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Landscape analysis for multi-hazard prevention in Orco and Soana valleys, North-Western Italy

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Abstract

A Civil Protection Plan has been drafted for a 600 km^2 mountainous region in NW Italy Consisting of Orco and Soana Valleys. It is a part of the oldest natural park in Italy and attracts several thousand tourists every year. The work is concerned with the analysis of relevant physiographic characteristics of this Alpine landscapehaving extremely variable geomorphology and possess a long history of instability. Thousands of records as well as digital maps (involving overlay and comparison of up to 90 GIS layers) have been analyzed and cross-correlated to find out the details of the events. The study area experienced different types of natural hazards, typical of the whole Alpine environment. Thus, the present area has been selected for such multi-hazard research in which several natural processes have been investigated, concerning their damaging effects over the land. Due to 36 different severe hazardous events at least 250 deaths have been recorded in the area since 18th Century, in the occasion of.

1 Introduction

Several physical processes of the Alpine environment can be considered dangerous (e.g. torrential floods, landslides, snow avalanches, wildfire, earthquakes) and they are commonly referred to as “natural hazards”. Those hazards have been investigated and mapped with a view to constructing a GIS database for the widest possible range of events expected in the Orco and Soana Valleys (Western Italian Alps). These valleys have incurred hundreds of casualties and extensive damage by avalanches, rock falls, soil slips, debris flows and flooding. A rockfall (250 m^3 approx.) have occurred in May 2013 in the vicinity of a settled area (Locana) that has once more confirmed the sensitivity of the territory. The present authors, involving to prepare a Civil Protection Plan (CPP) on behalf of the CNR-IRPI Institute, found that about 85 km^2 (about 15 % of territory) experience large landslides, involving up to several millions m^3 each and about 19 km^2 is affected by shallow slides, which are often part of larger slope collapses. Field investigations of stream deposits (geomorphological, stratigraphical and dendro-chronological), supported by historical records, have revealed that almost the entire stream network is prone to debris-flow, even in quiescent conditions. In some cases, channels are insufficient to contain the maximum discharge capacity. Attention was paid to the "wildfire" hazard, for which an algorithm was developed specifically to highlight the hazard-prone areas. In addition, the troublesome issue of coping with natural hazard in an area, where potential hazard and sustainable development are perennially interacting, have been raised through the comparison of past events and innumerable descriptions of past protection works. Taking into account the potential for tourism in a large portion of the area (Gran Paradiso National Park), the entire road network has also been mapped according to hazards.

2 The study area

The Orco and Soana Valleys of Torino Province cover an area of about 618 km^2 and comprise 12 Communes inhabited by 6000, rising up to about 10 000 in the Summer. The area is bounded by the regional Piemonte/Aosta border and by the NW Italy and SE France border (Fig. 1). The highest peak of the Gran Paradiso massif reaches 4061 m a.s.l. and is surrounded by glaciers, about 10 km^2 in extent. The area is subdivided into numerous sub-catchments, but in the whole only 50 minor streams strongly influence the torrential activity of the main stream.

Meteorological measurements have been extremely variable between recording stations because of varying local morphology and elevation. During winter air temperature fluctuates between strongly positive and negative values and occasionally reach to 25 °C. The average extreme ranges between 22.6 and −6.2 °C (Mercalli and Cat Berro, 2005). These fluctuating temperatures contribute to the physical weathering of rocks and thereby to the delivery of debris and other degradational slope processes.

Geologically, the area is dominated by the Upper Pennidic unit of the Gran Paradiso nappe, a unit mainly composed of coarse-textured gneiss and para-schist. The former being the framework of the massif, the highest peaks and the water divide between Orco and Aosta Valley draw their origin. The Gran Paradiso nappe consists of tectonic elements of the Dominio Piemontese, which are mainly of marine origin. The lithologies in these units possess strong contrasting competencies those are reflected in their morphological features. Ophiolite masses and calcareous-dolomitic elements appear as the more resistant units, whereas the calc-schists are less resistant and more prone to erosion. To the north-west of the Gran Paradiso massif, internal Pennidic structural units of the Gran San Bernardo unit form the Valsavarenche-Grand Nomenon massif is found, which is composed of grano-dioritic gneiss and granite. The protoliths consist of Permian magmatic bodies and their surrounding "country" rocks, i.e. Permo-Carboniferous poli-metamorphic schists. The Pennidic units outcropping in this area overlie the Dominio Piemontese units and the Gran San Bernardo unit appears to be folded and back-thrusted on calc-schist.

Generally, the study area is characterized by atypical U-shaped glaciated valley, molded during the Pleistocene and preserved in the tributary valleys above 2000 m, where the fluvial Holocene degradational processes (slope instability and stream activity) have been less destructive. The present day morphology causes the super-position and inter-digitations of deposits produced by glaciations, slope instability and fluvial erosion over the course of time. The glacial deposits occur at the heads of main and second order river incisions, and on the flanks of the minor "suspended" valleys at mid-high elevations (elevation should be given). They are prone to slope collapses and consist of pebbles and boulders in a sandy matrix. The transition zone between the very steep slopes and the valley bottoms is often marked by large but discontinuous talus. On the flanks and the bottom of recently glaciated valley heads, typically striated and smoothed surfaces are appearing. Other glacial features, e.g. cirques, are frequent and occasionally bear small lakes, which are generally not yet filled with debris.

Freeze-thaw and persistent snow cover may often lead to rock stream and solifluction processes, which typically produce lobate accretionary deposits. These are gradually carried downward by meltwater, usually just above the "tree-line". Couloirs (preferential paths for avalanches) are common and usually develop along the lines of structural weakness, which may be enlarged by erosional (mainly torrential) processes. Large gravitational bodies, typically but not exclusively Gravitational Slope Deformations (GSD), are revealed by scarp slopes (often tectonically-induced) and by the presence of discontinuities. The undercutting of valley bottoms by glacial activity, stream erosion, tectonics, climatic history, and very rarely by seismogenesis can be considered as the preparatory causes of gravitational processes.

The stream network (density, alignment and development) is clearly controlled by structural discontinuities (faults and joints) and the average drainage density is usually about 3 km km^{-2}. It occasionally exceeds to 4 km km^{-2}. In some cases neotectonic fault systems also affect the Quaternary deposits (Malaroda, 2004).

3 Methodology

Various data analysis approaches have been adopted in the present study (both sequential and collective). The work involved historical research, field geomorphological surveys and interpretation of aerial photographs at a scale of 1:15 000, which have been acquired at eight years interval over a period of 50 years (1954 to 2005). Based on this work numerous unstable elements have been identified, both on slopes and across the drainage network.

During the course of the project, hazard scenarios for avalanches, landslides and stream erosion have been developed. Continuous cross-correlations, with satisfactory reliability, among those events have been done with the help of such historical evidences. For each type of hazard, a range of potential effects has been evaluated in terms of their likely effect on small settlements and major infra-structure. Detailed rainfall analysis for a period of 82 years (1920–2002) has been done to evaluate the critical range of rainfall volumes that lead to instability and trigger slope failures. Analytical hydrological models have been used to simulate flood waves and to model debris flow magnitude, outflow direction and depositional extent in the flood affected built-up areas due to debris flow. This allows better estimation and quantification of the expected effects. To identify the optimum methodology we have ensured the reliability of our systematic search, collection, selection and critical validation of existing data and documentation. Omissions and uncertainties connected with such information were eliminated, wherever possible, by comparing the original documents of the CNR-IRPI. Special care have been taken to collect existing material, to normalize data approapriately in view of necessary cartographic transposition and to choice a meaningful map scale (1:5000). In terms of geology and geomorphology the studies by AEM (Hydro-Electric Power Supply Agency of Turin) have been followed. AEM manages half a dozen hydro-electric power plants in the Orco valley. The "technical annexes" (i.e. the geo-morphological units) of the Piano Regolatore Generale Comunale (PRGC) related to the town-planning within Communes has been used for this work.

The approval and subsequent adoption of the PRGC by Communal Administrations constitutes an official and responsible realization of the natural hazards posed by slope instabilities throughout the region. It also represents an acknowledgement of the hazard classes and inherent restrictions imposed by recent rules, especially after the disastrous flooding events of 1993 and 2000. The intrinsic limit for such annexes is the scale (1:10 000) and built-up area centric, not the whole region.

The hazard damage database have been generated from bibliographic sources, newspaper articles, unpublished documents of CNR-IRPI and several public archives, Communes of the Orco valley (e.g. Fig. 2) and from the online archives of Regione Piemonte. A systematic attempt has been made to examine the historical evidence of instabilities (largely from field and aerial photographs) and to verify numerous descriptions of ancient slope failures (many of which date back to the middle of the 17th Century). It includes old nomenclature of stream channels that might have changed in morphology and description of protection works (Fig. 2). To analyze the effects of the events we have exploited the detailed historical research of the CNR-IRPI and other researchers, from documents in national archives, libraries and other public bodies, and correlated them through interviews with local residents and eye-witnesses. A substantial chronology (unpublished) of the events which have produced damaging effects since 1030 AD in the region of the western Alps (including the Orco Valley) has also been produced. All flood and landslide events of the last thirty years have been regularly surveyed and published by the authors.

For preparing land use, special attention has been paid to the forest cover, taking into account: (1) the key role exerted by vegetation on slope stability conditions and (2) the potential threat of wildfire in the area under study. We have taken help from the unpublished forest maps, drawn by IPLA (Institute for the Study of Trees and Environment) for preparing such map. Specific GIS-based applications have been followed toidentify the wildfire-prone areas. Weather, wind characteristics, slope aspect, vegetation and elevation have also been considered and combined in a original algorithm.

Field recognition represents a further step towards the integration and testing of information drawn from historical reports, other sources and photo-interpretation. Special attention has been paid to onsite surveys for detailed analysis of geomorphology of the slopes and sub-catchments liable to sudden sediment removal and transport. Recognition of present-day morphodynamic processes in relation to their location and initial conditions has been done with utmost care. Debris flow source areas (debris flows are most frequent during exceptional rainfall events) have been identified and quantified, in addition to depositional frozen lobes, levees, terraces and paths of previous channel flows on the fan areas. Care has been taken in assessing the contribution of depositional forms to instability processes, either directly by stream activity or by other conditioning causes, which may later lead to failure. Depositional forms recognized in the field have been, in some cases, ascribed to recent processes surveyed between 1977 and the present. In some cases older forms have been dated by accurate descriptions in historical documents. In case of inaccessiblity field evidence has been correlated with dendro-geomorphological data. The same sampling method has been found useful to define the stratigraphic relationships between depositional sequences along watercourses, and in the timing of debris discharged by slope failures and stream incisions. The torrential deposits caused by extraordinary events of last two centuries have been identified in this way. Old oaks are widespread, allowing the reliable derivation of tree ring ages despite the fact that oaks are less suitable than conifers for this purpose (Bollschweiler and Stoffel, 2009).

Through structural analysis and evaluation of the spatial distribution of rock discontinuities, we have assessed the importance of debris-source areas and preferential routes for the passage of debris flows.

The work has been conceived as a digital database and a series of map layouts using ArcGIS 9.1. Many surveys could not be completed punctually because of inaccessibility at some sites, either through deterioration of tracks and footpaths or because of erosion, rockfall and/or dense vegetation. Attention has been given on the processes potentially affecting settlements (permanently or temporarily occupied), roads, and recreational structures. Morphometric parameters of drainage network have been assessed in order to determine the elements concurring to express the magnitude possible, based on the formula proposed by the authors (Tropeano and Turconi, 2000, 2003) to evaluate the maximum volume of debris and sediments, which should be carried downward in case of paroxysmal events.

It is generally accepted that a fully vegetated catchment may significantly reduce the likelihood of flooding. It has also been demonstrated, through experiments carried out in the 1980s (e.g. Caroni and Tropeano, 1981), that forest cover acts as an interceptor of prolonged, high intensity rainfall (i.e. $> 10\,\mathrm{mm\,h^{-1}}$) restricts runoff value up to 0.1–0.2 times, in comparison with bare soils. Forest soils can also retain large volumes of shallow groundwater compared to bare or shrub-covered surfaces. Lastly, forest management practices help to ensure that woody debris is not discharged into incised stream channels. Forest management in the Orco and Soana Valleys began in the 1900s, even on slopes which are difficult to manage and unsuitable for rapid root establishment. On 7 September 1925, the National Forestry Corporation began a general restoration programme to prevent slope degradation and flooding in several sub-catchments of the region. Such work continued up to and after the Second World War, but ceased in the early 1970s (according to CNR-IRPI archives). For example, the Rio Frera catchment, which was widely populated by larches until a half century ago, still appears in fairly good condition with regard to plant health, in spite of wildfire damage (Fig. 3).

Analysis of already available multi-source data and documentation, historical studies, photo-interpretation and field measurements has greatly improved knowledge in an area where the occurrence of natural hazards is still poorly understood. Such efforts mean (a) new insights into the geology, geomorphology, natural processes and event scenarios; and (b) the development of a ready-to-use informatics product which allows integration and comparison of significant elements.

4 Results and discussion

In the light of new regulations issued by the National and Regional Government on Civil Protection, awareness has been raised towards the fact that Civil Protection should not be limited to the emergency management, but in view of the need for hazard assessment and mitigation should also (a) provide knowledge of the phenomena to which a given area is exposed and (b) deal with the dispersal of information and results. Acquired knowledge on the processes operated in this region, must be translated into hazard scenarios. It should, therefore, be specified that the concept of “scenario” implies a series of evolutionary hypotheses about an active and growing, or potential phenomenon, with increasing damaging effects in the surrounding area of the process. On the basis of the various potential hazards, the development of research into probabilistic analysis through the timely application of analytical models is necessary.

The geomorphological evolution of the area can be visualised through the gigantic landslide systems (GSD), which have been triggered by post-glacial remodelling. About 60 types of landforms have been detected, with an estimated surface area between 0.05 and 19 km^2; the latter value refers to the uninterrupted series of coalescent landslide bodies and constitute the entire right slope of the lower Orco Valley. In the middle reaches of the Orco Valley, two other important collapses have been found on the right and left Valley slope respectively, i.e. downslope of the Locana village (9.3 km^2) and Rosone locality (5.1 km^2). A fourth gigantic landslide occupies the left slope of the lower reaches of the Soana Valley (covering ca. 5.9 km^2). The majority of historical and present-day instabilities involve much smaller volumes and occur in the middle reaches of the Orco Valley; e.g. out of the damaging events reported in the Banca Dati Geologica of the Regione Piemonte, 96 cases occurred between 1628 and 1997 and one third of these have been involved in torrential activity, while the remainder involved in slope failures.

Careful historical research reveals that natural hazard events (snow avalanches, landslides, rock falls and stream flood) in the Orco and Soana Valleys have occurred at least 480 times over 600 years. Attention has been paid to the interpretation of events affecting the low-order drainage network and tributaries, which have been coded as an inverse function of their recurrence interval, thus expressing the hazard. The exceptional rainfall events, still affect this area, (September 1993, October 2000) indicate that the most hazardous conditions (which may lead to the loss of life) are often related to rapidly or very rapidly-evolving processes, rather than stream processes. By "very rapid processes" we refer to rock falls, shallow slides (soil slips) and stony debris flows.

A previous study focusing on stream hazard in the Orco Valley has been widened to include all situations (e.g. Valley bottom, alluvial fan), where past channel changes and/or stream overflows have been documented over time. Small tributaries mixed with sedimentary forms, possibly connected to reciprocal flow interchanges, are likely to have occurred in the past, over the alluvial fans or even above the fans themselves. The latter occurrence is more hazardous, as seen recently in the Aosta Valley on October 2000, where 6 people died (Tropeano and Turconi, 2003). Another source of hazard arises due to the sudeen deposition of coarse sediments by minor tributaries that substantially impacts on the flow dynamics by temporary blockage or diversion of the main stream.

A thematic map has been prepared to illustrate the stretches of transport networks (roads and footpaths) affected by past, recent (and future) instability phenomena. Road (or footpath) stretches cover about 72 km; the sources of hazard mainly pertain to low-order streams (50.2 %) and major streams, using Horton's hierarchical index equal to 4 or above (47.3 %). Landslide and snow avalanche hazards account for 1.2 and 1.3 % respectively. This relatively low value may be misleading, since after more than 37 years of fairly scarce snowfalls, the winter of 2008–2009 saw huge snow fall on almost all Valley slopes to a depth up to above 10 m at 2296 m a.s.l. (Arpa, 2009). Huge avalanches affected several sites on the main Valley road; the largest of these severely disrupted the Regional road for a distance of almost 250 m.

About 90 layers have been prepared in the GIS-based inventory (Figs. 4 a–c). The slopes close to settled areas of landslide events have been mapped without dividing the initiation, transition and accumulation zones. These descriptions follow criteria suggested by operational rules prescribed in technical annexes of Urban Management Maps.

Four groups of slope instability have been identified, which have been suffixed by "a" or "q", to denote their *active* or *quiescent* states respectively:

- Rock falls (of both block and coarse detritus).
- Deep-seated landslides and/or GSD.
- Shallow slides (earth flow, soil-slip).
- Complex slides, including a wide range of instability processes of different origin (e.g. post-glacial, composite slides) and different kinematic type (rotational-translational, flow, slide) (Figs. 5–8).
- Composite processes inside the incisions, which cannot be discriminated by aerial mapping.
- Talus deposits of different origin, with large blocks, and part of glacial deposits, which should be (re)set in motion by complex but not remote start-up conditions.

The term “Sackung” (Zischinsky, 1969) refers to local subsidence or slope collapse, gravitational expansion or gravitational slope deformation with a deep sliding base (Schwab and Kirk, 2002; Ehret et al., 2005; McCalpin, 2011). Kinematically it is akin to deep *creep*, i.e. reciprocal or independent displacement by blocks (Brückl and Parotidis, 2005). In terms of dimensions, the most significant slope dynamic processes are the impressive and widespread *sackung* and/or GSD, which often affect entire Valley sections over a vertical extent of more than a kilometer and over an area usually in excess of a square kilometer (locally in the region of $> 5\,\mathrm{km}^2$). Such failures can reach about 100 m in depth and tens of millions m^3 by volume.

In this context it is important to explain the concept of “scenario” as an increasing series of evolutionary hypothesis of a given process (active or potential), and to further develop a degenerative sense the varying stability and safety conditions within a given area.

Previously published studies on this subject agree on the difficulties associated with making accurate forecasts of such events, despite the fact that they are supported by reliable precognitive technologies (such as detailed survey, geognostic and petrographic analysis, monitoring equipment and modeling). On the basis of similar situations in the Orco and Soana Valleys, it seems logical to propose, as an unequivocal evolutionary scenario for such instabilities, the hypothesis of block sliding involves the full Valley width and formation of a temporary damming lake. Owing to the difficulty of definition, even with reasonable approximation, of the possible evolutionary phases of such sequential processes, it seems more logical and realistic to define the upper envelope of dormant instability processes, which can be seen in the field or in aerial photographs.

Almost all stream hazards that can be seen here have been mapped for all stream orders from the 1st order to the main stream flows. The total length of the channel system accounts for 4200 km, which corresponds to an average drainage density of $6.8\,\mathrm{km\,km}^{-2}$. In terms of natural hazards this implies that the efficiency of channel conditions during floods is important, especially when interfering with man-made structures. Attention was focused on the geometric definition of the morphological units recognized and especially of the sedimentary processes (alluvial fans) through interpretation of the topographic maps at 1:5000 scale (year should be mentioned), and validated through careful examination of stereo-aerial photographs.

For analysing the main streams in the area, the present-day channel has been reconstructed, digitally captured and georeferenced from recent aerial photographs. From the geomorphological map a fairly complex pattern of processes can be seen, from which a simplified map of geomorphologic-hydraulic hazard has been drawn. This synthesis is a product of the original on-site analysis and of the complex revision and standardisation of technical documents provided by Communes under the URP (Urban Regulating Maps or PRGC in Italy). This strategy is necessitated both by current regulations and by the need for a final document acceptable to land administrators. By this way, a document which otherwise should be merely useful for bureaucracy and administration, has resulted in an "act" of identification and acceptance of the critical nature of situations in the area under consideration. The hazard map focuses and reports on the following elements:

4.1 Torrential hazard

This has been sub-divided into three classes (TR1, TR2 and TR3) according to their increasing probability of occurrence. Few examples of torrential hazard are provided in Fig. 9.

TR1 represents a conservative delineation, based on topographic and geomorphologic criterion, from contour lines of a strip of land close to the channel courses, which has a high probability of lateral erosion, deposit-widening and channel-deepening. Such a strip is established for homogeneity in a zone of few tens of meters wide on both banks of the stream. The width of this zone is in some cases overestimated for the easiness of reading, but it may also be underestimated where channels are poorly incised and in the intermediate and lower stretches of the channel network. Such zones have conventionally been defined, by geomorphological and topographic criterion, as the length as far as the fan apex the present-day preferential flow direction is also outlined on each fan.

To represent the flow path directions in the fan areas that can be acknowledged as elongated depressions radiating from the fan apex, an interpolation has been made which should result in the delineation of an area and exceeds the largest event magnitude expected (TR2).

The whole fan area represents a fairly good probability in case of a paroxysmal flood or abnormally huge debris flow, the physical invasion area of flows in extreme conditions should invade the whole fan surface. In the absence of specific simulation models (fitted to each catchment scale and characteristics, and based on suitably validated entry parameters) to corroborate such a hypothesis, we refer to the pejorative class (TR3).

4.2 Flood hazard

This refers to flood dynamics in Valley bottoms and two classes are identified (FR1 and FR2) in reference to the expected flood invasion, (a) flood hazard assessment is simply based on geomorphological criterion, and (b) on direct field survey and stereo aerial photo-interpretation. FR1 roughly corresponds to the present day channels in the main drainage network, while FR2 refers to a large inundation area. FR2 is drawn by the interpolation (when data are available) between extreme limits of the Valley bottom expansion, as dramatically illustrated by the heaviest flooding surveyed by the authors in 1993 and 2000. This area was deduced by geo-morphological interpretation of detailed aerial photographs.

4.3 Landslide hazard

The slope failures shown in the geomorphologic map (described in Sect. 4) have been grouped into two large classes (LR1 and LR2) reflecting the failure mechanism and the different hazard types caused in settled areas (in terms of intensity and rate of evolution). In the LR1 class (higher hazard) we have grouped rockfall, earth flow, soil slip, combined channelized processes, debris talus and unstable glacial deposits. 99 debris masses of potential instability have been detected, extending over the whole area of over 19 km^2. In the LR2 class we have grouped deep-seated landslides and complex slides, combining 65 detrital bodies with a total area of 85 km^2. The value above does not refer to the whole basin area, but only to slope instability processes in proximity to settled areas or those directly interacting with settled areas.

The triggering factor of stream floods and most landslides are considered here as "exceptional rainfall events". This may sound vague but it is accepted that, in general, such a definition applies to meteorological and hydrological events which cause damaging effects on the landscape.

Our research finds that events of a given magnitude and process recur periodically in the same localities and with the same physical behaviour and points to long-term instability. The most important variable is the colonization by humans, the effects of which may result in increasing potential damage or hazard. Back-analyses to accompany the maps illustrated here are intended to be both descriptive of past events and predictive of future hazard occurrences.

5 Conclusions

Due to the severe hazardous processes many lives have been lost in the area: at least 250 deaths have been recorded since 18th Century, in the occasion of 36 different dates/processes events. Victims by snow avalanche accounts for 59 %, by stream floods for 21 %; debris flows and rock falls are responsible for 12 and 8 % of deadly events, respectively.

The CPP should be viewed as the framework of a generic procedure of almost real up-to-date predictions, on the basis of geographical, geomorphological and historical knowledge of past events (Tropeano and Turconi, 2004). This work represents the first attempt of an overview of the physiographic characteristics of the whole Valley system incorporating and interfacing the safety conditions of slopes and streams with anthropogenic activities. The scope of the CPP may be limited, in that it cannot be relied upon to provide categorical prevention measures (which may be obtained only through far-sighted urban policy), but it allows very useful conclusions to be drawn on the variable susceptibility of different land units of sudden and catastrophic events.

This work allows a detailed classification of the entire area (at a scale of 1:5000) as a function of the historical hazard conditions ofany locality and time and verified present-day natural and anthropogenic conditions. Fieldwork has been involved in the exploration of archives and eye-witness accounts, and the progress of this work has been discussed and explained, step by step, with local communities and groups (stakeholders). As a consequence, the end-product of this work, i.e. the CPP, represents a unique collaborative effort between authors, administrators and local residents.

Many research topics remain to be developed, especially those concerning (a) the time period during which natural events of a given intensity may recur, and (b) the improvement of techniques and knowledge, at the highest possible detail and in relation to anthropogenic activities. Finally, in social terms, we find that the residents of such changeable and potentially hazardous mountain environments should be made fully aware of the hazards, since they have to live with them in order to make optimum of use the land.

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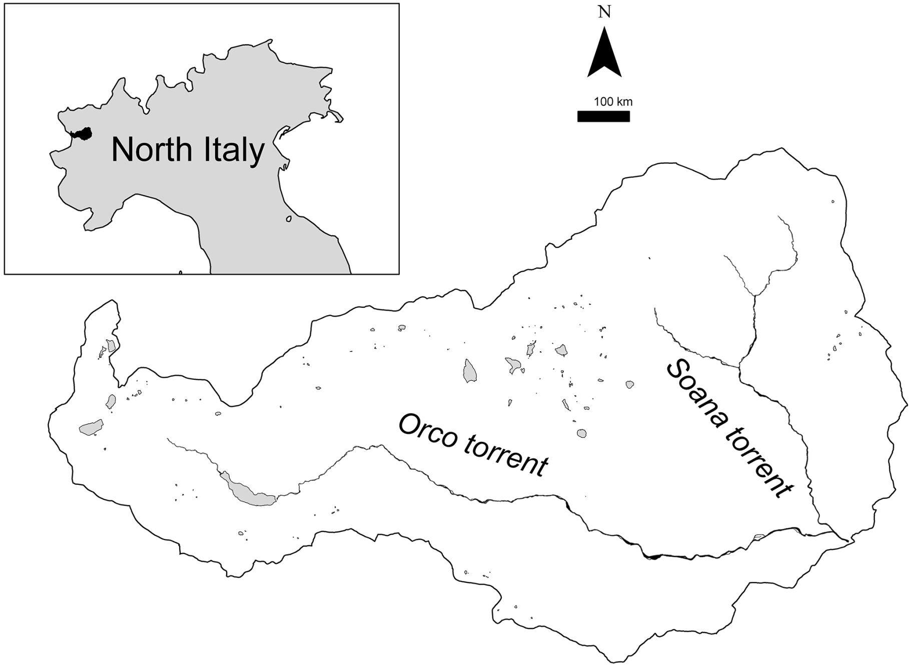

Figure 1. Sketch map of the study area (with main torrents and lakes).

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Figure 2. A village in the high Orco basin: very coarse deposits in the main channel as depicted in an old photograph (year 1952).

Figure 3. Frontal view of a minor catchment left to the Orco stream in which slope instability processes can be seen towards right; these have been re-activated in October 2000. In the foreground, mountain birches can be seen, on the left side of the catchment, in a 75 year old reforested area (Photo 25 February 2005).

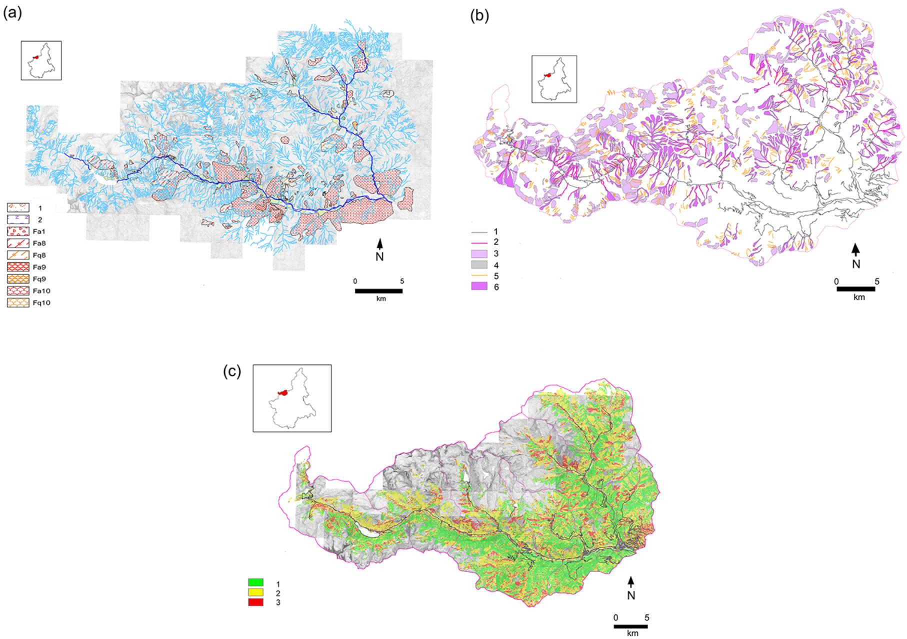

Figure 4. Demonstrative synoptic maps, obtained by combination of 90 layers at original 1 : 5000 scale, draft for the CPP of the Orco and Soana Valleys. **4a** – Geomorphological setup. 1 = detritus deposits, 2 = glacial deposits, Fa1 = active rockfall, Fa8 = active GSD, Fq8 = quiescentic GSD, Fa9 = recent soil slip, Fq9 = historical soil slip, Fa10 = active, complex landslide, Fq10 = quiescentic, composite landslide. **4b** – Multi-temporal occurrence of snow avalanches. 1 = road network, 2 = snow avalanche track, 3 = slope areas exposed to avalanches, 4 = areas provided with protective works, 5 = minor avalanches, 6 = avalanche-prone impluvia and minor catchments. **4c** – Wildfire-related risk classes, drawn by a purposely-developed algorhytm (see Sect. 3), for low, medium and high risk (1–3 respectively).

Figure 5. Right slope of a major catchment in the Orco Valley, near the stream head: a rock fall/soil slip process triggered by the extreme rainfall event of October 2000. The matrix-dominated nature of the materials is noteworthy and is connected to weathering products of the bedrock (Photo 11 June 2004).

Figure 6. In a steep-sloping sub-catchment in the upper Orco Valley, the right slope, affected by a deep-seated gravitational process, is underlain by disjointed earth blocks and extremely uneven ground surface (Photo 12 July 2004).

Figure 7. An example of the huge, disjointed stony blocks outcropping on the left slope of the Orco Valley, behind a settled area few hundreds meters downslope (Photo 21 July 2004).

Figure 8. Watershed of tributary of the Soana stream, incised in a deep-seated slope collapse deposit; typical features include trenches and counterslope surfaces, often with emergent water (Photo 31 July 2003).

Figure 9. Residual deposit of a debris flow (October 2000), which shows typical inverse gradation, along a left tributary of the Soana stream (Photo 8 August 2003).