years, the updating of the MIA takes place annually. Furthermore, an important activity in progress is the digitization of mass movements that took place before 2000, already

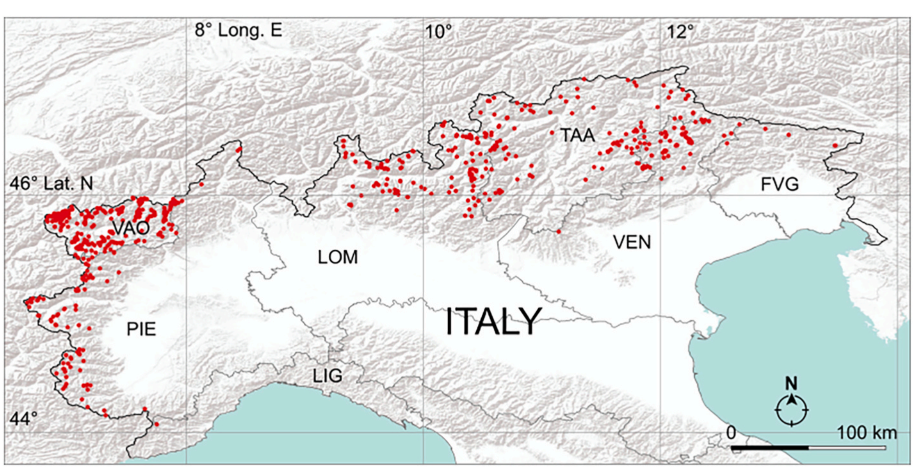

Fig. 6. Online consultation of the mass movements inventory in the Italian Alps. Geographical distribution of the 772 processes (red points) included in the mass movements inventory in the Alps, and the 7 administrative regions involved (LIG, Liguria; PIE, Piemonte; VAO, Valle d'Aosta; LOM, Lombardia; VEN, Veneto; TAA, Trentino Alto Adige; FVG, Friuli Venezia Giulia). Basemap QGIS WMS ESRI Terrain.

inventoried by the Research Institute for Geo-hydrological Protection.

New IT solutions are currently being developed, in order to improve the usability of the MIA. Information management systems are being tested to be applied to this inventory, capable of containing metadata (e.g. geoportals), in order to fulfill EU data requirements and the FAIR data directives. An important capability that we are developing in the MIA concerns the possibility of including images and/or videos relating to the processes inserted. Another important action that we are developing in the MIA is the inclusion of new fields in the dataset, such as those containing information on the geology of the site where the mass movement took place and, where these are present, on the damage at the infrastructures. This action requires a large amount of work because this new information must also be included for the processes already present, in order to make all the cases inventoried complete and homogeneous.

We also intend to verify the possibility of making the MIA interact with existing datasets at a regional and national scale, in order to activate a virtuous process whereby these datasets automatically provide the information of interest for the MIA, and the MIA can possibly integrate the information from the other datasets with original information: in fact, as already mentioned, mass movements occurring at high elevation may easily go unreported. In the future, the collaboration of stakeholders and citizens could give even more benefits to the development the tools like MIA. Participatory mapping approach are promising citizen science activities to move towards a collaborative and collective post-disaster mapping and contribute to producing updated landslide information. This would provide new opportunities to improve risk preparedness, assessment, and early action to landslide hazard and as well as raising awareness (e.g., Juang et al., 2019).

As a conclusion, this simple inventory is a practical tool for scientific community and government bodies studying the effects of climate change on high-elevation environments in the Alps. Moreover, it is a tangible contribution towards a European mass movements inventory, which can be continuously updated within the Alpine region. Agreements, collaborations, and exchanges between private entities, historians, research groups, or institutions that may have historical dataset or archives throughout the Alps could be useful in this regard.

Code availability section

No code or software has been developed for this research.

Authorship contribution statement

Guido Nigrelli is first author and corresponding author and made substantial contributions to idea development, inventory development, database development, manuscript development, data acquisition, data analysis, and interpretation of results.

Roberta Paranunzio made substantial contributions to inventory development, database development, manuscript development, data acquisition, data analysis, and interpretation of results.

Laura Turconi made substantial contributions to inventory development, manuscript development, data acquisition, data analysis, and interpretation of results.

Fabio Luino made substantial contributions to inventory development, manuscript development, data acquisition, data analysis, and interpretation of results.

Giovanni Mortara made substantial contributions to inventory development, manuscript development, data acquisition, and interpretation of results.

Michele Guerini made substantial contributions to database development, manuscript development, data acquisition, data analysis, and interpretation of results.

Marco Giardino made substantial contributions to inventory development, manuscript development, data analysis, and interpretation of results.

Marta Chiarle made substantial contributions to idea development, inventory development, database development, manuscript development, data acquisition, data analysis, and interpretation of results.

CRediT authorship contribution statement

Guido Nigrelli: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Supervision, Validation, Writing – original draft, Writing – review & editing. **Roberta Paranunzio:** Conceptualization, Investigation, Methodology, Validation, Writing – review & editing, Writing – original draft. **Laura Turconi:** Conceptualization, Data curation, Investigation, Methodology, Validation, Writing – review & editing, Writing – original draft. **Fabio Luino:** Conceptualization, Methodology, Validation, Writing – review & editing, Writing – original draft. **Giovanni Mortara:** Conceptualization, Investigation, Methodology, Validation, Writing – original draft. **Michele Guerini:** Data curation, Investigation, Methodology, Writing – review & editing, Writing – original draft. **Marco Giardino:** Conceptualization, Methodology, Writing – review & editing, Writing – original draft. **Marta Chiarle:** Conceptualization, Data curation, Methodology, Validation, Writing – original draft, Writing – review & editing.

Declaration of competing interest

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

Data availability

Data will be made available on request.

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References

Allen, S., Huggel, C., 2013. Extremely warm temperatures as a potential cause of recent high mountain rockfall. Global Planet. Change 107, 59–69. https://doi.org/10.1016/j.gloplacha.2013.04.007.

Arattano, M., Chiarle, M., Coviello, V., Nigrelli, G., 2023. Performance of the debris flow alarm system ALMOND-F on the rochefort torrent (val d'Aosta) on August 5, 2022. E3S Web of Conferences 415, 03002. https://doi.org/10.1051/e3sconf/202341503002.

Bajni, G., Camera, C.A.S., Apuani, T., 2021. Deciphering meteorological influencing factors for Alpine rockfalls: a case study in Aosta Valley. Landslides 18, 3279–3298. https://doi.org/10.1007/s10346-021-01697-3.

Barry, R.G., 2008. Mountain Weather and Climate. Cambridge University Press, New York.

Biskaborn, B.K., Smith, S.L., Noetzli, J., Matthes, H., Vieira, G., Streletskiy, D.A., others forty-two authors, 2019. Permafrost is warming at a global scale. Nat. Commun. 10, 264. https://doi.org/10.1038/s41467-018-08240-4.

Blondeau, S., Gunnell, Y., Jarman, D., 2021. Rock slope failure in the Western Alps: a first comprehensive inventory and spatial analysis. Geomorphology 380. https://doi.org/10.1016/j.geomorph.2021.107622.

Chiarle, M., Geertsema, M., Mortara, G., Clague, J., 2021. Relations between climate change and mass movement: perspectives from the Canadian Cordillera and the European Alps. Global Planet. Change 202. https://doi.org/10.1016/j.gloplacha.2021.103499.

Chiarle, M., Viani, C., Mortara, G., Deline, P., Tamburini, A., Nigrelli, G., 2022. Large glacier failures in the Italian Alps over the last 90 years. Geogr. Fis. Din. Quaternaria 45 (1), 19–40. https://doi.org/10.4461/GFDQ.2022.45.2.

Corò, D., Galgaro, A., Fontana, A., Carton, A., 2015. A regional rockfall database: the Eastern Alps test site. Environ. Earth Sci. 74, 1731–1742. https://doi.org/10.1007/s12665-015-4181-5.

Coviello, V., Chiarle, M., Arattano, M., Pogliotti, P., di Cella, U.M., 2015. Monitoring rock wall temperatures and microseismic activity for slope stability investigation at JA Carrel hut, Matterhorn. In: Engineering Geology for Society and Territory-Volume

1: Climate Change and Engineering Geology. Springer International Publishing, pp. 305–309.
Dal Piaz, G., Bistacchi, A., Massironi, M., 2003. Geological outline of the Alps. Episodes 26, 175–180. https://doi.org/10.18814/epiiugs/2003/v26i3/004.
Eisbacher, G.H., Clague, J.J., 1984. Destructive Mass Movements in High Mountains: Hazard and Management. Geological Survey of Canada, Ottawa.
Fratianni, S., Acquaotta, F., 2017. The Climate of Italy. Landscapes and Landforms of Italy, vols. 29–38. Springer Nature Switzerland AG.
Gariano, S.L., Guzzetti, F., 2016. Landslides in a changing climate. Earth Sci. Rev. 162, 227–252. https://doi.org/10.1016/j.earscirev.2016.08.011.
Giardino, M., Mortara, G., Chiarle, M., 2017. The Glaciers of the Valle d'Aosta and Piemonte Regions: Records of Present and Past Environmental and Climate Changes. In: Landscapes and Landforms of Italy, vols. 77–88. Springer Nature Switzerland AG.
Gobiet, A., Kotlarski, S., Beniston, M., Heinrich, G., Rajczak, J., Stoffel, M., 2014. 21st century climate change in the European Alps: a review. Sci. Total Environ. 493, 1138–1151. https://doi.org/10.1016/j.scitotenv.2013.07.050.
Gruber, S., Haeberli, W., 2007. Permafrost in steep bedrock slopes and its temperatures-related destabilization following climate change. J. Geophys. Res. Earth Surf. 112 https://doi.org/10.1029/2006JF000547.
Guerini, M., Giardino, M., Paranunzio, R., Nigrelli, G., Turconi, L., Luino, F., Chiarle, M., 2021. Slope Failures at High Elevation in the Italian Alps in the Period 2000-2020. Pangaea Data Publisher for Earth & Environmental Science. https://doi.org/10.1594/PANGAEA.931824.
Guzzetti, F., Peruccacci, S., Rossi, M., Stark, C.P., 2008. The rainfall intensity-duration control of shallow landslides and debris flows: an update. Landslides 5, 3–17. https://doi.org/10.1007/s10346-007-0112-1.
Hock, R., Rasul, G., others thirteen authors, 2019. High Mountain areas. In: IPCC Special Report on the Ocean and Cryosphere in a Changing Climate. https://doi.org/10.1017/9781009157964.004.
Huang, Y., Zhang, B., 2022. Challenges and perspectives in designing engineering structures against debris-flow disaster. Eur. J. Environ. Civ. Eng. 26 (10), 4476–4497. https://doi.org/10.1080/19648189.2020.1854126.
Huggel, C., Salzmann, N., Allen, S., Caplan-Auerbach, J., Fischer, L., Haeberli, W., Larsen, C., Schneider, D., Wessels, R., 2010. Recent and future warm extreme events and high-mountain slope stability. Philos. Trans. A. Math. Phys. Eng. Sci. 368, 2435–2459. https://doi.org/10.1098/rsta.2010.0078.
Jomelli, V., Pavlova, I., Giacona, F., Zgheib, T., Eckert, N., Alps, F., 2019. Respective influence of geomorphologic and climate conditions on debris-flow occurrence in the Northern French Alps. Landslides 16, 1871–1883. https://doi.org/10.1007/s10346-019-01195-7.
Juang, C.S., Stanley, T.A., Kirschbaum, D.B., 2019. Using citizen science to expand the global map of landslides: introducing the cooperative open online landslide repository (COOLR). PLoS One 14 (7), 1–28. https://doi.org/10.1371/journal.pone.0218657.
Lucchesi, S., Bertotto, S., Chiarle, M., Fioraso, G., Giardino, M., Nigrelli, G., 2019. Little Ice Age glacial systems and related natural instability processes in the Orco Valley (North-Western Italy). J. Maps 15 (2), 142–152. https://doi.org/10.1080/17445647.2018.1564382.
Luino, F., Barriendos, M., Gizzi, F.T., Glaser, R., Gruetzner, C., Palmieri, W., Porfido, S., Sangster, H., Turconi, L., 2023. Historical data for natural hazard risk mitigation and land use planning. Land 12, 1777. https://doi.org/10.3390/land12091777.
Luino, F., De Graff, J., Roccati, A., Biddoccu, M., Cirio, C.G., Faccini, F., Turconi, L., 2020. Eighty years of data collected for the determination of rainfall threshold triggering shallow landslides and mud-debris flows in the Alps. Water 12 (133), 1–29. https://doi.org/10.3390/w12010133.
Luino, F., 2005. Sequence of instability processes triggered by heavy rainfall in northwestern Italy. Geomorphology 66, 13–39. https://doi.org/10.1016/j.geomorph.2004.09.010.
Marchi, L., Cazorzi, F., Arattano, M., Cucchiaro, S., Cavalli, M., Crema, S., 2021. Debris flows recorded in the Moscardo catchment (Italian Alps) between 1990 and 2019. Nat. Hazards Earth Syst. Sci. 21, 87–97. https://doi.org/10.5194/nhess-21-87-2021.
Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S.L., others fifteen authors, 2021. Climate Change 2021: the Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. https://doi.org/10.1017/9781009157896.
Moos, C., Bebi, P., Schwarz, M., Stoffel, M., Sudmeier-Rieux, K., Dorren, L., 2018. Ecosystem-based disaster risk reduction in mountains. Earth Sci. Rev. 177, 497–513. https://doi.org/10.1016/j.earscirev.2017.12.011.
Mostbauer, K., Kaitna, R., Prenner, D., Hrachowitz, M., 2018. The temporally varying roles of rainfall, snowmelt and soil moisture for debris flow initiation in a snow-dominated system. Hydrol. Earth Syst. Sci. 22, 3493–3513. https://doi.org/10.5194/hess-22-3493-2018.
Nigrelli, G., Chiarle, M., 2023. 1991-2020 climate normal in the European Alps: focus on high-elevation environments. J. Mountain Sci. 20, 2149–2163. https://doi.org/10.1007/s11629-023-7951-7.
Nigrelli, G., Chiarle, M., Merlone, A., Coppa, G., Musacchio, C., 2022. Rock temperature variability in high-altitude rockfall-prone areas. J. Mountain Sci. 19, 798–811. https://doi.org/10.1007/s11629-021-7073-z.
Nigrelli, G., Chiarle, M., 2021. Evolution of temperature indices in the periglacial environment of the European Alps in the period 1990–2019. J. Mountain Sci. 18, 2842–2853. https://doi.org/10.1007/s11629-021-6889-x.
Nigrelli, G., Chiarle, M., Nuzzi, A., Perotti, L., Torta, G., Giardino, M., 2013. A web-based, relational database for studying glaciers in the Italian Alps. Comput. Geosci. 51, 101–107. https://doi.org/10.1016/j.cageo.2012.07.027.
Nigrelli, G., Fratianni, S., Zampollo, A., Turconi, L., Chiarle, M., 2018. The altitudinal temperature lapse rates applied to high elevation rockfalls studies in the Western European Alps. Theor. Appl. Climatol. 131, 1479–1491. https://doi.org/10.1007/s00704-017-2066-0.
Nigrelli, G., Marino, A.L.L., 2012. Dbclim: a web-based, open-source relational database for rainfall event studies. Comput. Geosci. 48, 337–339. https://doi.org/10.1016/j.cageo.2012.02.002.
Paranunzio, R., Chiarle, M., Laio, F., Nigrelli, G., Turconi, L., Luino, F., 2019a. Slope Failures in High-Mountain Areas in the Alpine Region. Pangaea Data Publisher for Earth & Environmental Science. https://doi.org/10.1594/PANGAEA.903761.
Paranunzio, R., Chiarle, M., Laio, F., Nigrelli, G., Turconi, L., Luino, F., 2019b. New insights in the relation between climate and slope failures at high-elevation sites. Theor. Appl. Climatol. 137, 1765–1784. https://doi.org/10.1007/s00704-018-2673-4.
Paranunzio, R., Laio, F., Chiarle, M., Nigrelli, G., Guzzetti, F., 2016. Climate anomalies associated with the occurrence of rockfalls at high-elevation in the Italian Alps. Nat. Hazards Earth Syst. Sci. 16, 2085–2106. https://doi.org/10.5194/nhess-16-2085-2016.
Paranunzio, R., Laio, F., Nigrelli, G., Chiarle, M., 2015. A method to reveal climatic variables triggering slope failures at high elevation. Nat. Hazards 76, 1039–1061. https://doi.org/10.1007/s11069-014-1532-6.
Paranunzio, R., Marra, F., 2024. Open gridded climate datasets can help investigating the relation between meteorological anomalies and geomorphic hazards in mountainous areas. Global Planet. Change 232, 104328. https://doi.org/10.1016/j.gloplacha.2023.104328.
Pavlova, I., Jomelli, V., Brunstein, D., Grancher, D., Martin, E., Déqué, M., 2014. Debris flow activity related to recent climate conditions in the French Alps: a regional investigation. Geomorphology 219, 248–259. https://doi.org/10.1016/J.GEOMORPH.2014.04.025.
Peruccacci, S., Gariano, S.L., Melillo, M., Solimano, M., Guzzetti, F., Brunetti, M.T., 2023. The Italian rainfall-induced LandslIdes CAtalogue, an extensive and accurate spatio-temporal catalogue of rainfall-induced landslides in Italy. Earth Syst. Sci. Data 15, 2863–2877. https://doi.org/10.5194/essd-15-2863-2023, 2023.
Piacentini, T., Calista, M., Crescenti, U., Miccadei, E., Sciarra, N., 2020. Seismically induced snow avalanches: the Central Italy case. Front. Earth Sci. 8, 1–27. https://doi.org/10.3389/feart.2020.599611.
Ponziani, M., Ponziani, D., Giorgi, A., Stevenin, H., Ratto, S.M., 2023. The use of machine learning techniques for a predictive model of debris flows triggered by short intense rainfall. Nat. Hazards 117, 143–162. https://doi.org/10.1007/s11069-023-05853-x.
Poratelli, F., Cocuccioni, S., Accastello, C., Steger, S., Schneiderbauer, S., Brun, F., 2020. State-of-the-art on ecosystem-based solutions for disaster risk reduction: the case of gravity-driven natural hazards in the Alpine region. Int. J. Disaster Risk Reduc. 51, 1–8. https://doi.org/10.1016/j.ijdrr.2020.101929.
Prenner, D., Kaitna, R., Mostbauer, K., Hrachowitz, M., 2018. The value of using multiple hydrometeorological variables to predict temporal debris flow susceptibility in an alpine environment. Water Resour. Res. 54, 6822–6843. https://doi.org/10.1029/2018WR022985.
Rebetez, M., Lugon, R., Baeriswyl, P.A., 1997. Climatic change and debris flows in high mountain regions: the case study of the ritigraben torrent (Swiss Alps). In: Climatic Change at High Elevation Sites. Springer Netherlands, Dordrecht, pp. 139–157. https://doi.org/10.1007/978-94-015-8905-5_8.
Rubel, F., Brigger, K., Haslinger, K., Auer, I., 2016. The climate of the European Alps: shift of very high resolution Köppen-Geiger climate zones 1800–2100. Meteorol. Z. 26, 115–125. https://doi.org/10.1127/metz/2016/0816.
Sacco, G.M., Nigrelli, G., Bosio, A., Chiarle, M., Luino, F., 2012. Dynamic taxonomies applied to a web-based relational database for geo-hydrological risk mitigation. Comput. Geosci. 39, 182–187. https://doi.org/10.1016/j.cageo.2011.07.005.
Savi, S., Comiti, F., Strecker, M.R., 2021. Pronounced increase in slope instability linked to global warming: a case study from the eastern European Alps. Earth Surf. Process. Landforms 46 (7), 1328–1347. https://doi.org/10.1002/esp.5100.
Schlögel, R., Kofler, C., Gariano, S.L., Van Campenhout, J., Plummer, S., 2020. Changes in climate patterns and their association to natural hazard distribution in South Tyrol (Eastern Italian Alps). Sci. Rep. 10, 1–9. https://doi.org/10.1038/s41598-020-61615-w.
Soldati, M., Borgatti, L., Cavallin, A., De Amicis, M., Frigerio, S., Giardino, M., Mortara, G., Pellegrini, G.B., Ravazzi, C., Surian, N., Tellini, C., Zanchi, A., 2006. Geomorphological evolution of slopes and climate changes in northern Italy during the Late Quaternary: spatial and temporal distribution of landslides and landscape sensitivity implications. Geogr. Fis. Din. Quaternaria 29 (2), 165–183.
Turconi, L., Nigrelli, G., Conte, R., 2014. Historical datum as a basis for a new GIS application to support civil protection services in NW Italy. Comput. Geosci. 66, 13–19. https://doi.org/10.1016/j.cageo.2013.12.008.
Viani, C., Chiarle, M., Paranunzio, R., Merlone, A., Musacchio, C., Coppa, G., Nigrelli, G., 2020. An integrated approach to investigate climate-driven rockfall occurrence in high alpine slopes: the Bessanese glacial basin, Western Italian Alps. J. Mountain Sci. 17, 2591–2610. https://doi.org/10.1007/s11629-020-6216-y.
Walter, F., Amann, F., Kos, A., Kenner, R., Phillips, M., de Preux, A., Huss, M., Tognacca, C., Clinton, J., Diehl, T., Bonanomi, Y., 2020. Direct observations of a three million cubic meter rock-slope collapse with almost immediate initiation of ensuing debris flows. Geomorphology 351, 106933. https://doi.org/10.1016/j.geomorph.2019.106933.
Wanner, H., Rickli, R., Salvisberg, E., Schmutz, C., Schüepp, M., 1997. Global climate change and variability and its influence on alpine climate - concepts and observations. Theor. Appl. Climatol. 58, 221–243. https://doi.org/10.1007/BF00865022.
Wood, J.L., Harrison, S., Reinhardt, L., Taylor, F.E., 2020. Landslide databases for climate change detection and attribution. Geomorphology 355. https://doi.org/10.1016/j.geomorph.2020.107061.