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Debris flow and debris flood hazard assessment in mountain catchments

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ABSTRACT

Debris flow and debris flood phenomena threat the life of thousands of citizens living in mountain areas and endanger buildings and infrastructure worldwide. The assessment of the probable magnitude of these events is a key process in hazard mapping and the research community has been improving their comprehension of this topic in the last decades and consequently the capacity to predict the impacts of such events. The study analyses the current state of the art for hazard mapping and it pays particular attention to the concept of residual hazard. Through an extensive analysis of events that caused major damages, processes, factors and basin conditions, which are strictly related to debris flow and debris flood events, are investigated in order to improve the hazard-mapping reliability. Drawing from a thorough analysis of the literature and four complex events directly investigated, the study proposes a procedural framework to develop more reliable sets of possible scenarios for hazard mapping. The developed methodology proposes to include in the hazard assessment of mountain catchments (i) exogenous forces (climatic forces, natural and anthropic disturbances), (ii) alteration of the system condition (countermeasures malfunctions/failure and bed/banks erosion) and (iii) flow type variation (spatial and temporal variation of the flow and change in transport typology). The result is a perspective hazard map that takes in account all these factors and processes together with an estimation of their mid-long term evolution, accounting for climate change conditions. Here, future catchment responses are incorporated in a global catchment view, which allows the prediction of seemingly infrequent processes that are sometimes not rare for certain mountain basins. The proposed framework aims to assist practitioners and civil authorities in better defining the hazard classes for a given area thereby reducing uncertainty related to possible debris flow and debris flood events.

1. Introduction

In the Alpine region, people and settlements are exposed to different natural hazards such as rockfalls, snow avalanches, landslides and floods. In particular, hydrological hazards represent the main source of risk for citizens living in the mountainous region, as debris flows and debris floods cause severe damage every year (Zimmermann and Keiler, 2015). These phenomena are different from river floods, since they are characterised by the presence of debris material and the high slope of the channel network (Church and Jakob, 2020; Takahashi, 2007). Due to the short concentration times and high flow velocities, debris flows and debris floods result difficult to predict (Hürlimann et al., 2008). Therefore, an accurate hazard evaluation of exposed areas is fundamental to prevent disastrous consequences and design mitigation structures. The associated hydrological risk for a certain area derives from the likely combination of occurrence and the consequences towards values at risk (Crozier and Glade, 2005). In particular, the definition of risk involves three elements: (i) consequences on human goods and lives, (ii) an occurrence probability, and (iii) a context in which the risk could take place (Renn, 2008). Regarding natural hazards, risk is calculated as a function of the probability of event occurrence in a defined scenario and the derived consequences of elements exposed to that risk (Varnes and Commission on Landslides, 1984).

Vulnerable elements are delineated from land use maps and the related value assessment (Keiler et al., 2004). Instead, to compute the hazard map, different scenarios are developed and evaluated to predict the probable impact magnitude of future events. Therefore, the major source of uncertainty derives from the hazard map, since the vulnerability map represents elements of a certain value for humans, directly identifiable from topographic maps, aerial photos, field surveys, or official documents (i.e., property records). Moreover, the relative degree of vulnerability can be set according to vulnerability curves (Fuchs et al., 2007). Regarding debris flows and debris floods, different methodologies are commonly used to estimate the magnitude of debris flows and

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debris floods for different scenarios associated with a certain probability of occurrence. These methods can be divided into three main classes (Marchi et al., 2010): historical and geomorphological (Aulitzky, 1980), empirical (Ikeya, 1989; Rickenmann, 1999) and numerical models (McDougall and Hungr, 2004; O'Brien et al., 1993). The results of this analysis can indicate the possible areas of impact of hydrogeological hazards. The parameters used to assess the magnitude of the scenarios are normally a combination of maximum flow height, velocity and pressure (Barnhart et al., 2021; Hürlimann et al., 2006; Kean et al., 2019; Melo et al., 2020). Consequently, the impact area is divided into classes defined by national and/or regional regulations defining these parameters thresholds. Commonly, an area affected by a natural hazard is usually divided into four zones: high, medium, low and no hazard. In some cases, between the low and no hazard, the residual hazard class appears. Although the first four classes are commonly well defined by authorities, the determination of the residual hazard class, when present, often results challenging to interpret since the description and the procedures for its definition are not as clear, complete and exhaustive as for the other classes. In several regulation the residual hazard is targeted by flood hydrographs with very high return period (e.g. larger than 300 years).

Usually residual hazard is the hazard associated with rare events in terms of chain of events and conditions, and therefore it may not be correct to strictly relate it with a hydrological return period. Effectively, the residual hazard should also incorporate all processes and elements that may increase the magnitude of an event over a certain threshold, which can be classified as rare or extremely rare. These scenarios could also be associated to the hazard that remains after the implementation of mitigation measures designed for a target return period, by the interaction with other processes (i.e. process chains), or by environmental changes with respect to actual conditions (Turkington et al., 2016). For this purpose, a comprehensive accurate analysis of the processes connected to debris flow and flood events must be conducted in order to better define what can be assigned in the standard classification of hazard or what can represent residual hazard.

In the setting of mountain streams, a knowledge gap exists in the scientific literature and also in national and regional regulations involving the topic of hazard assessment derived through the analysis of multiple scenarios. In particular, which scenarios should be incorporated is not clearly identified, and in particular which factors and processes related to the flow. In such a context other processes and elements that may increase the event magnitude are not considered. Conversely, several debris flows and debris floods characterized by disastrous consequences are not always defined as exceptional from the hydrological point of view. This proves that in some cases such events might have been predicted only if the hazard evaluation processes had taken into account an objective and systematic analysis of the factors affecting the magnitude and propagation of the event. In this circumstance, the scientific community has the goal to clearly identify and describe processes and factors that must be taken into account to further improve the hazard mapping. Moreover, since hazard mapping needs to set up scenarios characterized by long return periods (greater than 50 years), forecasted scenarios should incorporate the effect of climate change. In such a sense, different studies already highlight the shift in magnitude and frequency caused by climate change on debris flow and debris flood events and on processes that can affect the magnitude of the events (Hirschberg et al., 2021b; Stoffel et al., 2014b). Therefore, climate change should be attempted at least in hazard mapping and consequently also in the design of torrent countermeasures.

This study directly addresses such aspects, first analysing the actual protocols and methodologies for hazard mapping and then discussing the concept of residual hazard, to better define it. The related gap of knowledge is identified and further discussed in the second section. In the third section, the analysis highlights processes and factors related to debris flow and debris flood phenomenon that must be better considered to improve the hazard assessment (e.g. changes in the flow characteristics or effect of natural/artificial disturbance, malfunction of countermeasures). Successively, the fourth section, accounting for the literature position and for four meaningful events described in the Appendix, aims to propose a procedural framework to help in the building of a set of suitable scenarios for hazard mapping.

The study therefore reports and investigates extreme debris flows/floods occurring in mountainous areas identifying the processes that can increase the event intensity and consequently defining the cases in which the residual hazard is present. In this context, the study defines and provides information and methods to improve the hazard assessment with a particular regard to residual hazard. The study will lead practitioners and civil authorities to improve the representation of probable impact areas with the related intensity, taking into account processes that could affect the flow motion. At the same time the study highlights insights and methods that would be deepened to further improve hazard assessment and mapping.

2. Hazard assessment in mountain catchments

The straightforward approach for hazard mapping of a certain area threatened by hydrogeological processes is the development of multiple scenarios. Scenarios serve to predict probable flow depths and velocities of events with different features and magnitudes. The thresholds to define different standard event intensities are generally associated to return periods in the interval between 30 and 300 years (Riedl, 2010). This definition is actually the most widespread way to derive hazard mapping in different regions around the world. As mentioned in the introduction, the residual hazard class, in Switzerland, is determined by flow events characterized by a return period greater than 300 years (BAFU, 2016). Also in Austria, residual hazard is defined by the 300 years return period threshold (Embleton-Hamann, 2007). So, according to different methodologies reported in the literature, the setup of the residual hazard seems to be a straightforward implementation. The input data that can be varied to obtain residual hazard scenarios depend on the procedure adopted to generate the scenarios for hazard assessment (Hürlimann et al., 2008; Rickenmann, 2016). Some examples are the increase in the precipitation amount, solid and fluid volume, bank and bed erosion rates, and decrease of friction parameters between the flow and the terrain and within the flow. However, when predicting the impact areas of rare events (i.e. for return periods greater than 100–300 years), the framework for hazard assessment should consider the effect of climate change on the input variables used to derive hazard scenarios (Jakob, 2019). Furthermore, the input variables obtained through the statistical analysis of past events could not be suitable to perform reliable scenarios for basically two reasons. First, the frequency-magnitude relations are based on past events and estimated through direct (Riley et al., 2013) or indirect (Stoffel and Bollschweiler, 2008) measurements: in most regions the period of measurements is limited to around 100–200 and 1000–5000 years for direct and indirect measurements, respectively. This means that data used to derive extreme scenarios may not be reliable. A technique such as Peaks Over Threshold (Bačová-Mitková and Onderka, 2010) to derive extreme value distributions (e.g. Generalized Pareto Distribution (Martins et al., 2020) could help to estimate the variables of extreme scenarios. Second, in a climate change context, different variables affecting mountain channel processes (e.g. rainfall, sediment availability, or propensity to erosion) would have a decreasing or increasing trend due to the combination of different factors (Flaounas et al., 2013; Hirschberg et al., 2021a; Stoffel et al., 2024).

To address the extreme complexity related to such processes, BAFU (2016) proposes to integrate the evaluation of debris flow and debris flood hazard with particular and infrequent hazard scenarios, which may differ from the one experienced within the catchment, following the concept of "thinking the unthinkable". Each scenario should be ranked based on likelihood of occurrence, and the selection process should also be motivated. However, natural hazards can emerge in a variety of ways, including rapidly intensifying, abruptly changing, or deviating from predicted consequences (Hürlimann et al., 2006). Consequently, assessment of the relationships between probabilities of occurrences and intensities is intrinsically affected by uncertainties, enhancing errors in hazard assessment and planning actions. The quantification of uncertainties is therefore crucial. BAFU (2016) proposes to apply statistical approaches to define the intensity-probability of occurrence relationship and the corresponding uncertainties for a given hazard scenario. Since processes occurring during rare events may be difficult to define, the uncertainties for these events should be defined accordingly. Regarding the concept of residual hazard, it has been also defined as the hazard remaining after the implementation of mitigation strategies (Buchecker et al., 2016; Büchele et al., 2006; Frazier et al., 2020), or by the unexpected interaction with other processes (process chains), or by environmental changes with respect to the actual conditions.

The residual hazard should be incorporated in the risk assessment and planning as reported in the EU Directive (Directive 2007/60/EC). Remembering that the risk is the probability combination of the intensity of a hazard event and its negative consequences (Hewitt and Burton, 1971), there is always a certain degree of 'residue' risk, and this has always to be assessed to identify possible consequences.

A concise clear definition of residual risk has been provided by Renn and Sellke (2011) as the unknown and tolerable risk related to the consequences on human threats. This definition is more open and less restrictive with respect to those associating the residual hazards/risks to the failure of the protection works.

3. Factors and processes influencing hazard scenarios

3.1. Rainfall intensity and pattern

The amount of rainfall and its time distribution are key parameters that directly affect the magnitude of debris flow and debris flood scenarios. In contrast to large river floods, debris floods and debris flows are characterised by a short lead time between the generating storm and the increase in discharge. The installation of an efficient real-time storm monitoring station for risk reduction might not be adequate (Creutin et al., 2013). Therefore, the characteristic assessment of rainfall events is of great importance for the setup of hazard scenarios. Amount and intensity of precipitation influence the sediment recruitment that can occur within the channel (bed and bank destabilization) and through the transport of debris material available in source areas (Iverson, 1997). In hazard assessment, rainfall scenarios are usually based on statistical analysis (e.g. Extreme Value Theory) of series of recorded precipitation with the aim of maximizing the peak discharge in a given catchment. Most of the times, such rainfall patterns are characterized by a single peak of high rainfall intensity. This choice is motivated by many observations as reported in numerous studies in the literature (Mitchell et al., 2022). However, rare events have been noticeably increased in magnitude by antecedent rainfall events, prolonged events with a peak at the end, or by precipitation patterns depicted by multiple peaks of high intensity. Since residual hazard aims to predict the impacts of such rare triggering conditions these factors should be considered.

Regarding antecedent rainfall events, Hirschberg et al. (2021a) and Abancó et al. (2016) reported that preceding events do not significantly affect the occurrence of runoff-generated debris flow events but have positive feedback on their magnitude. This aspect can be explained by the increase of the pre-existing pore water pressure that favours the entrainment processes at the passage of the flow (Iverson, 2012; McCoy et al., 2012). However, other studies reported that the intensity of the triggering rainfall does not always affect debris flow magnitude or there are not clear conclusions for some particular events (Hirschberg et al., 2019; Pastorello et al., 2020). For landslide-generated debris flow, the antecedent rainfall conditions would increase the probability of slope/sediment deposit failure by lowering the shear strength and consequently increasing the potential volume that can fail as reported in the studies of Kim et al. (2021) and Siman-Tov and Marra (2023).

Similar to antecedent rainfall events is the effect of prolonged precipitations. The repercussion on mountain catchments of prolonged events could be an increase in magnitude through the destabilization of large areas enhancing the solid volumes involved in debris flows and debris flood events. With the increase of pore water pressure, hillslope instability can drastically increase since deeper layers are also at high failure risk (Wang and Sassa, 2003). The repercussions on mountain floods are the recruitment of larger volumes of debris material through bed and bank erosion and through the interaction with hillslope shallow landslides. The recent Vaia storm that affected the eastern Italian Alps in October 2018 was characterized by a 72 h rainfall event with a peak of high intensity at the end (Borga and Zaramella, 2020; Davolio et al., 2020). The effects of this event were dramatic, with several mountain basins that produced debris flow and debris flood events. Among these, in the Rio Rotian (Trento Province, Italy) the check dam series were destroyed, and the flow caused high erosion rates (the description is reported in Section A.1 and in Baggio and D'Agostino (2022)). Regarding debris flood and bedload transport, Rainato et al. (2021) reported the effects of the Vaia storm in two dolomitic catchments. Similar triggering conditions are reported in Chen et al. (2006) where the Typhoon Xangsane (characterised by two consecutive days of rainfall) triggered a large landslide which turned into a debris flow event in the Chonho area (northern Taiwan). In some circumstances, prolonged rainfall events can also directly trigger high magnitude flows instead of short and intense events. Chiarle et al. (2007) and Zimmermann and Haeberli (1992) reported that nine debris flow events occurred in the Alps at high altitude were triggered by a combination of prolonged rainfalls and the presence of a buried glacier within the debris. In burned areas, Parise and Cannon (2012) observed that some debris flows were caused by prolonged rainfalls through the propagation of landslide failures triggered by infiltration processes. The study of Mostbauer et al. (2018) also observed that a similar triggering type occurs with rapid snowmelt or rain-on-snow episodes. Regarding these processes, different studies identified them as the primary debris flow triggers in different regions worldwide (Bondevik and Sorteberg, 2021; Decaulne et al., 2005; Tichavský et al., 2022). In particular, snowmelt induced debris flows are expected to increase in a climate change context, with temperatures 2–4 °C higher than the present (Beniston and Stoffel, 2016).

Another type of precipitation pattern that could dramatically increase the mountain flood magnitude is that characterised by two or more consecutive peaks of high intensity (Fig. 1 for an example). Here, we refer to those consecutive flow events triggered by two or more distinct peaks in rainfall and not to the dynamics of debris flow and debris flood events that are intrinsic characterized by multiple surges within the same event. High intensity rainfalls can occur consecutively, interrupted by a short period (commonly few hours) of no rain, as reported in Piper et al. (2016). The consequences of this rainfall pattern may lead to (i) the mobilization of the deposited material of the first event by the flow initiated from the second rainfall event, (ii) increase erosion rate of the second event due to the channel destabilization caused by the first event and (iii) decrease in the functionality of countermeasures (depositional squares, open check dams or sediment traps) for the arrival of the second event. An extreme debris flow triggered in this way is reported in Baggio et al. (2021) and described in Section A.2, where two discharge peaks of high rainfall intensity have been developed. Severe erosion rates were observed within the channel and on the banks.

The selection of the input hydrograph in terms of peak discharge, sediment concentration, amount of debris volume and discharge pattern is a crucial point for model simulation. The study of Mitchell et al. (2022) accurately addressed this topic, demonstrating how the inflow conditions influence the model results and consequently the impact areas. Therefore, the examples reported in this study and the literature clearly indicate the need to consider alternative inflow conditions for hazard planning when predictive models are adopted.

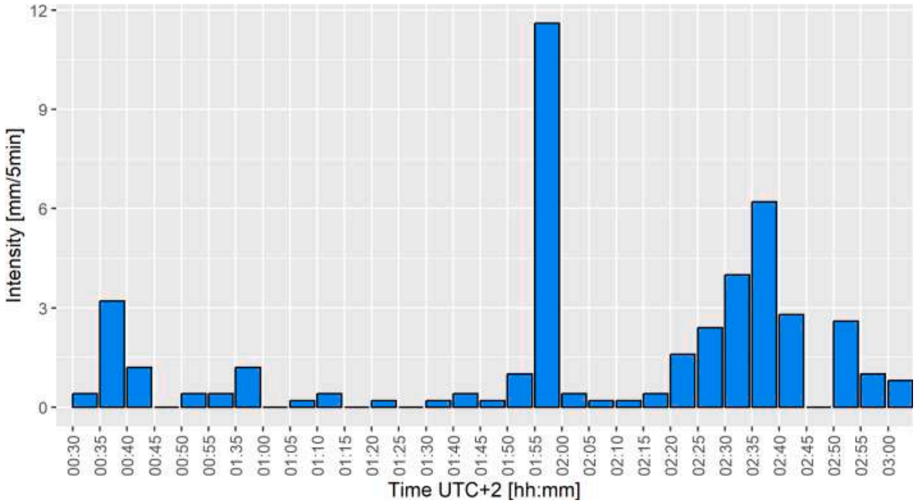

Fig. 1. Example of a recorded rainfall pattern characterized by two peaks of high intensity. The two rainfalls triggered two consecutive debris flow events in the Cancia torrent (see Section A.3).

3.2. *Solid component*

A crucial point in hazard assessment of torrent floods is the availability of sediment that can trigger an event of debris flow or can be entrained by the flow and transported downwards. In mountain catchments, debris material can derive from shallow landslides, sediment source areas mobilized by intense runoff (Baum et al., 2011; Ellen et al., 1982) or caused by channel flow destabilization (Berger et al., 2011), Fig. 2. In the context of residual hazard (return periods equal or higher than 100 years), the mobilized solid volume can be severely higher than those predicted by classical hazard assessment scenarios.

Regarding the sediment sources areas, it is crucial for an adequate hazard planning to detect their location and if possible, estimate the solid material that can be mobilized along with intense runoff. Mapping can be performed using satellite images, LiDAR data, UAV or field surveys (Blasone et al., 2014). The following step consists of assessing their degree of connection with the stream network and then the potential amount of sediment that can be delivered and entrained by the flow (D`Agostino and Bertoldi, 2014; Rainato et al., 2018). This key point has been investigated through the use of indices or physically based procedures capable of quantifying the sediment (dis)connectivity between the various regions of a given catchment or with respect to a given outlet (Heckmann and Vericat, 2018; Wohl and Scott, 2017). Such maps help in identifying the degree of connection between a sediment source and a target area, such as the stream network or the basin outlet (Cavalli et al., 2013; Martini et al., 2022). Moreover, sediment (dis)connectivity can also be adapted to depict the changing conditions of a given catchment by adapting the parameters related to the impedance of sediment fluxes (Martini et al., 2020; Pellegrini et al., 2021). Most of these (dis)connectivity indices predict the propensity of connection between source areas and target areas in terms of geomorphological forces (slope, contributing area, etc.). A further improvement will be towards a

Fig. 2. Bed erosion (left panel) and bank collapse (right panel) occurred in the Rio Rotian channel and in the Ru di Roccia channel respectively. Both the pictures are taken in the dolomitic area of the Eastern Italian Alps.

quantification of such connectivity in terms of sediment transport and delivery downwards. The use of high-resolution DoD can help in this direction, depicting the functional connectivity (Heckmann and Vericat, 2018) and assessing the volume of material entrained (Blasone et al., 2014). However, the prediction of sediment amount supplied to the channel is hard to derive, since the cycle of sediment yield not only depends on debris supply and runoff intensity but also from geomorphic conditions (Loye et al., 2016). The study of Schlunegger et al. (2009) analyses the sediment deposits in the fan of the Illgraben catchment observing that both processes of rockfall and lateral landslide contributed to the initiation of debris flow. In recent burned areas the majority of debris flow sediment derives from hillslope erosion and lateral shallow landslides (DeLong et al., 2018; Rengers et al., 2016). It emerges that sediment supply from hillslope is a site-specific process and its quantification is a crucial step in estimating the potential volume of a single event. Therefore, further studies are needed to improve the quantification of sediment transfer between the slopes and the channel network, particularly at single-event scale.

Sediment can also derive from the channel bed, through processes of recruitment. A thick layer of sediment can potentially be entrained depending both on the reach characteristics (i.e., slope, confinement), sediment properties (i.e., grain size, compaction, antecedent pore water pressure) and flow features (i.e., event duration, peak discharge, sediment content) (Cannon et al., 2003; Iverson et al., 2011; Iverson and Ouyang, 2015). Regarding observations of erosion pattern (derived through the analysis of DoD), the maximum eroded volumes for every meter of channel length (along the flow path) can be in the order of 50 – 110 m^3 (Hungr et al., 2005; Marchi and Cavalli, 2007; Marchi and D'Agostino, 2004). Extreme erosion rates have been detected in Kazakhstan (Scheidl et al., 2013) with values up to 300 m^3 for every meter of channel length due to bank collapse. Therefore, the amount of material that can be entrained during the flow propagation can be really noticeable, and in several cases, it can dramatically increase the magnitude of debris flow or flood events (Bertoldi et al., 2023; Gregoretti et al., 2019). For this reason, mass flow models should incorporate erosion processes to reliably represent possible future events. Accordingly, a set of routing models have developed the simulation of bed and banks erosion to improve the reliability of observed events (Hussin et al., 2012; Mergili et al., 2017; Rosatti and Begnudelli, 2013). Different case studies showed that they successfully back-calculated mass flow propagation together with erosion processes (Abancó and Hürlimann, 2014; Baggio et al., 2021; Berger et al., 2011; Frank et al., 2017; Mergili et al., 2019). However, in risk assessment the incorporation of erosion processes is still also limited because they are influenced by several factors, such as geology, bed rock outcrop, bank collapse phenomena, depth of loose sediment, debris erodibility, flow discharge, and slope (Berti and Simoni, 2005; Kronfellner-Kraus, 1984; McCoy et al., 2012; Takahashi, 2000), which are usually difficult to estimate and in most cases spatially dependent. Nonetheless, erosion should be taken into account in risk assessment scenarios, since extreme mountain flood events are commonly associated with channel bed destabilization and erosion (Baggio et al., 2021; Benito et al., 1998; Gregoretti et al., 2019). Most of the simulation tools incorporating entrainment processes are empirically based and they adopt local erosion coefficients, which are not easily exportable to other conditions. An attempt to physically model the process of bed erosion and entrainment has been reported in Pudasaini and Fischer (2020a) and Pudasaini and Krautblatter (2021). Simulation tools would certainly benefit from such approaches to improve their reliability.

Extreme scenarios should also take into consideration climate change impacts on sediment production and connection with the channel network. The study of Hirschberg et al. (2021b) investigated the impact of future climate variations on the production of debris material for debris flow events. In the Alpine region, debris is mainly the result of frost-weathering and rockfalls (Bardou and Delaloye, 2004; Bennett et al., 2014). These processes are consequently influenced by climate change and preliminary studies highlighted different sediment production trends based on elevation (Hirschberg et al., 2021b; Stoffel et al., 2024). At high altitude, the increase of temperature and number of free snow-cover days will increase frost-weathering processes and also make sediment retained within permafrost potentially available (Jomelli et al., 2004; Stoffel et al., 2014a). Instead, at low altitude the availability of sediment would be expected to decrease (Coulthard et al., 2012; Francipane et al., 2015; Kim et al., 2016) due to reduction of frost-weathering and the increase of vegetation implying the stabilization of hillslopes and hindering sediment fluxes towards channel network (Estrany et al., 2019; Temgoua et al., 2016).

3.3. *Complex events*

Mountain river floods can exhibit complex behaviour such as change in sediment concentration, stop and go motion, dam break phenomena and bank collapse. Regarding the change in sediment concentration, here we focus mainly on the decrease of the solid component as an effect of deposition since the increase through bed destabilization and sediment entrainment has been analysed and discussed in Section 3.2.

As reported in many studies, e.g. Prancevic et al. (2014) and Watters and Robert (1983), landslides can induce debris flow events and subsequently they could evolve into a debris flood regime. The transformation from landslide motion or landslide depositions to debris/fluid behaviour has been extensively investigated as a triggering process of debris flows (Fleming et al., 1989; Hu et al., 2020; Iverson, 1997). Conversely, the change in flow behaviour from debris flow to debris flood has been poorly investigated. Even if most of the debris flow events stop when the morphology of the flow area enlarges or becomes less steep (e.g. slope angle less than 5°) in some cases the change in flow characteristics can occur especially when the runoff is still intense. The change can occur mainly through two mechanisms: decrease of sediment concentration and/or progressive sediment deposition due to channel morphology or check-dam interactions and flow dilution due to incorporation of entering water fluxes (Church and Jakob, 2020). An example of such a mechanism was reported in section A.2 where the debris flow material deposited at the confluence with the main channel of the valley was progressively eroded, developing a debris flood event that flooded the downhill village. In the Gadria creek (northern Italy) this process was captured in a reverse way, during which a debris flood event became debris flow (Nagl et al., 2020). Other extreme and rare mechanisms can also change the flow type. Examples are GLOFs (glacial lake outburst flooding) (Emmer, 2018), ice/rock avalanches impacting glaciers or moraines (Shugar et al., 2021), volcanic eruptions (Pierson, 1986) or dam break of natural or artificial structures (Manville et al., 1999). These events involving different types of flow processes, from mass movements to clearwater fluxes with suspended sediment can be complicated to predict due to the change in flow rheology. In any case, hazard mapping of high mountain or volcanic environments should be aware of the occurrence of such processes taking into consideration that the impact areas of these rare events can result even several kilometres away from the triggering zones, as reported in some studies (Anacona et al., 2015; Sattar et al., 2022). The prediction of such complex phenomena involving different types of mass movements can result difficult due to the change in flow behaviour and entrainment and deposition processes. Their back-calculation can greatly benefit from the use of numerical multi-phase models (Aggarwal et al., 2017; Mergili et al., 2018; Pudasaini and Fischer, 2020b).

Another type of flow interaction is with the vegetation cover. In many cases, forested fan areas and riparian forest zones have been shown to be able to provide a protective function against debris flows, hindering the flow motion, promoting sediment deposition, and reducing the runout distances (Bettella et al., 2018; Booth et al., 2020; Cui et al., 2023; Michelini et al., 2017). On the other hand, the forested areas along the flow path potentially provide large wood that can worsen the debris flow hazard scenario. The role of large wood (generally defined as woody pieces, branches and logs of at least 1 m in length and a diameter > 10 cm) within mountain channels and its impacts on sediment dynamics, channel morphology, flood magnitudes and channel ecology have been extensively evaluated and discussed in the scientific literature (Comiti et al., 2016; Ruiz-Villanueva et al., 2016; Swanson et al., 2021; Wohl and Scott, 2017). Although the effects of large wood are widely considered within the flood hazard and relative risk assessment procedures, this seems to be less common for debris flows (Jakob et al., 2022; Mazzorana et al., 2009a). Debris flows can recruit large wood within the channel (May and Gresswell, 2003; Piton et al., 2024a) by eroding the banks of steep mountain channels surrounded by forest cover, while large wood already deposited within the channel (Fig. 3, left panel) is mobilized and transported downstream by the flows and delivered to the channel outlet (Mazzorana et al., 2009b). Inside headwater streams, transported large wood deposits by bends, narrow gullies, and obstacles, such as already existing log jams (Faustini and Jones, 2003; May 2007). Especially within narrow channels, log jams act as natural dams that store sediments upstream and form continuous terraces that decrease the local slope of the channel and increase streambed roughness, reducing the sediment transport capacity (May and Gresswell, 2003). Intense discharge can cause the outburst of these elements (dam break effect) leading to the formation of disruptive floods (Spreitzer et al., 2018; Steeb et al., 2017). Large wood increases the debris mass and intensifies the impact force. Therefore, the movement of wood-laden debris flows has a strong disruptive potential that worsens hazard scenarios (Watabe et al., 2013). Transported large wood can accumulate at bridge piers, increasing the flood risk and worsening the scour that damages the foundation of the piers, resulting in a possible bridge failure (Pagliara and Carnacina, 2010; Panici et al., 2020).

In some parts of the world, debris flows and debris floods events are strongly dependent on other natural hazards occurring within mountain catchments. For example, the connection between debris flows occurrence and recent wildfires in forested catchments has been acknowledged since the 1930 s in the western part of the USA and Canada (Cannon and DeGraff, 2009; Jordan, 2016; Raymond et al., 2020). The occurrence of debris flows in these areas is mainly a consequence of wildfire events, posing significant hazards, especially during the first rainy season following the wildfire. Acknowledging these problems, the physical processes and hazard aspects of post-wildfire debris flow have been extensively studied in the scientific literature. Wildfires lead to the loss (total or partial) of the forest cover and litter, ash deposition, alteration of soil and rock properties, and the development of water-repellent soils. As a result, the hydrological conditions of the catchment will become profoundly altered. The hydrological response of the catchment changes is due to the decrease in the rainfall infiltration capacity of the soil (Wieting et al., 2017). The loss of organic matter in the more superficial layer of soil can result in reduced soil stability and more easily erodible soil. Consequently, surface and channel runoff will increase, enhancing surface erosion rates and sediment yield. The initiation of fire-related debris flows is caused by two primary processes: (i) erosion and entrainment of material by surface runoff or (ii) infiltration-triggered failure and mobilization of a discrete, shallow landslide mass (McGuire et al., 2021b; Tang et al., 2019), Fig. 3 right panel. Erosion and entrainment often result in the formation of rills on steep hillslopes, evolving into debris flows if sufficient material is entrained. Shallow landslides, triggered by prolonged storm rainfall, are another mechanism for debris flow initiation (Cannon and DeGraff, 2009; Cannon and Gartner, 2005; Jordan, 2016; Parise and Cannon, 2012). The time since the wildfire occurrence is identified as a crucial factor for assessing the rainfall triggering threshold in the study of McGuire et al. (2021a). It also reports that the expected debris flow volume would decrease by a factor of three following one year of recovery. Regarding post wildfire debris floods, rainfall intensity duration thresholds are crucial in determining the event occurrence (Ebel, 2020). In particular, the years immediately after a wildfire are the most dangerous in terms of debris flood magnitude (Liu et al., 2022). Therefore, when severe environmental changes occur also the hazard map must be updated in short time, to identify new possible impact areas and then limit the possible consequences at the lowest. Furthermore, after a wildfire, trees that have been burned often fall due to strong winds or the decay of their woody material. This material can become a significant source of large woody debris inside channels (Rengers et al., 2023; Wasklewicz et al., 2023).

Fig. 3. Log jam in the Ru di Roccia channel (left panel), eastern Alps, Belluno, IT and a flash flood event occurred after a wildfire (right panel) in British Columbia, CA,
Source: Geertsema and Highland (2011).

Earthquakes are another natural hazard that can influence debris flow and debris flood activity. During earthquake events a large amount of loose sediment is produced by rock falls, rock avalanches and landslides happening simultaneously (Ni et al., 2012; Zhuang et al., 2010). The increased availability of sediment prone to be transported by following precipitation events and the widespread instability inside mountain catchments increase debris flows and debris floods triggering susceptibility in the years immediately after the earthquake. Indeed, the rainfall threshold for debris flow and debris flood triggering seems to decrease substantially compared to the threshold observed before the earthquake (Chen and Yu, 2011; Lin et al., 2004; Marino et al., 2022; Tang et al., 2009). The increased frequency of occurrence of debris flows and debris floods events decreases progressively with the removal of the finer debris friction and re-vegetation of the slopes (Domènech et al., 2019).

3.4. *Incorrect function or failure of countermeasures*

Different types of torrent control countermeasures have been built in mountain catchments worldwide with the aim of reducing the level of hazard and consequent risk to citizens and infrastructures (Mizuyama, 2008; Rodríguez-Morata et al., 2019). Their functionality is based on the reduction of sediment transport, flow velocity, bed erosion and impact force (Huebl and Fiebiger, 2007; Piton et al., 2024b). Countermeasures are normally sized and located in strategic zones of the catchment identified through the analysis of past events and scenarios related to different return periods (Osti and Egashira, 2008). Moreover, old structures may not be fully appropriate to decrease the hazard level of current or future events due to age and decay of their stability, changing geomorphological conditions and eventually type of flood event or increased severity (Hübl et al., 2005). Torrent mitigation structures are commonly designed to support the stress caused by an event of a certain return period, implicitly admitting a certain level of hazard that inevitably always remains. In the past, structure failure mainly involved the collapse of check dams, since they are the most widespread countermeasures built in mountain channels (Piton et al., 2016). Moreover, the trend of their possible failures is increasing in those mountain areas where these structures have been built extensively during the last two centuries and local authorities decided to abandon their maintenance due to sustainability reasons. Even if countermeasure failures are quite rare, in some circumstances they may occur and the consequences can be disastrous (Fig. 4, left panel). Examples of these tragic events are reported in Benito et al. (1998), Chen et al. (2015), Cucchiaro et al. (2019) Wang (2013), White et al. (1997) and in Section A.1 for a recent high magnitude debris flow that caused the collapse of a check dam series (Baggio and D'Agostino, 2022). A failure of a sediment trap due to extraordinary water levels is reported in Strauss et al. (2024), consequently triggering an intense bedload transport downward. For this reason, the probability of structure failure or uncorrected functioning should be always taken into consideration within the hazard assessment.

Another type of uncorrected functioning of mitigation measures can involve retention open check dams and sediment traps. The mitigation performance of such countermeasures can be suddenly reduced in the case of immediate obstruction of the opening (D'Agostino, 2010; Piton et al., 2024b). This can occur because of large boulders and large wood transported in the front of the flow (Fig. 4, right panel). When large wood reaches retention structures it tends to accumulate and forms barriers that clog the barrier's filter, causing the increase of flow levels, sediment trapping and siltation (Chen et al., 2020; Rossi and Armanini, 2020). The storage capacity of the check dam for subsequent debris flows is reduced and can result in an overflow of the structure (Piton et al., 2020). The interaction of large wood with torrent countermeasure structures and the potential loss of their hazard mitigation effects is a fundamental aspect to consider in hazard assessment. Unfortunately, few studies have been conducted and they are often limited to experimental researches carried out on physical modelling (Chen et al., 2020; Scheidl et al., 2013; Shrestha et al., 2012; Wang et al., 2022; Xie et al., 2023).

The construction of countermeasures in some cases may lead to the increase of hazard level in areas located downwards, previously not potentially affected by flood events or only affected in rare cases. An example could be the construction or the improvement of a convey channel in the fan areas which aims to maximize the discharge capacity of debris flow or debris flood. Such a type of countermeasure is

Fig. 4. Check dam failure (left panel) and obstruction of the opening of a sediment trap by a large boulder (right panel). Both the pictures were taken after the disastrous event of the Rio Rotian reported in section A.1.

obviously beneficial for adjacent areas, but it could increase the level of hazard in downward areas both by creating new zones prone to be flooded and increasing the intensity of the possible dynamic impact on them. In this circumstance there is a sort of direct hazard transfer. A similar process has occurred in the Cancia creek (south-eastern Alps, Italy), where the construction of a channel (to protect houses built in the 1960s) moved the fan apex downwards and consequently the depositional area and the hazard zone have been transferred (Panizza et al., 1998) due to a clear modification of the runout zone. An extensive description of this type of hazard transfer is reported in Section A.3.

4. Discussion on improving the hazard scenarios

Debris flow and debris flood are hydrogeological hazards that jeopardise inhabitants and infrastructures of mountain areas. To protect these areas and plan the most appropriate mitigation strategies, the hazard and risk assessment of these phenomena is essential. We should also consider that peculiar, rare debris flow or debris flood events may result in catastrophic and/or unforeseen impacts, which fall into the wide category of residual hazards. To limit these last to a few, really unpredictable cases, a comprehensive and precise hazard assessment is necessary in order to build a set of hazard scenarios that is tailored both to debris flood/flow processes and basin features. Such a meticulous assessment would also allow the design of more targeted and effective mitigation measures.

As described in Section 2, the classical hazard assessment methodologies derive hazard levels by defining the relationship between the intensity of an event and its probability of occurrence considering the associated factors and processes that can enhance its magnitude. However, the definition of these relationships is affected by great uncertainties. Given the same hydrological probability of occurrence, the intensity of events may vary from that expected, either because of a stochastic component or because of the occurrence of unexpected processes not previously observed. For example, a debris flow event with a magnitude defined based on a rainfall event with a return period of 30 years could reach the intensity expected for a hydrological event with a return period of 100 years due to factors other than hydrological (e.g. a sudden sediment–water release caused by the collapse of temporary clogs formed in the channel network). In general, the processes occurring during frequent events are easier to characterise, because of the higher number of observations and the consequent easier definition of the associated intensities. This characterization is more challenging for rare, scarcely experienced, events (Brunner et al., 2021). These uncertainties can result in over- or underestimation of the hazard and, consequently, the risk, causing over- or under-sizing of mitigation strategies. The flood event that occurred in the Cancia village in July 2009 (Section A.3) was the result of an unexpected precipitation pattern (Fig. 1). The mitigation system, consisting of a retention basin, mitigated the first debris flow event by stopping it and storing the sediment in the retention basin. Nevertheless, after 20 min, a second peak of precipitation triggered a smaller debris flow event. The check dam potentially had the capacity to mitigate the second debris flow, however, due to the sediment already stored inside the retention basin, not only the mitigating effect of the system was lost but the negative consequences on the retention check dam were even magnified (a surge directly stressed and destroyed the crest of the structure). Although the two debris flows would have been mitigated by the check dam if they had occurred in two separate events, the consecutive passage of two “mitigable” debris flows due to an unexpected precipitation pattern increased the level of hazard posed by that particular event. Although a certain degree of uncertainty cannot be avoided, hazard assessment procedures should take a step forward and reduce these uncertainties, considering hazard scenarios that represent the current state of the catchment, its possible evolution, the time–space variability of the processes and probable system alteration during the same event. By adding these components, the hazard scenarios should be more representative of the possible outcomes of a debris flow or debris flood event. The improved hazard scenarios could then be used in the definition of “informed” and basin specific hazard maps (Fig. 5).

Information about channels and catchment morphology, sediment and large woody debris availability, structural and operational status of control structures, and the presence of obstructions within channels, at bridges, culverts and control structures, should not be limited to the situation at the moment of the analysis but expanded to a reasonable future time span (e.g., a period accounting for the life expectancy of the existing/under construction protection measures, or the planning of anthropogenic modifications). In fact, mountain basins undergo various processes that can quickly modify their geomorphology, hydrology and land-use. Both natural disturbances and human activities can significantly affect the conditions that define the potential for future debris flow or flood occurrences. These changes in the system can influence the availability of sediment and large woody debris, alter the channel morphology (e.g., formation of obstructions), affect flow behaviours, and impact the effectiveness of existing control measures. Natural disturbances, anthropogenic activities, and climatic processes are processes not necessarily related to the hydrological cycle of a given catchment that may directly or indirectly modify the system conditions, triggering susceptibility of channel/hillslope instabilities, and the process dynamics. Table 1 presents a list of the main exogenous factors that may affect debris flow and debris flood hazard in mountain catchments. To complete the specific situation of the basin system under analysis, a classification could be added to each disturbance factor, providing an estimate on its level of worsening and/or amplifying the baseline risk scenario. This amplification effect of hazard should be related to the increase of exposure for buildings and infrastructures (Barnhart et al., 2024). Three degrees could be sufficient in order to simplify this empirical/experience-based ranking: a value of 1 meaning minimum, 2 indicating a distinct modifying effect, 3 in case the disturbance might go far beyond the baseline scenario.

Exogenous forcings can have direct effects, occurring during the hydrological event, and indirect effects, influencing processes before the hydrological event. For example, the landslide that occurred within the Rio Rudan catchment described in Section A.4 altered the channel morphology and increased sediment and large woody debris availability. The deposit acted as a quasi-permanent barrier for the flowing sediment and large woody debris, further enhancing their availability. The recruited large wood may be entrained by certain flood events and then intercepted downstream by the retention check dam filter, causing its anticipated clogging and a lower effectiveness at event scale. Moreover, the landslide deposit might suddenly collapse or being fluidified, increasing the overall magnitude of the event, or creating a severe dam break surge. All these alterations may occur during a debris flow or debris flood event or between one event and the next. Debris flows/floods are also natural disturbances that alter the conditions of the catchment. After these events, modifications can commonly be observed in channel morphology, bank stability, sediment and large wood availability, and condition and functionality of the control structures. Information on exogenous forcings within the watershed will lend greater solidity to the definition of hazard scenarios. These can be implemented to understand what alterations in system conditions are most likely to occur. The alteration and evolution of the system conditions (Table 2) pose great uncertainty in the prediction of hazard, resulting in catastrophic outcomes of debris flow and debris flood events. Similarly to Table 1, an impact score (1/2/3) may help in highlighting the most delicate conditions of the basin and in the building of the “informed hazard map” (Fig. 5).

The collapse of the entire control structure system during the Rio Rotian event (Section A.1) due to extreme erosion of the channel bed, was a circumstance hardly imaginable and for this reason considered a residual hazard. The hazard assessments usually consider a full functioning of existing protection structures within the channel. However, their mitigation function may be affected either by some exogenous

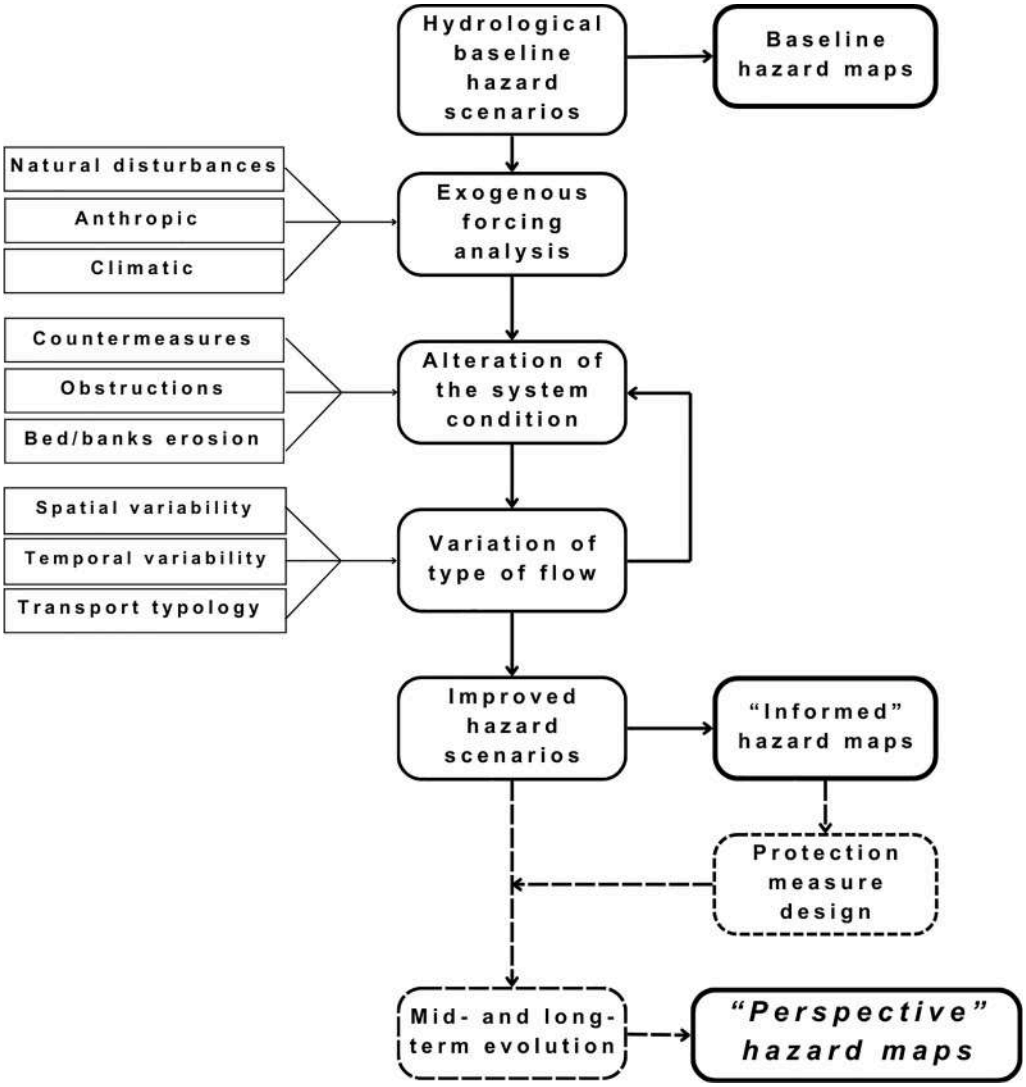

Fig. 5. Processes and factors that can affect the hazard scenarios and the procedure to derive the informed and perspective hazard maps.

forcing (e.g., large woody debris recruited within the channel and clogging the filter of a slit check dam) or by extreme collisions (e.g. boulders) or erosive flows during an event capable of undermining or bypassing the structures (Barbini et al., 2024; Piton et al., 2024b). The other source of uncertainties in debris flow and debris flood hazard assessment is given by the possible variability of process types. As seen in the event of 2009 in the village of Cancia (Section A.4), unforeseen peculiar precipitation patterns and subsequent releases may cause the ineffectiveness of the control works. This may also lead to a variation in flow type (e.g., a debris flow deposit is successively mobilized by intense water discharge, developing a debris flood event; please refer to the case study of the Rio Gere, Section A.4). The spatial, temporal and flow type variability of processes (Table 3) should therefore be evaluated together with the possible variation in the condition of the whole system. These components may deeply affect one another: the alteration of the system condition may cause a change in process type, and vice versa. To try to predict the evolutions that these alterations may entail, it is desirable that a further analysis of the change in system conditions is conducted along with the related association to an impact degree with respect to the baseline scenario. According to our experience (study cases reported in the appendix) and literature findings (Table 3) this last impact tends often to be significant (score 2 or 3), because the baseline scenario is generally quite 'flat' in terms of spatial and temporal variability. Conversely, steep mountain basins are really sensitive to spatial/temporal changes of rainfall inputs, sediment source availability and water–sediment characteristics of the flow, so easily turning the event dynamics and related magnitude.

Accounting for Tables 1-3, a framework is then available to build an informed hazard map (Fig. 5) based on a well-thought-out and dynamic concept of the catchment, which can truly support the overall setting of debris flow and debris flood scenarios. Informed hazard scenarios can also be used for a more tailored design of mitigation measures (Fig. 5) and even to abandon any option of intervention in case it results as ineffective in many probable impacting scenarios.

A further step for the improvement of hazard assessment procedures consists of taking into consideration the possible mid-term evolution of the catchment, considering a specific additional 'perspective' hazard scenario (Fig. 5). The outcomes of a scenario may be used as a base for evaluating how the hazard situation may change in the future and how the current adopted implementations of mitigation measures could modify the hazard maps in the medium (e.g. 20 years) or long run (e.g. 50 or more years). An example of a perspective hazard map is derived by multiple simulation scenarios performed for an area of the Rio Gere-Bigontina catchment (its description is reported in section A.2), particularly analysing the area surrounding the village of Alverà (Figure A2, panel A). The hazard classification used for this example is the regulation of the Eastern Italian Alps for mapping area exposed to debris flow and associated related phenomena as a matrix of flow depth and flow

Table 1
Exogenous factors affecting the magnitude and frequency of debris flow and debris flood events.

Disturbances /Factors		**Effects on Hazard assessment**	**Impact** Score			**Reference**
Natural	Previous DF/DFD/flash flood	Alteration of channel morphology, increase sediment availability	1	2	3	(Chen and Wang, 2017; Chien-Yuan et al., 2008; Pastorello et al., 2018)
	Landslides / Shallow landslides	Channel obstruction, increase sediment availability	1	2	3	(Cannon and DeGraff, 2009; Cannon and Gartner, 2005; Chen et al., 2006; Iverson, 1997; Jordan, 2016; Parise and Cannon, 2012; Wang and Sassa, 2003)
	Windstorms	Recruitment of large wood, Increase in the sediment contributing areas	1	2	3	(Galia et al., 2021, Galia et al. 2018)
	Wildfires	Promotion of overland flow, increase sediment mobilization	1	2	3	(Cannon and DeGraff, 2009; Jordan, 2016; Raymond et al., 2020; Rengers et al., 2023; Wasklewicz et al., 2023)
	Snow avalanches	Increasing the availability of sediments, Recruitment of large wood	1	2	3	(Bardou and Delaloye, 2004; Kemper and Scamardo, 2023)
	Earthquakes	Loose co-seismic deposits production, Slope instability	1	2	3	(Chen et al., 2011; Domènech et al., 2019; Lin et al., 2004; Marino et al., 2022; Ni et al., 2012; Zhuang et al., 2010)
	Rock avalanches	Increase sediment availability, channel obstructions favouring dam-breaks	1	2	3	(Frattini et al., 2016; Shugar et al., 2021)
	Glacial lake outburst floods (GLOFs)	Increase of water volumes and peak discharges	1	2	3	(Cui et al., 2010; Emmer, 2018; Medeu et al., 2022)
	Forest cover degradation	Recruitment of large wood, landslides, soil erosion	1	2	3	(Mikuś and Wyżga, 2020)
	Eruptions	Rapid melting of large snow and ice volumes, collapse of volcanic edifices, creation of voluminous easily erodible deposits	1	2	3	(Pierson, 1995; Vallance, 2005)
Anthropic	Forestry operations	Decrease in slope stability	1	2	3	(Imaizumi et al., 2008; Preti, 2013)
	Land-use changes	Alteration of catchment hydrology, increase sediment availability	1	2	3	(Lorente et al., 2002)
	Morphological changes	Increase sediment availability, Changes in the flow behaviour	1	2	3	(Cucchiaro et al., 2019; Panizza et al., 1998)
Climatic	Permafrost degradation	Increase availability of loose sediment	1	2	3	(Damm and Felderer, 2013; Deline et al., 2021; Zimmermann and Haeberli, 1992)
	Snow melting processes	Alteration of the flood hydrograph	1	2	3	(Beniston and Stoffel, 2016; Bondevik and Sorteberg, 2021; Mostbauer et al., 2018; Parise and Cannon, 2012; Tichavský et al., 2022)
	Frost weathering	Increase sediment availability	1	2	3	(Bardou and Delaloye, 2004; Bennett et al., 2014; Jomelli et al., 2004; Stoffel and Bollschweiler, 2008)
	Reduction of snow cover	Liberation of additional sources of unconsolidated material	1	2	3	(Hirschberg et al., 2021b; Stoffel et al., 2014a)
	Increased rainfall intensities	Alteration of catchment hydrology	1	2	3	(Stoffel et al., 2014a; Turkington et al., 2016; van den Heuvel et al., 2016)
	Splash erosion	Increase sediment availability	1	2	3	(Providoli et al., 2002)

velocity (Distretto delle Alpi Orientali, 2021). The baseline hazard panel of Fig. 6 reports the hazard map derived with a standard approach by calculating an input hydrograph for different rainfall intensities and including the effect of the retention open check dam that has been built immediately upward the village for protecting it. Hazard scenario 1 is calculated by assuming an intense erosion rate in the channel reach immediately upstream of the open check dam and associated with a rainfall return period of 300 years. Hazard scenario 2 incorporated the consequences of a debris flow event impacting the deposition basin already filled up by a previous event. The perspective hazard map is the combination of the previous three maps.

As shown in the baseline scenario, the simulated flow did not flood the village even with a hydrograph derived with a rainfall of return period equal to 300 years. With the integration of two scenarios accounting for probable processes that may occur in case of extreme events, it is possible to observe the partial inundation of the village. Even if the two additional hazard scenarios simulate different initial conditions the resulting inundated areas are really similar, indicating that the buildings in the right-ward of the channel are the most exposed to possible inundations.

This means that the existing open check dam mitigates most of the events that can occur in the catchment, but at the same time a potential hazard is still present in case of an overload of sediment input to the same protection structure. The differences between the baseline scenario and the perspective hazard map are evident and it is a matter of public authorities to decide if this is an acceptable risk or if there is the need to design new structures (i.e., channel consolidation or increasing the sediment storage capacity of the open check dam).

Another option is the mandate of relocation of the residents (with economic compensation) if a minimum level of risk cannot be reached. This approach is recently approved in France with the article L561-1 of the Environmental Code (Plans de Prévention des Risques Naturels, PPRN). Similar legislations have been approved also in Japan (Disaster Countermeasures Basic Act), Australia (National Disaster Resilience Framework), New Zealand (Resource Management Act).

In literature, there are some other methodologies and frameworks for debris flows and debris floods hazard assessment (e.g., Jakob et al., 2022b; Mazzorana et al., 2009; Mazzorana et al., 2013). Likely, these approaches are still poorly adopted by practitioners and public authorities because of a certain complexity. The framework of Fig. 5 and Table 1-3 offers the advantage of being quite direct, aiming to focus the importance of a conceptual dynamic knowledge of the catchment and all hazard factors probably involved in mountain catchments, and accounting in the same time for literature experiences.

Table 2
Variation of system conditions that could be observed in debris flow and debris flood channels.

Disturbances /Factors		**Causes**	Effects on Hazard Assessment	**Impact score**	**Reference**
Structure failures	Check dam and/or bank protection destruction (total or partial)	Low maintenances, intense impact with boulders and large wood	Loss of mitigation action against DF and DFD	1 2 3	(Baggio and D'Agostino, 2022; Benito et al., 1998; Cucchiaro et al., 2019)
	Filters clogging	Large boulders, large wood	Loss of the ability to laminate the flood, overtopping of the structure	1 2 3	(D'Agostino, 2010; Fei and Wang, 2024)
	Retention basin totally or partially full for previous surges/events	Previous DF or DFD events, intense bedload	Overtopping of the structure	1 2 3	(Böll et al., 2008; Chen et al., 2021; Piton and Recking, 2016)
Obstructions/ dam breaks	Bridges piers obstructions	Large wood and sediment deposition	Structure failure (total or partial), overtopping of the structure	1 2 3	(Chen et al., 2022; Panici and de Almeida, 2018; Zhang et al., 2023)
	Cross-sections obstructions	Large wood and sediment deposition	Dam break events	1 2 3	(Costa and Schuster, 1988; Dang et al., 2009; Xiangang et al., 2017)
	Flow avulsion from expected path	Morphological changes of channels, large wood and sediment deposition	Unexpected flooded areas	1 2 3	(de Haas et al., 2018; Densmore et al., 2019; Herbert et al., 2024)
Bed/banks erosion	Bank collapse	Sediment entrainment	Avulsion	1 2 3	(Ge et al., 2014; Hungr et al., 1987; Lyu et al., 2017)
	Sediment and large wood entrainment	Debris flow interaction with channel bed and banks	Increase of sediment in the flow	1 2 3	(Baggio et al., 2021; Berger et al., 2011; Gregoretti et al., 2019)
	Check dams' failures	Low maintenances; unexpected events	Increase of sediment in the flow, channel destabilization	1 2 3	(Lucas-Borja et al., 2021; Ramirez et al., 2022; Zhang et al., 2019)

Table 3
Sources of variability that could affect the flow types and magnitude of probable debris flow and debris flood events.

Variability sources			Effects on Hazard Assessment	**Impact Score**	Reference
Spatial	Multiple release areas – Simultaneous trigger		Increased flow magnitude	1 2 3	(Chen et al., 2017; D'Agostino and Bertoldi, 2014; Steger et al., 2022)
	Multiple release areas – Subsequent trigger		Multiple flow surges, backfilling of the retention structures and reduction/inhibition of protection capacity	1 2 3	
Temporal	Precipitations Patterns	High intensity rainfall peak after long duration rainfall	Increase flow magnitude	1 2 3	(Gregoretti and Fontana, 2008; Marra et al., 2016; Pastorello et al., 2018)
		Rainfall event with multiple peaks	Multiple flow surges	1 2 3	(Baggio et al., 2021; Chen et al., 2017; Jakob, 2007; Kean et al., 2013)
		Long duration – variable intensity	Soil saturation, hillslope/banks/bed instability, increase magnitude	1 2 3	(Chen et al., 2006, 2017; Pellegrini et al., 2021; Rainato et al., 2021)
		Sequence of rainfall events (triggering or non-triggering)	Backfilling of the retention structures and reduction/ inhibition of protection capacity, increase antecedent soil moisture condition	1 2 3	(Milne et al., 2009; Piton and Recking, 2016)
	In-channel obstruction – dam break release		Multiple flow surges, increase in flow magnitude	1 2 3	(Capart et al., 2001; Chen et al., 2004; Cui et al., 2013)
Variation of transport typology	Increase in sediment concentration		Sediment deposition inside the channel, formation of obstructions, increased flow magnitude	1 2 3	(Church and Jakob, 2020; Nagl et al., 2020; Simoni et al., 2020)
	Decrease in sediment concentration		Bed and banks erosion, sediment entrainment	1 2 3	(Lancaster and Casebeer, 2007; Pierson and Scott, 1985; Simoni et al., 2020)

5. Conclusions

The study has summarised important research efforts to drive and address hazard assessment in debris flow/flood mountain catchments. The features of these types of basins make it necessary to incorporate a panel of conditions, which are difficult to standardize and often poorly considered by the regulations of public authorities (e.g., the laws are mainly focused on the return periods of triggering-rainfall intensities or on the effect magnitudes). Accordingly, in mountain catchments, the separation between the concept of hazard and residual hazard seems to be almost evanescent because the residual hazard cannot just be associated to high return period scenarios or the failure of protection measures, but the separation is rather an output of the assessment of composite scenarios (e.g. setting and combination of conditions over certain thresholds).

The main outcome stemming from different studies reported in the literature and our case studies suggest that the milestone for debris flow/ flood hazard assessment seems to be a global specific understanding of

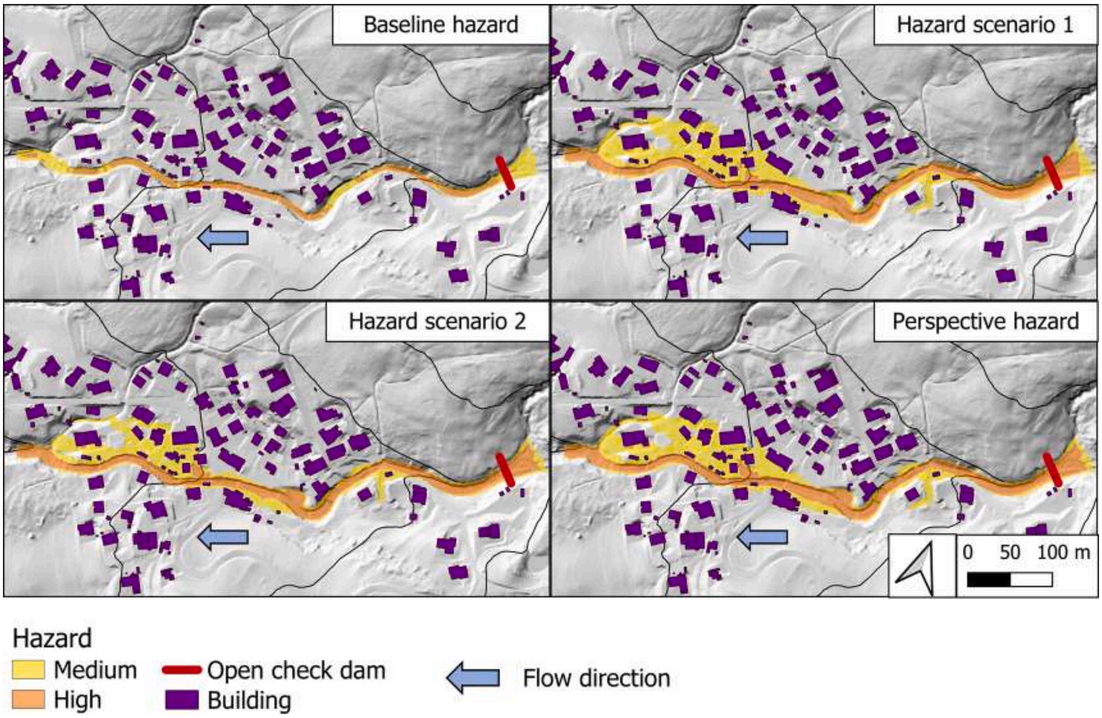

Fig. 6. Example of the calculation of the perspective hazard map following the procedure proposed in Fig. 5 for the village of Alverà, within the Bigontina catchment (for an overview of the area please refer to Figure A2 and section A.2).

the watershed and the interactions of phenomena within it. Understanding how processes occur and attempting to cover a wide reliable range of actual possibilities – disturbance factors, system conditions, process variability and related impacts – would substantially decrease the level of uncertainty in hazard assessment and it would be beneficial to corroborate those conditions that are provided by standard/hydrological events with ‘target’ return periods.

CRediT authorship contribution statement

Tommaso Baggio: Writing – original draft, Methodology, Investigation, Conceptualization. **Marco Martini:** Writing – original draft, Methodology. **Francesco Bettella:** Writing – review & editing, Resources, Methodology. **Vincenzo D’Agostino:** Writing – original draft, Supervision, Conceptualization, Methodology.

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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Appendix A. Examples of events

In this section, we report four debris flow events for which the observed or potential disastrous consequences are assessed as part of the residual hazard. The debris flow of the Rio Rotian channel that occurred on the 29th October 2018 caused the collapse of the series of 15 check dams. In the Rio Gere catchment, the debris flow of the 4th August 2017 was enhanced by intense entrainment processes and a particular rainfall pattern. On the 18th July 2009, the Cancia catchment produced an intense debris flow that impacted some houses due to the construction of an artificial channel in the 1960 s and the compliance of a rainfall pattern characterized by two peaks. In the Rudan catchment a large landslide that occurred on the 15th December 2020 deposited most of the moved material within the channel; in the case that a debris flow or a flood occurs, the deposited material may increase its destructive potential for a dam break effect.

A.1. Rio Rotian – 29th October 2018

The Rio Rotian is a mountain basin located in the autonomous province of Trento, south-eastern Alps (IT). The extension of the basin is 2.4 km^2 and the mean slope is equal to 26.4°, ranging from an altitude of 2048 to 824 m a.s.l. The channel results very incised because of the geology of the area (Figure A1–A). In fact, the basin is formed by alluvial and glacial deposits in the lower part (below the altitude of 1300 m a.s.l.) and by loose layers of clay and limestone in the upper part. Therefore, the quantity of sediment that can be mobilised may be extreme. The main sources of sediment are the banks and the bed of the channel, together with shallow landslides that could be released by the adjacent steep slopes. The mean channel slope is equal to 11.9° for a length of 4.8 km. In 1977 it was consolidated with a series of 15 check dams (Figure A1–A) characterized by a mean height of 5.3 m (range 2.9–7.8 m). In the past, two severe debris flow events were recorded in 1776 and 1882. Both can be classified as mud debris flows due to the presence of big boulders transported by a matrix of fine sediment and water. The two events deposited most of the material in the fan area and in 1776 the volume transported stopped the flow of the Noce torrent, in the main valley, deviating it from its original path.

In 2018 a severe storm called Vaia affected the eastern Alps with extreme rainfalls and winds. In particular, the rain hit the catchment for three consecutive days, from 27th to 29th of October, for a precipitation amount of 359 mm, corresponding to a return period of 300 years (Borga and Zaramella, 2020). On the 29th October the rainfall intensity increased in the evening and analysing the 3 h cumulated precipitation, Borga and Zaramella (2020) deduced a return period of 100 years. The basin, already stressed by two days of precipitation, on the 29th October produced an extreme debris flow event. Along the channel, the flow entrained debris material and it completely broke the 15 check dams (Figure A1–B). The consequence was the instant relaease of material retained by the check dam and destabilization of the channel bed that enhanced the process of bed erosion. The flow, which increased in volume, flooded the village located in the fan area, depositing boulders of the order of 1 – 3 m in diameter (Figure A1–C).

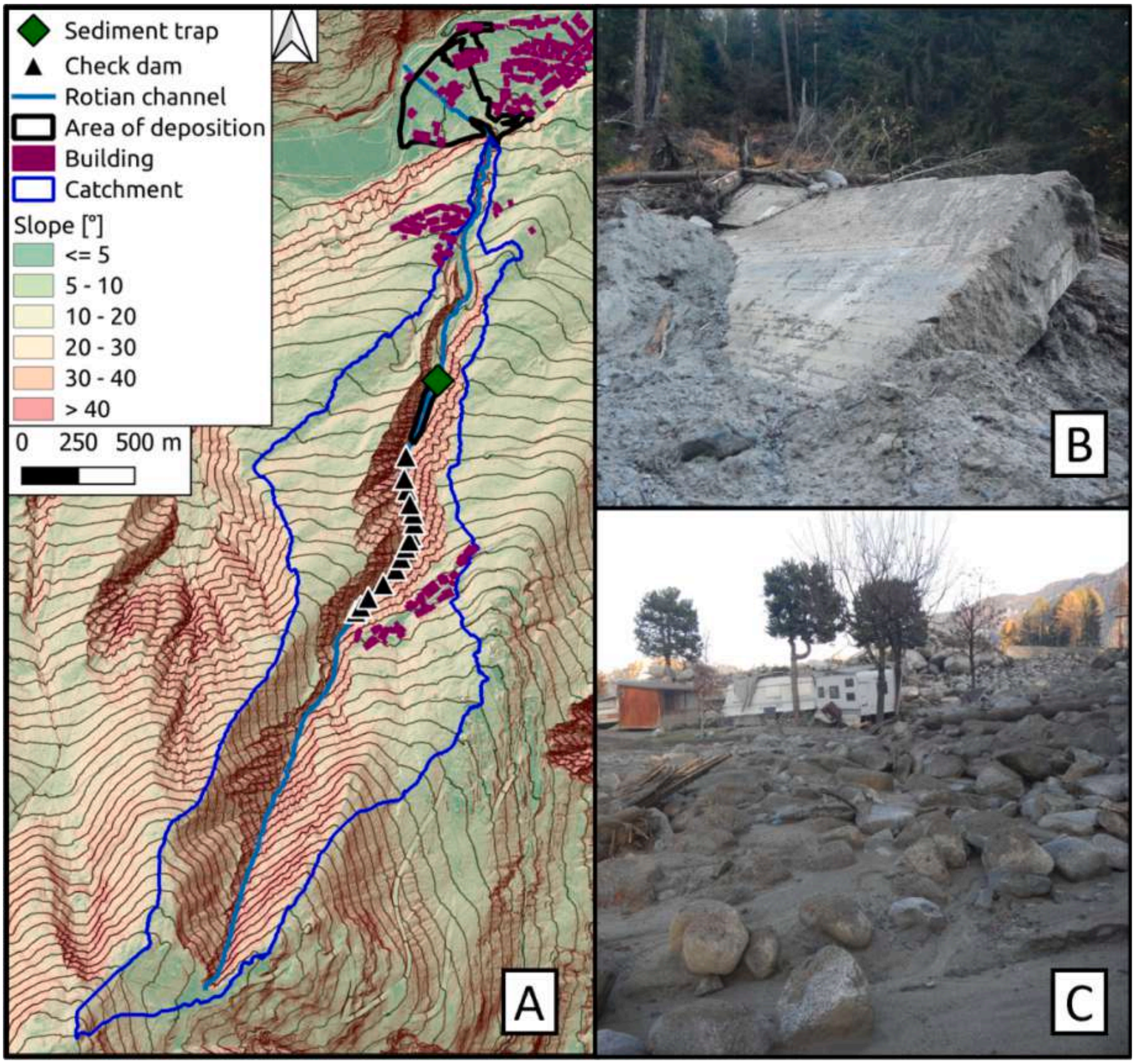

Fig. A1. Pictures representing: A) the morphology of the catchment, indicating the location of the damaged check dams and the main depositional areas of the debris flow; B) a check dam damaged by the 2018 event; C) the depositional area in the alluvial fan. The contour lines elevation difference is 25 m.

A.2. Rio Gere and Bigontina – 4th August 2017

The Rio Gere is a mountain stream located in the eastern Alps near the town of Cortina d'Ampezzo (IT). The elevation ranges from 3221 to 1650 m a.s.l. for an extent of 1.7 km^2 (Figure A2–A) The mean basin slope is equal to 42°, while the main channel length and slope are equal to 3276 m and 20°, respectively. Regarding geology, the basin is formed by dolomite rocks. The channel network of the basin is deeply incised in the bedrock in the upper part, while in the lower part the main channel passes through colluvial deposits and is defined by banks 2 – 5 m high (Figure A2–C). Consequently, the amount of sediment that can be entrained in the lower part of the basin is potentially really high. Downwards the channel merges with the Bigontina torrent. Near the confluence, the regional road SR48 crosses the Gere channel. The bridge has been hit by different debris flow events in the last decades and some of them deposited debris material on the road and adjacent parking lot (D'Agostino et al., 2018).

During the evening of the 4th August 2017 between 10:00 p.m. and 12:00 p.m., the Gere basin was hit by a severe thunderstorm. The most intense part of the rainfall event had a duration of 2 h for which a cumulated amount of 110 mm was recorded. The rainfall was characterized by two peaks of high intensity (10.1 mm/5min at 10:10 p.m. and 10.8 mm/5min at 11:40 p.m.) that consequently triggered two debris flow surges. The statistical analysis of the nearby meteorological stations assessed the magnitude of the event as an estimated return period of between 100 and 300 years (D'Agostino et al., 2018). In this event a large quantity of debris material was eroded and entrained in the lower part of the channel. The flow destroyed the bridge and deposited part of the material in the adjacent parking lot and part continued to flow down the Bigontina torrent. Indeed, the debris flow material deposited by the Gere channel at the confluence with the Bigontina channel was successively entrained by the intense water discharge. The fluidized material started moving downwards creating a debris flood event (Church and Jakob, 2020) that flooded the village of Alverà (Figure A2–B).

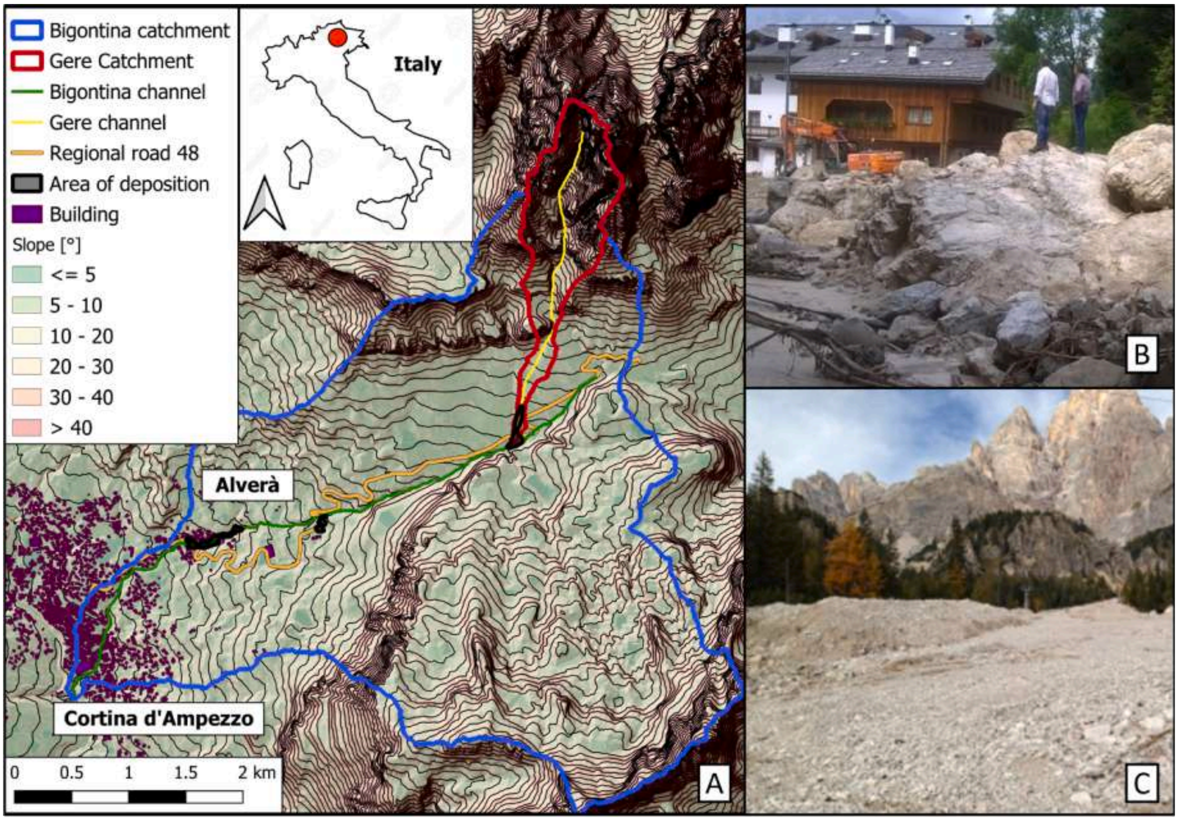

Fig. A2. Pictures representing: A) the morphology of the catchment, indicating the Alverà village and the regional road 48 with the main depositional areas of the event; B) the debris deposit located immediately above the Alverà village (note the big boulders transported by the intense debris flood event); C) the depositional area at the confluence between the rio Gere and the Bigontina torrent. The contour lines elevation difference is 25 m.

A.3. Cancia – 18th July 2009

The Cancia basin is located on the southern face of the Antelao peak (3264 m a.s.l.) in the Dolomites area (eastern Alps, Italy). The catchment has an area of 2.45 km^2 and the main channel is deeply incised in dolomitic rocks (Figure A3–A). The upper part of the catchment (between 2200 and 1700 m a.s.l.) is characterized by a large deposit of debris material close to the angle of repose (Simoni et al., 2020). Therefore, the availability of entrainable sediment in the case of intense water runoff is really high (Figure A3–C). Downwards, from 1700 to 1000 m a.s.l., the main channel becomes more incised in the colluvial deposit that has a width of 150 – 75 m. The slope becomes gentler, decreasing from 35° in the source area to 15° in the depositional zone. The lower part of the channel has been reduced in width and the banks increased in order to decrease the hazard and risk of flood to the new part of the village (so-called "villaggio AGIP") built between 1946 and 1961 at an elevation between 1050 and 1250 m a.s.l.. However, the creation of this new channel moved the geomorphological apex of the fan downwards, closer to the older houses of Cancia village located at an elevation of 1050 – 930 m a.s.l. In order to protect these houses a retention basin was built after a medium magnitude debris flow event that occurred in 1996.

The debris flow reported in this study occurred in the early morning of the 18th July 2009, triggered by a storm with two successive peaks of high intensity rainfall (Fig. 1), the first of which resulted more extreme (estimated return period equal to 50 years). The lag time between the two peaks was assessed as 20 min. The first peak (11.6 mm/5min) produced a debris flow event that filled the retention area constructed right above the old village, at 1000 m a.s.l. for an estimated volume capacity of 30,000 m^3 (Figure A3–B). The second peak, even if less intense (6.2 mm/5min) than the first one, generated another event that did not stop in the depositional area (because it was already filled), flooding the houses located downhill. The characteristic of the 2009 event is then the residual hazard of a retention basin filled up with sediment by a preceding debris flow event. The case study of the Cancia creek is meaningful since the apex of the fan is artificially modified by the construction of the channel to lower the hazard level for new settlements. This construction increased the level of danger for other settlements and infrastructures at lower altitude, making the building of a new retention basin unavoidable.

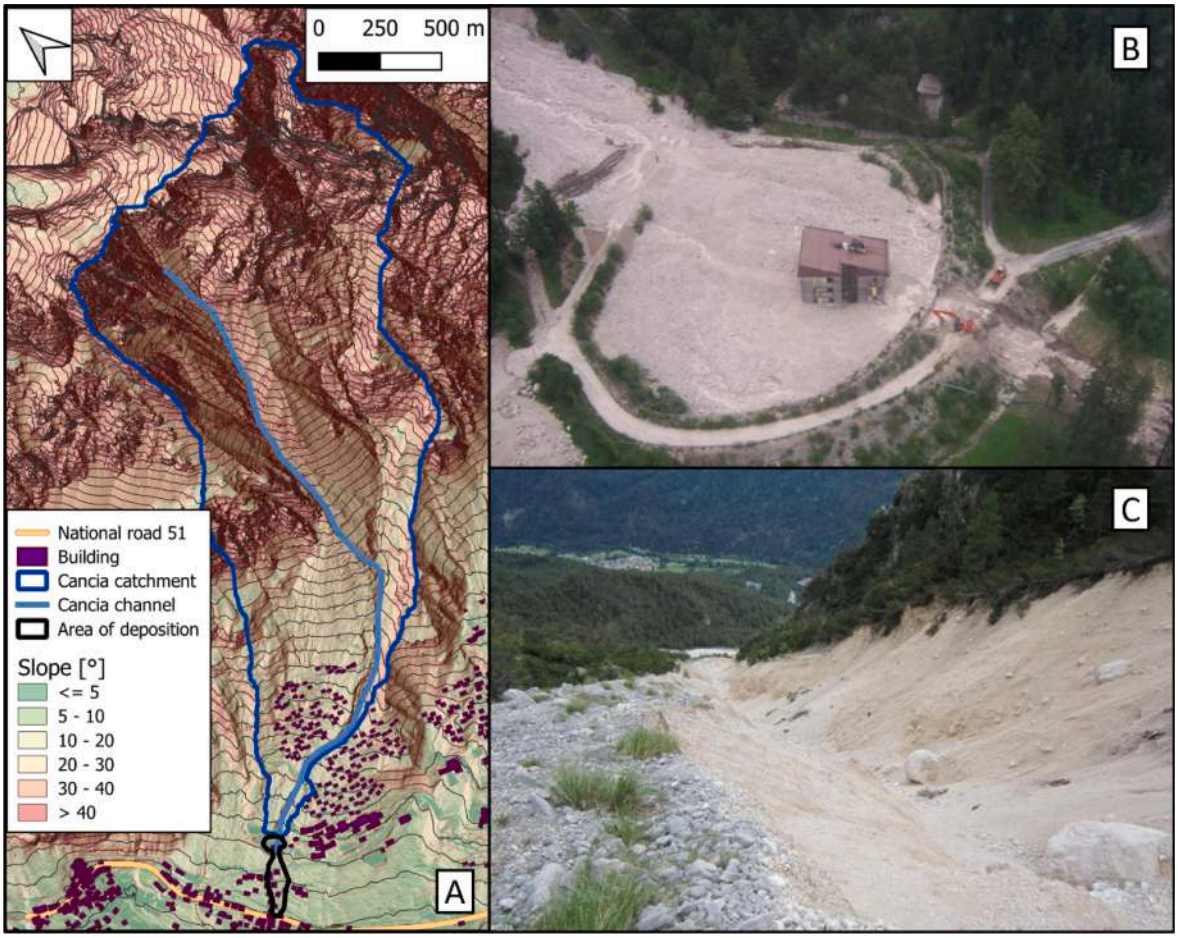

Fig. A3. Pictures representing: A) the morphology of the catchment, showing the depositional area of the 2009 event; B) the retention basin immediately after the event; C) the upper part of the Cancia channel at an elevation of about 1700 m a.s.l. (downward view). The contour lines elevation difference is 25 m.

A.4. Rudan – 15th December 2020

The Rudan catchment is located in the municipality of Vodo di Cadore, in the eastern Alps (Veneto region, Italy). The basin has an extension of 2.71 km^2 and a mean slope of 46° (altitude range 3264 – 788 m a.s.l.). The main channel starts just south of the Antelao peak, passing through a source area (so-called “Vallon dell’Antelao”) and merging with the Boite torrent (Figure A4–A and C). Above the confluence, around 800 – 880 m a.s.l., part of the village of Vodo di Cadore is located near the intersection of the national road SS51 and the main channel. The area has been affected in the last decades by different debris flow events, which in some cases damaged houses and temporarily interrupted viability. To reduce the risk associated with debris flow events an open check dam has been built 50 m above the bridge of the national road.

On the 15th December 2020, an intense rainfall event triggered a wide shallow landslide that deposited most of its volume within the main channel (Figure A4–B). The deposited material and flow of the channel generated a low-magnitude debris flow event (estimated total volume of 10,000 m^3). However, after this event most of the material transported by the landslide remained in the channel (estimated through a field survey in 40,000 m^3). The future implications of the actual conditions of the debris flow channel could be an increase of the magnitude of debris flow events, since the deposited material could easily be entrained. The possibility of a dam break event is likely and consequently the increase in risk toward citizens and infrastructures. The case study of the Rudan catchment highlights the changes in the conditions of the channel and implications on the availability of debris material. The deposited material is likely to decrease the frequency of low magnitude of debris flow events due to the barrier effect of the landslide deposit (Baggio et al., 2022). However, prolonged events could destabilize the sediment deposit, leading to intense debris flood events (characterized by a great availability of sediment) or in the case of abrupt release, the formation of a high magnitude debris flow event.

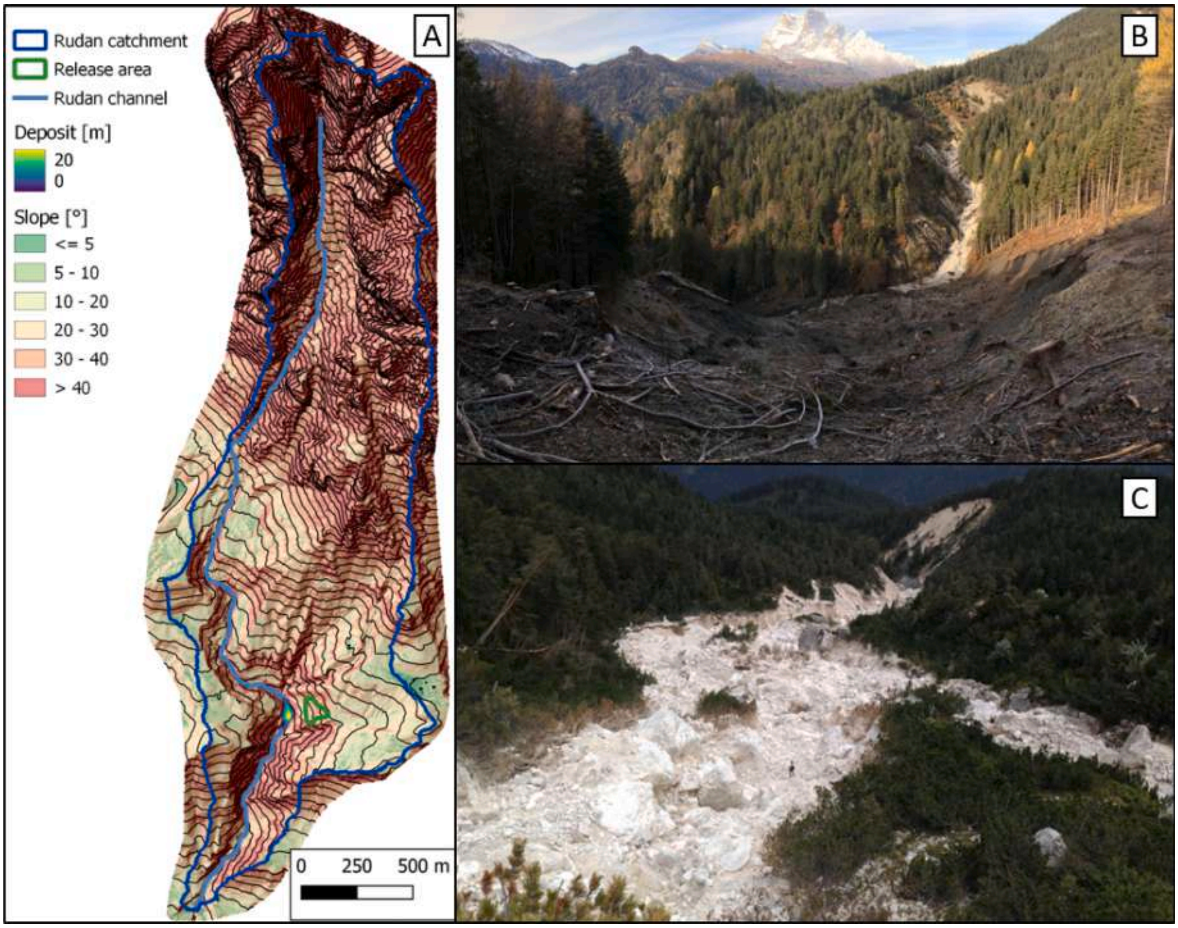

Fig. A4. Pictures representing: A) the morphology of the catchment, showing the landslide release area and in-channel deposit; B) the downward view of the landslide area with the channel; C) the upper part of the Rudan torrent (above the landslide area). The contour lines elevation difference is 25 m.

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