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Debris Flows Risk Analysis and Direct Loss Estimation: the Case Study of Valtellina di Tirano, Italy

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Abstract: Landslide risk analysis is one of the primary studies providing essential instructions to the subsequent risk management process. The quantification of tangible and intangible potential losses is a critical step because it provides essential data upon which judgments can be made and policy can be formulated. This study aims at quantifying direct economic losses from debris flows at a medium scale in the study area in Italian Central Alps. Available hazard maps were the main inputs of this study. These maps were overlaid with information concerning elements at risk and their economic value. Then, a combination of both market and construction values was used to obtain estimates of future economic losses. As a result, two direct economic risk maps were prepared together with risk curves, useful to summarize expected monetary damage against the respective hazard probability. Afterwards, a qualitative risk map derived using a risk matrix officially provided by the set of laws issued by the regional government, was prepared. The results delimit areas of high economic as well as strategic importance which might be affected by debris flows in the future. Aside from limitations and inaccuracies inherently included in risk analysis process, identification of high risk areas allows local authorities to focus their attention on the "hot-spots", where important consequences may arise and local (large) scale analysis needs to be performed with more precise cost-effectiveness ratio. The risk maps can be also used by the local authorities to increase population's adaptive capacity in the disaster prevention process.

Keywords: Debris flows; Risk analysis; Economic losses; Central Alps; Italy

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Introduction

Landslides are among the most frequent and damaging natural hazards in mountainous regions. They cause thousands of casualties and economic loss on the order of billions of dollars annually (Schulz et al. 2009) impacting on housing, roads, railways and other facilities in urban and rural areas. For years, government and research institutions worldwide have focused their attention on landslide risk analysis, assessment and management. Under this perspective, the estimation of probable future loss is a matter of increasing interest to those concerned with development planning or with the management of facilities or public administration in hazard-prone regions which have a past history of disasters. Fundamental to this planning process is an understanding of what to expect (DMTP 1994). Consequently, within an integrated risk management strategy, risk analysis is a crucial aspect. It involves an analysis and combination of both theoretical and empirical data relating: the probabilities of known disaster hazards of particular force or intensity occurring in each area; and the loss expected to result to each element at risk in each area from the impact of each potential disaster hazard.

A well-known report, provided by Varnes and the IAEG Commission on Landslides and other Mass-Movements (1984), defines landslide risk as "the expected degree of loss due to a landslide (specific risk) and the expected number of lives lost, people injured, damage to property and disruption of economic activity (total risk)". Ten years later, DMTP (1994) describes risk as "the expected loss (lives lost, persons injured, damage to property, and disruption of economic activity) caused by a particular phenomenon; risk is a function of the probability of particular occurrences and the loss each would cause". AGS (2000) defines risk as "a measure of the probability and severity of an adverse effect to health, property or the environment and often estimated by the product of probability and consequences". Risk has been expressed by ISSMGE TC32 (2004) as "the measure of the probability and severity of an adverse effect to life, health, property, or the environment. It is the probability of an adverse event times the consequences if the event occurs". Crozier and Glade (2005), in simple but understandable terms, state that "risk can be seen as having two components: the likelihood of something adverse happening and the consequences if it happens. The level of risk thus results from the intersection of hazard with the value of the elements at risk by way of their vulnerability". More precisely, the authors define landslide risk as "the anticipated impact or damage, loss or cost associated with that hazard".

UNISDR (2009) expresses risk as "the combination of the probability of an event and its negative consequences". This definition closely follows the definition provided by the ISO/IEC Guide 73 (2002, 2009) in which the term risk emphasizes the consequences in terms of "potential loss for some particular case, place and period". Guzzetti (2005) states that risk can be "mathematically expressed as the product of the probability of the occurrence and the probability of the consequence". Couture, in 2011, defines risk as a "combination of the likelihood or probability of occurrence of an event and the related consequences". Moreover, the author insightfully differentiates between specific risk (the risk of loss or damage to a specific element at risk resulting from a specific hazardous affecting event) and total risk (the risk of loss or damage to all specific elements at risk from all specific hazardous affcting events).

The calculation of risk, whatever the final aim of the study may be, generally needs to consider several types of loss in relation to the different (physical/functional/operational, socio-economic, socio-cultural, ecological/environmental, political/ institutional) dimensions concerning a single or a group of elements (organized in systems, communities) at risk. This propensity to suffer damage due to hazard exposition, known in literature as vulnerability, has many different connotations that could be summarized in at minimum two different perspectives. One is based on an engineering and natural science point of view, the other on a social science outlook (Glade 2003, Blahut and Klimeš 2011). In relation to the components (dimensions) of vulnerability, each school of thought takes into account and privileges different views. Definitions of vulnerability are reviewed and listed by Cutter (1996), Weichselgartner (2001), Klein et al. (2003), Glade (2003), Adger, (2004), Fuchs et al. (2007), Papathoma-Köhle et al. (2011), Sterlacchini et al. (2013) among the others.

As reported in Glade (2003) and Sterlacchini et al. (2013), the expected degree of loss can be quantified either on a metric scale (in terms of a given currency/monetary unit) or on a non-numerical scale (based on social values or perceptions and evaluations). The type of scale is strictly related to the type of damage, referred to tangible or intangible loss. Tangible loss can be measured and quantified in relatively easy way and include physical damage to assets, disruption of business activities or emergency response and relief costs. On the other hand, intangible loss comprise of death and injured people, damage to landscape, psychological consequences of disasters and are very hard to measure or quantify. Among tangible loss, it is generally accepted that saving life is the highest priority of each disaster prevention and mitigation option. Human life represents a special case since its intrinsic value when threatened by a hazard is incalculable (Galli and Guzzetti 2007). However, in some cases, attempts to quantify human life in monetary terms have been performed (Linneroth 1979), especially in life insurance calculations, out of which arises many ethical questions. On the other hand, many types of loss can be converted into economic cost, a practical way for considering a wide range of effects. Alexander (2000, 2005), Galli and Guzzetti (2007) state that, when expressed economically, the degree of loss of the elements at risk can be defined in terms of:

- monetary value, defined as the price or current value of the asset, or the cost to reconstruct or replace it with a similar or identical asset, if totally destroyed or written off;
- intrinsic value, defined as the extent to which an asset is considered important and irreplaceable, and;
- utilitarian value, defined as the usefulness of a given asset or the monetary value of its usage averaged over a specified time span.

Natural hazard/disaster risk viewed from the perspective of the insurance industry and disaster management was thoroughly analysed by Chen et al. (2012, 2013) and Hsu et al. (2012). Despite its application to Taiwan conditions, the general approaches and conclusions are useful and feasible for the analysis in other areas.

In landslide risk studies, two different approaches are generally distinguished (Crozier and Glade 2005): quantitative risk analysis (QRA in this study), usually applied at large/local scale, and qualitative risk analysis, usually performed at smaller scale. QRA is expressed on a numerical scale concerning hazard probability, values of elements at risk, degree of loss and economic consequences. Specifically, the estimation of potential loss and economic consequences may provide useful information to local decision-makers for further cost-benefit analysis in support of an effective allocation of human and economic resources needed to deal with disaster preparedness and response. However, the cost-benefit analysis (whatever may be its main aim or object) needs the analysis of a long list of gains and loss, many of them hardly quantifiable in monetary terms (Ganderton 2005). Therefore, according to the findings of van Westen et al. (2006), a proper landslide QRA at a regional scale (1:25,000 to 1:50,000) still seems to be a step too far. On the contrary, qualitative risk analysis uses word form, descriptive or numeric rating scales to describe the magnitude of potential consequences and the likelihood that those consequences will occur (ISSMGE TC32 2004) in order to obtain risk classes.

Concerning the scale of analysis, in large scale studies, the expected degree of loss may be expressed by using quantitative information, concerning the process type, its intensity (usually quantified as height of accumulation or impact pressure) and the characteristics of the elements at risk (Borter 1999; Fuchs et al. 2007; Quan Luna et al. 2011) or by qualitative methods (Bell and Glade 2004; Fell and Hartford 1997). On the contrary, in regional scale analysis (as performed in this study), the physical, mechanical and structural parameters related to damaging events as well as to the elements at risk are not usually available, due to their economically unsuitable collection. For this reason, some assumptions have to be set up, before performing risk analysis, especially concerning vulnerability. From this point of view, the usage of vulnerability curves (relating hazard intensity with damage data) for risk calculation on a regional scale proposed by the literature (Borter 1999; Fuchs et al. 2007; Quan Luna et al. 2011; Papathoma-Köhle et al. 2012) is very limited. Expressing vulnerability over a regional scale is difficult due to large structural differences among the assets under analysis as documented by Papathoma-Köhle et al. (2011). Some of the wide list of recent approaches to risk quantification at a regional scale (1:25,000-1:50,000) are presented hereafter: Michael-Leiba et al. (2003) performed a GIS-based regional landslide and debris flow risk analysis in Cairns Community (Australia) based on hazard polygons characterized by magnitude-recurrence relations and shadow angles. These have been overlaid by vulnerabilities of resident people, buildings and roads in order to obtain a quantitative estimation of the total risk. Bell and Glade (2004) develop a new raster-based method for quantitative risk analysis for landslides in NW Iceland. They calculate individual and object risk to people in buildings and total risk considering different vulnerabilities and probabilities of spatial, temporal and seasonal impact of debris flows and rock falls. Remondo et al. (2005, 2008) carry out a raster-based statistical analysis to model quantitative landslide risk in northern Spain (Bajo Deba area). The final result is a risk map (and associated tables) combining potential loss (€) per pixel (1×1 m) for a 50-year period, considering both direct and indirect economic loss. Probabilistic landslide risk analysis, considering direct cost only, is applied also by Zêzere et al. (2008) in the area north of Lisbon (Portugal). Different raster-based hazard scenarios are modeled and combined with vulnerability maps of the exposed elements (whose reconstruction cost is known) and risk is estimated in €/pixel (5 × 5 m).

More recently Klimeš and Blahut (2012) performed a hazard and risk analysis in the area of Outer-western Carpathians in the Czech Republic. They considered two landslide types (deep seated and shallow landslides respectively) to establish susceptibility and hazard models. Consequently, they used the hazard modeling results to prepare risk maps for different elements at risk (linear, point, areal). Using semi-quantitative approach to estimate the resulting risk of economic looses, they obtained positive feedback from local authorities dealing with landslide hazard and risk. Lin et al. (2012) applied fuzzy-based risk analysis model for debris flows in the Hualien area of Taiwan. Their results proved to be suitable for the area in terms of resultant ration success and normalized relative error. Recently, Blahut et al. (2013) applied two different regional models to obtain rockfall hazard and risk quantification for two municipalities in Northwestern Czechia. They applied Swiss methodology (OFAT, OFEE, OFEFP 1997) to estimate hazard and consequences of landslides. Their results show that different morphology of the studied areas can result in rather diverse hazard and risk estimates.

1 Objectives

In this study, according to the definition provided by Varnes (1984) (i.e. risk is function of hazard, vulnerability and value of the elements at risk) and the scale of analysis, the final aim is to perform a debris flow risk analysis by quantifying the direct monetary loss due to the occurrence of debris flow events at a regional scale in a Consortium of Mountain Municipalities (Valtellina di Tirano, Italy). A previous knowledge of the magnitude of the expected loss due to debris flows, during a specified time period, is a key-action in order to choose the best prevention and mitigation options and to decide how to allocate resources properly, with the intention to maximize the potential benefits at an acceptable cost (Sterlacchini et al. 2007). Results coming from this study may be of great interest for several potential local decision makers (public administrators, spatial and urban planners and managers, insurers, lawmakers and authorities responsible for preparedness and response activities in the field of Civil Protection) in order to determine the prospective physical effects and the economic consequences due to the occurrence of a damaging event.

In the study area, a qualitative, institutionally-based hydrogeological risk map was already available (Lombardy Region 2005). It was derived by the application of a risk matrix relating 5 hazard classes with 4 vulnerability classes (see section 3.2). In this way, the territory under study is classified in 4 risk classes. Although this institutionally and legislative-based methodological approach is a simple mechanism to increase visibility of risk and assist the decision making process, it has some drawbacks concerning both hazard and vulnerability assessment that can undermine the efficacy of its practical use.

In terms of hazard, the input maps consider different types of hydro-geological events but no quantitative information concerning spatial or temporal probability is provided. In effect, hazard classes are mainly the results of geomorphological observations and mapping activities given that statistic/deterministic modeling techniques have never been applied in this approach. Moreover, some terminological confusion arise since the expected degree of loss may be included in the description of the hazard classes (e.g. H4, see paragraph 3.2 for more details).

From the vulnerability side, expected impacts and the related degree of loss are never taken into account (even qualitatively) and only the strategic importance of a generic infrastructure in a given territory or the presence of human beings in different building types is considered in the definition of the four vulnerability classes.

Similarly, no information concerning the value of the elements at risk is provided. As a consequence, the final risk map is a "weak" tool, not properly able to provide useful information to the local decision makers in their daily work, except as a set of qualitative risk classes among which to choose, following an expert-based procedure. In this study, in order to overcome some of the above mentioned disadvantages , a raster-based (pixel size: 10×10 m) methodological approach is proposed leading to the calculation of semi-quantitative risk maps, together with corresponding risk curves. The risk maps express the geographic distribution of the expected direct monetary loss due to the occurrence of debris flow events over a given period of time. Risk curves have the purpose of reflecting the expected degree of loss against the respective hazard probability in a more straightforward way.

In this study, different economic values of the elements at risk have been considered to obtain a sound quantification of the direct monetary loss: reconstruction/rehabilitation cost and market value. The former is what it would cost to rebuild/rehabilitate buildings with materials of like kind and quality and it is usually applied for insurance claims; the latter is what a buyer would pay for a building, including the lot. The use of these values can have advantages and drawbacks. The main advantage of using reconstruction cost for prospective damage estimation is that this parameter is tabulated yearly and made available by public bodies and/or private building companies. It can be easily applied to calculate direct monetary loss only if the physical degree of loss is well-documented. This information is rarely available over large areas (as for regional studies) and, for this reason, the use of reconstruction cost is quite unfeasible given the high level of uncertainty related to the physical effects due to the occurrence of debris flow events. On the contrary, the main disadvantage is that it is approximately uniformly distributed over large areas and peculiar disparities between economically different zones cannot be well distinguished. Moreover, reconstruction cost could experience speculative changes very difficult to take into account in case of adverse and unpredictable environmental conditions as for natural disasters.

The use of market value to estimate direct monetary loss concerning the different types of buildings and land use has the advantage of discriminating between areas of higher and medium economic importance from economically marginal areas. For example, a building is expected to have a higher market value if included in tourist resorts rather than in rural areas; or high quality south-facing slope vineyards producing D.O.C. (Controlled Origin Denomination) or D.O.C.G. (Controlled and Guaranteed Origin Denomination) wines, will have higher value than low quality north-facing slope vineyards. In both cases, the reconstruction cost is expected to be very similar, while market value will be highly different. On the contrary, the main disadvantage is due to its changes over time, mostly related to speculative reasons or other changing circumstances. As a consequence, direct monetary loss estimation should be considered in a "static" way, relevant only for the time of analysis.

In this study, reconstruction cost is used for those assets (buildings and infrastructure) whose main function is to provide public services to population since these assets cannot be monetized at an official local real-estate market. For the other assets located on the territory the market value has been used. It is relevant for local planners and managers in order to define in advance the economic value at stake when performing economic analysis of alternatives at a regional scale. It is an easy way to calculate and be aware of the potential direct monetary loss for each risk scenario. This finding together with the number of people potentially affected in each scenario can be used to rank the most-at-risk areas with the final scope to prioritize the prevention and mitigation measures on these "hot-spots".

After the map calculation, the semi-quantitative risk maps are compared each other and to the institutionally-based qualitative risk map.

2 Study Area

Debris flow risk analysis was carried out in a Consortium of Mountain Municipalities of Valtellina di Tirano (Lombardy Region, Italy). The study area covers about 450 km^2 and comprises 12 municipalities located in the Valtellina Valley

(Central Italian Alps, Figure 1). From a geomorphologic point of view, Valtellina represents the upper drainage basin of the Addax River which flows in a flat alluvial plain up to 3 km wide. The lowest altitude in the study area is about 350 m a.s.l. near San Giacomo di Teglio where Addax River flows out from the study area. The highest elevation is reached in the northern part of the study area on Cima Viola Peak (3,370 m a.s.l.). In the highest altitudes, glacial and fluvial-glacial landforms are prevalently present. Nevertheless, torrential and erosive processes have changed some of these glacial morphostructures. The lower part of the valley flanks are covered with glacial, fluvial-glacial, and colluvial deposits of variable thickness. The bottom of the main valley is filled with alluvial deposits and the alluvial plain is well developed. Alluvial fans, at the outlet of tributary valleys, can reach a considerable size, with a longitudinal length up to 3 km. The valley has a prevalently U-shaped profile derived from Quaternary glacial activity.

From a geological point of view, the bedrock of

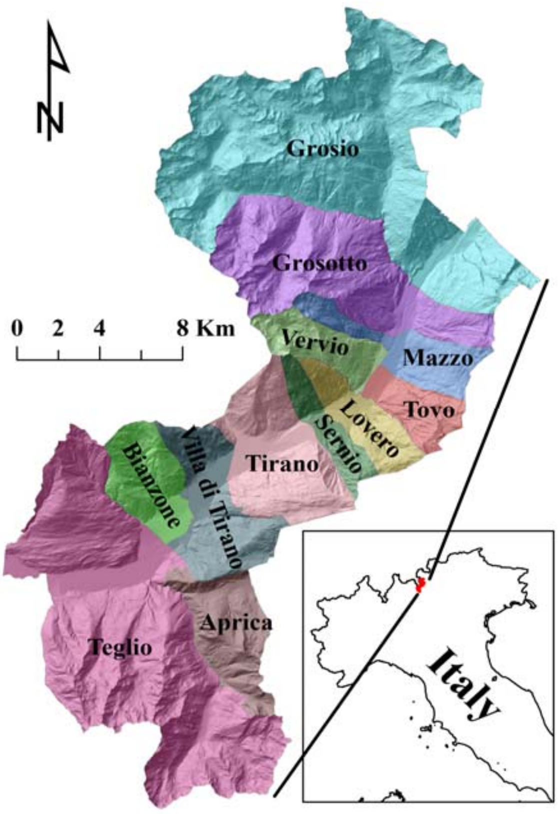

Figure 1 Location of the study area, showing the 12 municipalities of CM Valtellina di Tirano.

the northern part of the study area is composed mainly of metamorphic rocks (gneiss, micaschists, phyllites). In the southern part metamorphic rocks are represented by Edolo micaschists and quarzites belonging to South-alpine basement, with subordinate sedimentary rocks. Due to the proximity of the Periadriatic fault (an important regional tectonic lineament), wide cataclastic and mylonitic zones are present. The climate of the study area shows high differences in mean annual precipitation due to high differences in altitude and slope aspect. Precipitation is strongly controlled by altitude and varies from 726.6 mm/year in Tirano (430 m a.s.l. at the bottom of the valley) to 1,188.6 mm in Aprica (1,181 m a.s.l. located on a north facing slope) (Agostoni et al. 1997).

Land use in the study area is strongly controlled by climate and relief, in terms of altitude, slope gradient and slope aspect. Farming and light industry is concentrated on the bottom of the valley and on alluvial fans, while the lower parts of south facing slopes are covered by vineyards and apple orchards. The remaining slopes are covered with leafy forests till the altitude of 600-700 m a.s.l. From this altitude till 1,000 m a.s.l. chestnut trees prevail in the forests. From 1,400 m a.s.l. coniferous trees start to dominate and reach (as single trees) altitude of 2,300 m a.s.l. (Agostoni et al. 1997). At higher altitudes only alpine meadows, scarce vegetation and bare rocks are present.

The total number of inhabitants of the twelve mountain municipalities is about 30,000. Most of them are settled on the bottom of the valley, about one third in Tirano. Most of the people work in services (61.9%), followed by industry (32.4%) and farming activities (5.7%). The average unemployment rate is around 5%.Valtellina valley is mainly a tourist area with important agricultural vocation. Tourism represents more than one third of the overall added value produced in Valtellina and the tourism-oriented service sector generates about 70% of the overall income (Camera di Commercio 2008). On the other side, agriculture plays a very important role; the valley is famous for the cultivation of apples and also for the production of high quality wines (some of them having quality assurance label D.O.C. or D.O.C.G.). These agricultural activities have been intensively practiced for many years representing one of the most important sources of sustenance for the local economy.

Valtellina has an unenviable history of intense and diffuse landslides whose cause is the combination of high precipitation rates with a general lack of maintenance of the territory (i.e. cleaning of drainage channels, maintenance of mitigation works, complicated bureaucracy, etc.). As a consequence, landslides are among the most significant hazardous events in the area as well as one of the primary causes of casualties and economic loss. According to Agostoni et al. (1997) and GeoIFFI (2008), many landslide types and processes are present in the study area (Blahut et al. 2012). The largest slope processes consist of deep-seated slope gravitational deformations (DSSGD) which are mostly connected with the presence of the main active fault systems. Paleolandslides are also present in the area. Other landslides acting in the area consist of a variety of types (translational and rotational landslides, flow-like landslides, rock falls, debris flows). Debris flows are probably one of the most dangerous landslide types, due to its high-velocity and short-time development. The most destructive landslide events, triggered by heavy rainfalls, are recorded during the months of May 1977, May 1983, May 1987, November 2000, November 2002, and July 2008 (Cancelli and Nova 1985; Guzzetti et al. 1992; Crosta 1998; Crosta et al. 2003; Akbas et al. 2009). Field surveys allowed the mapping of shallow soil slips, slumps and soil-slip debris flows affecting Quaternary covers. Concerning the 1983 event, three debris flows caused 18 casualties in the area of Teglio municipality (Blahut et al. 2012). For that reason, debris flow hazard and risk analysis is of high importance given that it constitutes the basis for risk management strategies and dissemination of risk information towards general public.

3 Methodological Approach and Data Used

In order to overcome some of the drawbacks related to the use of the institutionally and legislative-based risk map (map A, Lombardy Region 2005), a methodological approach is designed and applied in order to produce two different semi-quantitative risk maps (map B and C). It starts from the well-known risk equation presented by Varnes (1984) and applied and tested in many previous studies (Michael-Leiba et al. 2003; Bell and Glade 2004; Remondo et al. 2005):

$$R = H \times V \times E \quad (1)$$

where *R* represents risk, H represents hazard, V represents vulnerability, E represents elements at risk.

These semi-quantitative risk maps provide two different alternatives concerning the assessment of the direct monetary loss as a consequence of the occurrence of a single hazard event. In effect, risk maps B and C are calculated by using different types of hazard maps, different degrees of loss and different monetary values (in terms of market value and reconstruction/rehabilitation cost) of the elements at risk as inputs of the risk analysis, as described in the following paragraphs. In this way, some different risk scenarios can be designed and analyzed, each one with its own risk curves enclosed, useful to define different expected direct monetary loss against the respective hazard probability. The methodological approach here discussed, aside from limitations and inaccuracies (inherently included in the risk analysis process), is flexible enough to allow decision makers to change/refine/modify the input parameters of the analysis at their own convenience to derive valuable information for designing different spatial planning alternatives.

The flowchart of the methodology applied in the risk analysis is shown in Figure 2. The two upper boxes represent the inputs of the analysis (hazard and elements at risk-related maps). The central box corresponds to the core of the analysis providing all the useful information concerning the calculation of both the institutionally-based risk map and the semi-quantitative risk maps. In this study vulnerability is considered as the expected degree of loss from a debris flow hazard. The lower box concerns the risk curves associated to each of the semi-quantitative risk maps to quantify the expected direct monetary loss against the respective level of hazard. Finally, arrows symbolize the data flow.

3.1 Data preparation

The approach proposed in this study used only inputs with similar resolution (1:10,000) which are consequently rasterized as 10×10 m cells. Information needed for the creation of risk maps at

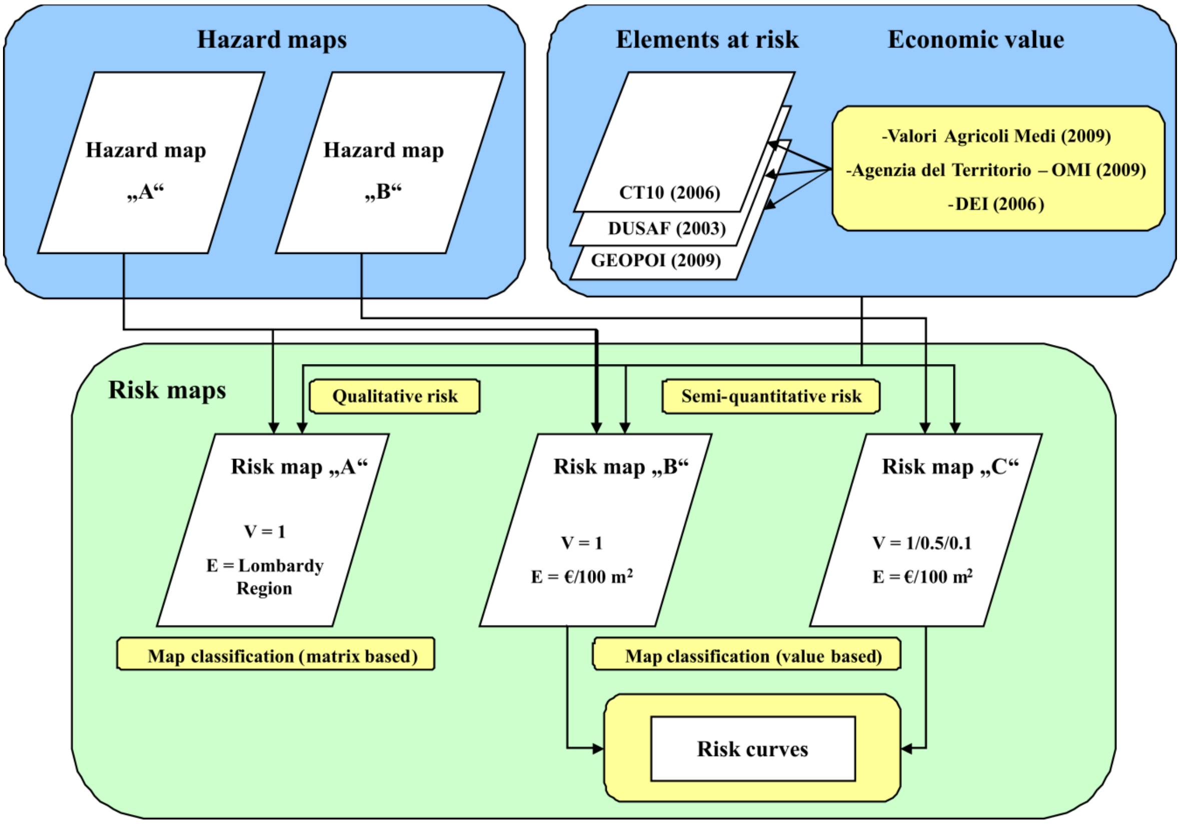

Figure 2 Flowchart of the risk mapping and analysis methodology.

a regional scale consists of two main parts: 1) information about hazard, that is the probability that a particular danger (threat) occurs within a given period of time (ISSMGE TC32 2004); and 2) information about the elements at risk, their economic values and the expected degree of loss. In the study area, among the different types of mass-movements, high-frequency low-magnitude events are the most recurrent damaging events (Crosta et al. 2003) that caused significant loss of life and damage to the territory and its vulnerable elements in the past.

Two different hazard maps are already available for the study area and originally derived by applying different types of models. First, a debris flow susceptibility map is used as initial input for hazard analysis; it is calculated by the use of the Weights-of-Evidence modeling technique (Blahut et al. 2010a), a Bayesian statistics aimed to delimit areas of high/low potential for debris flow initiation. This map is the final result of a four-step analytical process: [to make reading easier, suggest the following format:

(1) Preparation of the debris flow inventory and factor maps;

(2) Calculation of accountability and reliability indices for a preliminary susceptibility analysis and selection of an appropriate combination of the factor maps for detailed analysis;

(3) Evaluation and validation of the obtained susceptibility maps; and

(4) Comparison of the results and selection of the final map.

Concerning step (1), a debris flow inventory map is compiled by photo-interpretation of 2001 aerial photographs (DF2001). Then, the 573 debris flow scarps are subdivided into two mutually exclusive subsets (each containing 50% of the total number of debris flow scarps) by a random selection: the former (success subset) is used to calibrate the models, while the latter (predictive subset) to validate the models. Concerning the factors, the following are used in the analysis: altitude, internal relief, planar curvature, profile curvature, slope, slope aspects, and flow accumulation, lithology, land use and distance to faults. Then, temporal probabilities are calculated based on comparison of two different debris flow inventories, from 1981 and 2001 (Blahut et al. 2010b). After that, debris flow run-out zones and hazard classes are calculated by using an empirical GIS-based model (Flow-R), proposed by Horton et al. (2008). Two hazard maps are prepared and then used to assess two different semi-quantitative risk maps:

- hazard map A (Figure 3A) that delimits five debris flow hazard classes with corresponding probabilities;
- hazard map B (Figure 3B) that has the same class delimitation of potential debris flows as hazard map A but four out the five hazard classes (namely, very high, high, medium, low) have been further subdivided into three sub-classes, each delimiting potential spreading areas characterized by different impact probabilities. (For more information about the hazard maps preparation and calculation, please refer to Blahut et al. (2010b).)

The elements at risk considered in this study refer to different types of buildings, roads and land use potentially affected by debris flows in the study area. Although the importance of the main two-track railway from Sondrio to Tirano (a primary railway mainly used by commuters and for goods transport) and the narrow-track railway from Tirano to St. Moritz via Bernina Pass (a secondary railway mainly used by tourists), they are not considered in the risk analysis given the lack of information concerning their costs of reconstruction/rehabilitation. Moreover, there are many other classes of elements at risk located on the study area that do not have any specified economic value set by the official resources. However, it has to be noted that many of them have intangible value associated with their environmental importance as natural resources (glaciers, rivers, lakes), or linked with its public importance (junkyards, quarries). These values are hardly definable even by environmental economists (Hanley and Spash 1993). As a consequence, they are not taken into account in this study and it is decided to use only available official values which

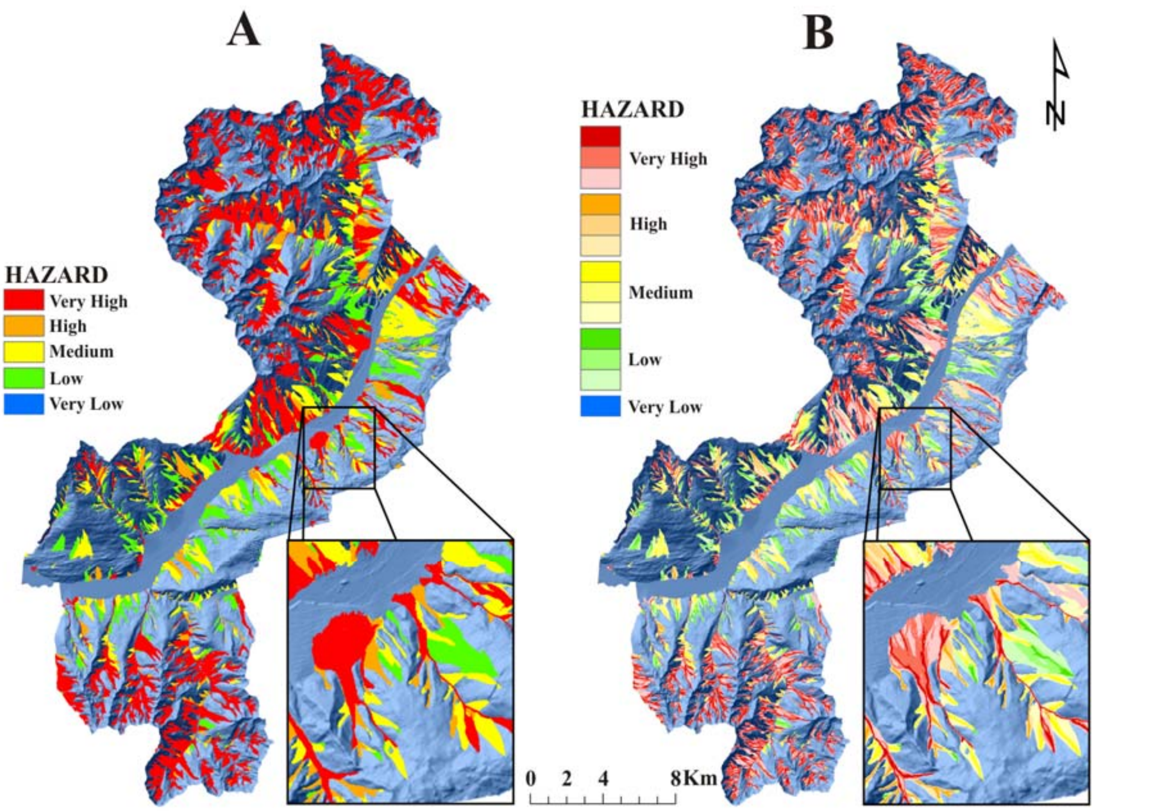

Figure 3 Input hazard maps used in the risk analysis. A – hazard map A, with 5 hazard classes; B – hazard map B with 5 hazard classes and 12 sub-classes. Corresponding occurrence probabilities are: very high hazard class – 0.224783 × 10^{-4}, high hazard class – 0.033754 × 10^{-4}, medium hazard class – 0.006456 × 10^{-4}, low hazard class – 0.002323 × 10^{-4}, very low hazard class – 0.000042 × 10^{-4}. After Blahut et al. (2010b).

are easily accessible and updateable in further studies. Information about the elements at risk is derived from several datasets taking into account the same resolution of inputs:

- Regional land use vector maps from the DUSAF Project (2003) are used to delimit urban and rural areas (as well as forests and areas without vegetation).
- Regional database at 1:10,000 scale (CT10 2006) in vector format is used to obtain transport ways (roads and railways) in the study area.
- GEOPOI® polygons (GEOPOI 2009) from Territorial Agency of Lombardy Region are used to obtain more precise delimitation of urban areas with different market values of buildings.
- DB2000 (2009) from the Consortium of Mountain Municipalities of Valtellina di Tirano is usd to delimit percentage of houses in urbanized areas of the land use map.

Firstly, GEOPOI® polygons (GEOPOI 2009) are imported from the original KML format into SHP format and several corrections are made to obtain precise delimitation of areas with homogenous market values of real properties, matching the areas of municipalities of the Consortium (Figure 4). Consequently, those polygons are used to subdivide urban areas in the land use map of the DUSAF Project (2003). The difference in prices of real properties varies considerably according to the GEOPOI® zones considered. Highest price per m^2 is reached in central and semi-central zones of Tirano and Aprica municipality (2,375 €/m^2 and 1,760 €/m^2 respectively) because Tirano is the capital and largest town of the area and Aprica is the main touristic resort of the area. The lowest prices of real estate properties are in the rural zones of the small municipalities (Tovo, Mazzo, Lovero) reaching maximum of 1,000 €/m^2. The variety of prices is shown in Figure 4. Afterwards, roads from the database CT10 (2006) are divided into two groups: primary and secondary. Given their strategic importance in the regional/transnational transport system, state roads (Strada Statale - S.S.) number 38 connecting Sondrio with Bormio and number 39 connecting Tirano with Edolo via Aprica pass are classified as primary roads and all the other roads are classified as secondary. Finally, a raster map (pixel sixe: 10×10 m), portraying the geographical distribution and the type of the

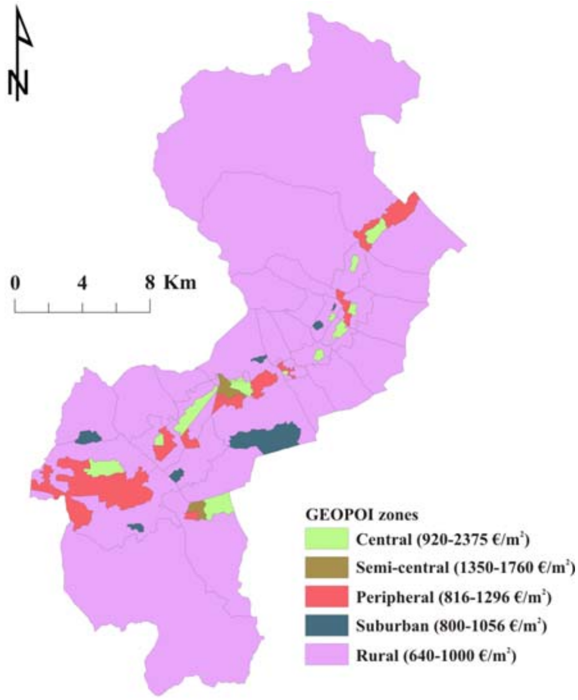

Figure 4 GEOPOI® polygons of the study zone used to delimit areas of different real estate values.

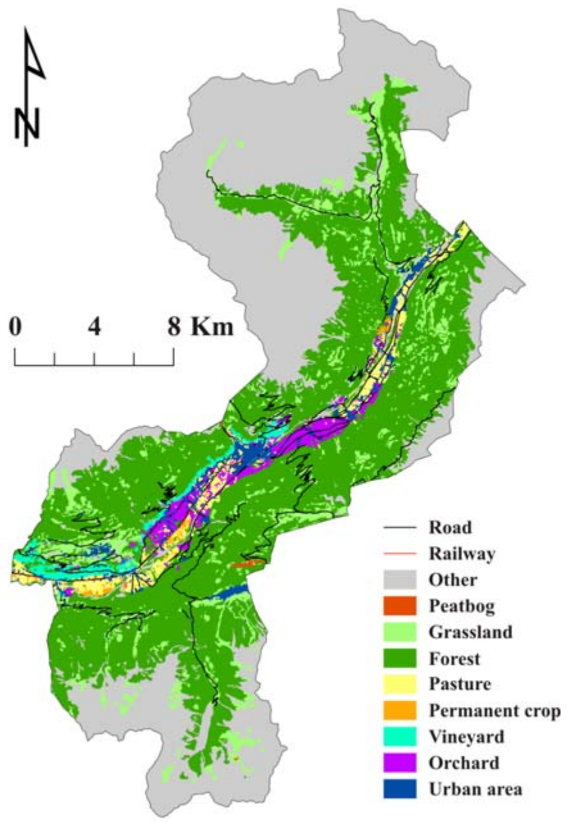

Figure 5 Elements at risk map derived for the study area. The classes are generalized in order to keep visual readability.

elements at risk, is prepared by joining formerly described layers (Figure 5).

3.2 Qualitative classification of the elements at risk

In this study, an institutionally-based, qualitative risk map is prepared by using a simple risk matrix (Lombardy Region 2005) by which the territory of the Consortium can be classified in four risk classes according to the possible consequences to the elements at risk caused by hydrogeological hazards. In this matrix (Figure 6) five classes of hazard (H) are plotted against four classes of elements at risk (E). In more detail:

H1 - Very low hazard. Areas with no or very low probability to be affected by damaging events in the future due to their morphological setting.

H2 - Low hazard. Areas never affected by damaging events in the past or with low probability to be affected in the future due to the presence of existing protection measures.

H3 - Medium hazard. Areas affected by damaging events in the past or with medium probability to be affected in the future. Low flow depths (of between 20 and 30 cm) are expected.

H4 - High hazard. Areas with high probability to be affected in the future. High levels of erosion and deposition are expected causing considerable damage to protection measures.

H5 - Very high hazard. Areas with very high probability to be affected in the future, including the current riverbed and its surroundings and paleo-riverbeds expected to be reactivated during extreme events.

	H1	H2	H3	H4	H5
E1	R1	R1	R1	R1	R2
E2	R1	R1	R2	R2	R3
E3	R1	R2	R2	R3	R4
E4	R1	R2	R3	R4	R4

Figure 6 Official risk matrix provided by Lombardy Region (2005). H1 to 5 – hazard levels, E1 to 4 – elements at risk classes, R1 to 4 – risk levels.

Concerning the elements at risk, they are divided into four groups, considering their strategic importance and the expected presence of people in case the element at risk is being affected by a hazard:

E1 - Woods, rural areas and state lands not suitable for building.

E2 - Rural areas suitable for building, not strategic public infrastructure (secondary roads, narrow-track railways), public parks, environmentally protected zones and valuable agricultural areas (vineyards and orchards).

E3 - Strategic public and private infrastructure (primary roads, two-track railways, aqueducts, power lines, oil pipelines, dumpings, quarries).

E4 - Urban areas, industrial and commercial areas, toxic wastes dumping grounds, hotels and resorts and camping grounds.

Rules and criteria used to assign elements at risk to each class are not clearly provided by the regulator.

The four risk classes, originating from the matrix, are described as follow:

R1 - Moderate risk. Marginal social and economic damage to cultural and environmental heritage is expected.

R2 - Medium risk. Minor damage to buildings, infrastructure and environmental and cultural assets is expected. Damage does not affect the safety of the people, the practicability of the buildings and the functionality of socio-economic activities;

R3 - High risk. Safety of the people can be threatened. Functional damage to buildings (involving their impracticability), infrastructure and cultural and environmental heritage is expected; interruption of socio-economic activities is possible.

R4 - Very high risk. Loss of human lives and serious injury to persons are expected. Serious damage to buildings, infrastructure and cultural and environmental heritage is expected; critical interruption of socio-economic is expected.

3.3 Monetary value of the elements at risk

In this analysis, market values are used for private properties and land use and reconstruction cost for public buildings and facilities whose main function is to provide public services to population and not to be monetized at the official local real-estate market.

To each element at risk class, the proper monetary value is assigned using available information:

- Real-estate market values for the second half of 2008 available from the webpage of the Italian Territorial Agency (Agenzia del Territorio - OMI 2009);
- Values of the agricultural land in Sondrio Province in 2008 (Valori Agricoli Medi 2009);
- Reconstruction costs of roads issued by the Society of Engineers and Architects of Milano DEI 2006).

Urbanized areas in the land use map (1:10,000) do not accurately delimit each house or building. As a consequence, after a statistical analysis is performed on a random sample, it is assumed that houses or buildings cover about 25% of each urban area polygon of the land use map. This is also in accordance to calculations and comparisons made between the land use map and the available cadastral database (DB2000 2009). DB2000 includes all the assets located in the study area, mapped at 1:2,000 scale and originally used by local planners and managers and Civil Protection authorities. Market values of real estate properties in urbanized areas were estimated from house and building market values of the second half of 2008, available on the webpage of the Italian Territorial Agency where minimum and maximum prices per m² of different types of buildings in different GEOPOI® polygons are provided. As the working scale (1:25,000 - 1:50,000) and data availability do not permit to fully distinguish between different types and usage (private, public, commercial, etc.) of structures, an average value for each GEOPOI® polygon is calculated for an average state of private houses and buildings. They form more than 90% of the house and building stock in the study area and, according to analysis and in-situ observations, a two-story house or building represents the most representative state. Consequently, to obtain an average value of urban areas per each cell (10×10 m), the average price per m² is divided by 4 (1/4 of the urban area is covered by houses or buildings) and multiplied by 2 (average number of stories).

Prices per pixel (100 m²) concerning rural areas are estimated using information about average market values of agricultural land in the Sondrio Province in 2008 (Valori Agricoli Medi 2009). Damage to agricultural land can be distinguished into two types: 1) loss of production, due to the destruction of crops and accumulation of sediments and 2) cost for cleaning up the affected area. In this study, the market value represents the quality and status of the agricultural areas, not taking into account the two above mentioned types of loss. Highest values per hectare are related to apple orchards (90,500 €/ha) and vineyards (59,200 €/ha), while the lowest values relate to the forested areas (4,000 €/ha) and grassland/ pastures (2,400 €/ha). It has to be noted that low values of forested areas are caused by the system of calculation which considers only the value of land without taking into account the value of the timber. The estimation of the price of timber is very difficult. However, in the majority of the forests, woods have an environmental protective function and are not considered as market goods. For this reason, only the value of the land is considered in this analysis.

Table 1 Values of the elements at risk used in the analysis of prospective direct economic losses. Information about value is not available for railways, junkyards, quarries, degraded land, shrubs and bushes, vegetation on rocks, scarce vegetation, glaciers, water, rivers and bare land.

Element at Risk	2008 value	€/pixel
Urban area	640-2,375 €/m²	32,000-118,750
Primary road	20 €/m²	2,000
Secondary road	15 €/m²	1,500
Orchard	90,500 €/ha	905
Vineyard	59,200 €/ha	592
Permanent crop	50,400 €/ha	504
Pasture (intensive)	49,200 €/ha	492
Swamp/peat-bog	7,700 €/ha	77
Forest (without timber)	4,000 €/ha	40
Pasture/grassland (high altitudes)	2,400 €/ha	24

Public roads do not represent a private property and do not have a market value. So, only reconstruction/rehabilitation cost is estimated per m² of primary and secondary roads using available information (DEI 2006). All the values calculated for the elements at risk are summarized in Table 1.

3.4 Preparation of risk maps

3.4.1 Risk map A

Risk map A is calculated in a purely qualitative way using the official risk matrix, considering the hazard classes of the hazard map A. This map classifies the elements at risk according to the Directive issued by the Lombardy Region (2005). As stated before, the Directive under consideration provides all the information needed to prepare an institutionally-based hazard map. The result, mostly founded on geomorphological evidences and field mapping activities, does not provide any useful information concerning the spatial and temporal probability of occurrence of hazardous events and for that reason is not supportive of the aim of the study. Moreover, given the different methodological approaches, risk map A could not be properly compared with risk maps B and C. However, a simple overlay is performed in order to analyze the most evident differences and similarities among these maps.

3.4.2 Risk map B

As already stated, the risk equation provided by Varnes (1) is used to prepare the risk maps B and C. In the case of risk map B, hazard classes with corresponding hazard probabilities are overlaid by the elements at risk map with corresponding economic values. The degree of loss is assumed to be 1.0, meaning that an impact of a debris flow will lead to a total loss of the exposed assets. This assumption (generally known as worst-case scenario) does not express the realistic situation but it is being applied (Fell and Hartford 1997; Michael-Leiba et al. 2003) as the definition of the degree of loss at a regional scale. This assumption makes analysis difficult to perform given that volume/intensity information is very rarely available from hazard maps. Assuming the degree of loss to be 1.0, we can assess the maximum potential damage and the related direct monetary loss. Risk map B is calculated by multiplying overlaid hazard and elements at risk maps. The resulting map is then reclassified into 4 distinct risk classes.

3.4.3 Risk map C

In the calculations of risk map C, different degrees of loss are assigned to the probability of each debris flow run out sub-class composing the original hazard map. In this study, after a literature review, a semi-quantitative approach is selected to express vulnerability in terms of degree of loss (Table 2). Three vulnerability values (0.1, 0.5, and 1.0) are assigned to each of the debris flow impact sub-classes. The low impact probability sub-class is assigned a vulnerability value of 0.1. Only aesthetic or light functional damage to the assets is expected. The Medium impact probability sub-class is assigned vulnerability value of 0.5 and medium to high functional or light structural damage to the assets is expected. The highest impact probability sub-class is assigned a vulnerability value of 1.0 in which structural damage to the assets (buildings, roads, vineyards, etc.) is expected.

The authors are aware of the high level of assumptions made in this part of the analysis. However, the results should represent more realistically the risk situation than simply estimating a single vulnerability value (1.0) for the whole debris flow affected area (risk map B). Moreover, stakeholders can consider different types of debris flows, with different intensities and impact probabilities and in so doing change the degree of loss assigned to each hazard sub-class in

Table 2 Different suggested values related to vulnerability assessment with respect to debris flows. The approach adopted in this study uses three-class classification system for the three sub-classes of the hazard map B delimiting different zones of impact probability on vulnerable elements. Modified after Fuchs et al. (2007).

Author	Hazard intensity/Impact probability on vulnerable elements			
	Low	Medium	High	Very high
Cardinali et al. (2002)	A*	F*	S*	S*
Fell and Hartford (1997)	0.1	0.4	0.7	1.0
Michael-Leiba et al. (2003)	0.1		1.0	
Bell and Glade (2004)	0.1	0.2	0.5	NS
Romang (2004)	NS	0.1 - 0.2	0.5	NS
Borter (1999)	NS	0.1	0.5	NS
Applied approach	0.1	0.5	1.0	

Note: NS=not specified; A*=aesthetic; F*=functional; S*=structural the analysis.

Risk map C (as risk map B) is calculated by multiplying the overlaying hazard, degree of loss and elements at risk maps. The resulting map is reclassified in the same way as risk map B in order to make these two maps comparable.

3.4.4 Risk curves

After the calculations of risk maps B and C, corresponding risk curves are calculated. In this analysis, risk curves show the relationship of the hazard probability and the total value of the exposed elements at risk (expected direct monetary loss). Hazard probabilities are extracted from the hazard maps and the total value of the elements at risk is calculated by summarizing all reconstruction cost and/or market value of the assets under analysis lying in the corresponding hazard areas.

4 Results and Discussion

4.1 Qualitative risk map

Hazard map A is overlaid with the elements at risk map classified according to the methodology provided by Lombardy Region (2005). After reclassification by using the official risk matrix, a qualitative risk map (map A) for the study area is obtained (Figure 7A).

4.2 Semi-quantitative risk maps and risk curves

The semi-quantitative economic risk maps B and C are shown in Figure 7 (B and C). Maps are classified into four classes portraying the probability of direct monetary loss per pixel per year. In the very low risk class (dark green) areas without expected direct monetary loss are included and cover about 40% of the study area on both maps. Low risk class (light green) is attributed to zones with low prospective monetary loss (0-10 € × 10-4/cell/year). These areas cover about the same percentage of the area (59%) on risk maps B and C. Areas in the low risk class are usually zones of low economic value (forests, pastures, and low-valuable agricultural areas) and low to medium hazard. Medium risk class (yellow, 10-1,000 € × 10-4/cell/year) covers an area of 1.20% and 1.08%, respectively. In this class usually roads and valuable agricultural areas with medium to high hazard are present. High risk class (red, >1,000 € × 10-4/cell/year) covers a very small area (of about 0.19% and 0.14%, respectively). Only urban areas are present in this class within high to very high hazard zones. All the results are also summarized in Table 3.

From the results it can be seen that no particular reduction in the high and medium risk class is made after the application of the different degrees of loss in the preparation phase of the

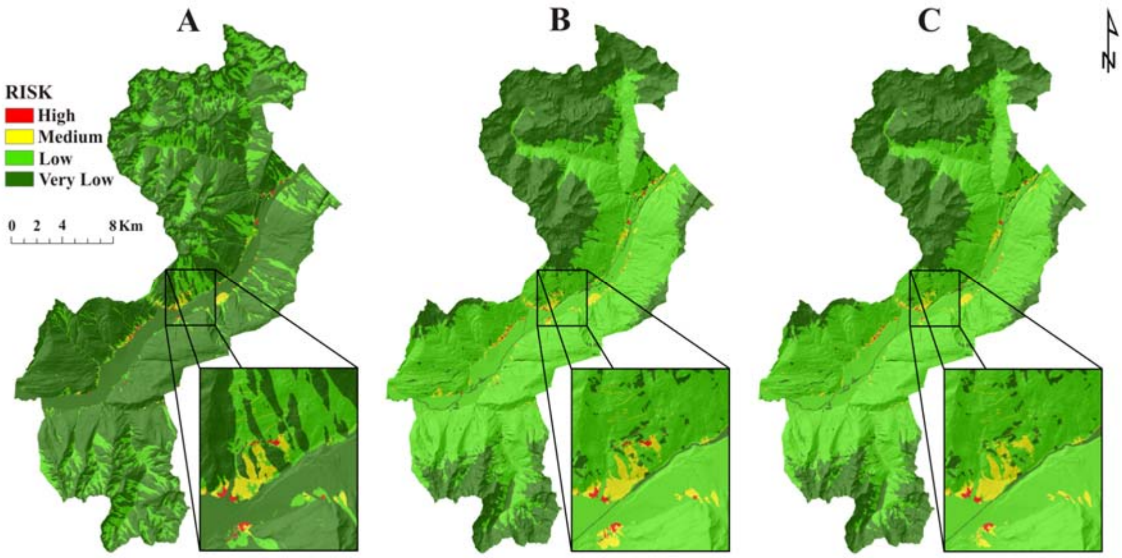

Figure 7 Debris flow risk maps for the CM Valtellina di Tirano. A – Qualitative risk map A; B – Direct economic risk map B; C – Direct economic risk map C.

semi-quantitative risk maps. However, some reductions can be noted when only the highest class is analyzed. In this case, the high risk area is reduced by about 27% (0.23 km²) in the risk map C compared to the high risk area in the risk map B. As a result, risk map C should be used to better delimit potential areas affected by debris flow hazard which can cause significant damage. Some other differences among the maps can be appreciated after the calculation of the risk curves (Figure 8, Table 4).

In the graph, the hazard probability is plotted against the cumulated amount of prospective direct monetary loss in each hazard class on a log-normal scale. Calculated curves for risk maps B and C have almost a similar shape. However, risk curve for map C is shifted down and left, calling for lower prospective direct monetary loss. This is caused by the application of different degrees of loss in the preparation of these two maps. Using available information about past debris flow events in the area (Blahut et al. 2012; Quan Luna et al. 2011), it can be stated that the use of a degree of loss equal to 1 grossly over-estimates reality. Statistically, the total destruction of assets (buildings in particular) likely occurs only when the building is situated directly in the path (channel) of the debris flow (Quan Luna et al. 2014). From this point of view, the use of risk map C is more appropriate and should give more reliable information to the end-users.

Calculated risk curves could be easily used by local decision makers to calculate the cost-effectiveness ratio for potential countermeasures.

Table 3 Summary of areas and percentage of risk classes concerning risk maps B and C

Risk class	Value (€/pixel/year) map B	Area (km²) map B	% of area map B	Value (€/pixel/year) map C	Area (km²) map C	% of area map C
No risk	0	179.08	39.66	0	179.08	39.66
Low	0 - 10	266.20	58.95	0 - 10	266.97	59.12
Medium	10 - 1,000	5.43	1.20	10 - 1,000	4.88	1.08
High	1,000 - 26,704	0.85	0.19	1,000 - 16,859	0.62	0.14

Table 4 Total economic value of assets (in thousands of EUR) in hazard areas concerning risk curve of risk map B (derived from hazard map A) and risk curve of risk map C (derived from hazard map B)

	Risk curve B		Risk curve C	
Hazard	Value of assets per class	Cumulative value of assets	Value of assets per class	Cumulative value of assets
Very low	€ 4,394,264	€ 5,336,625	€ 4,394,264	€ 4,799,551
Low	€ 185,027	€ 942,361	€ 86,796	€ 405,288
Medium	€ 268,797	€ 757,335	€ 131,225	€ 318,492
High	€ 114,672	€ 488,537	€ 46,097	€ 187,266
Very high	€ 373,866	€ 373,866	€ 141,169	€ 141,169

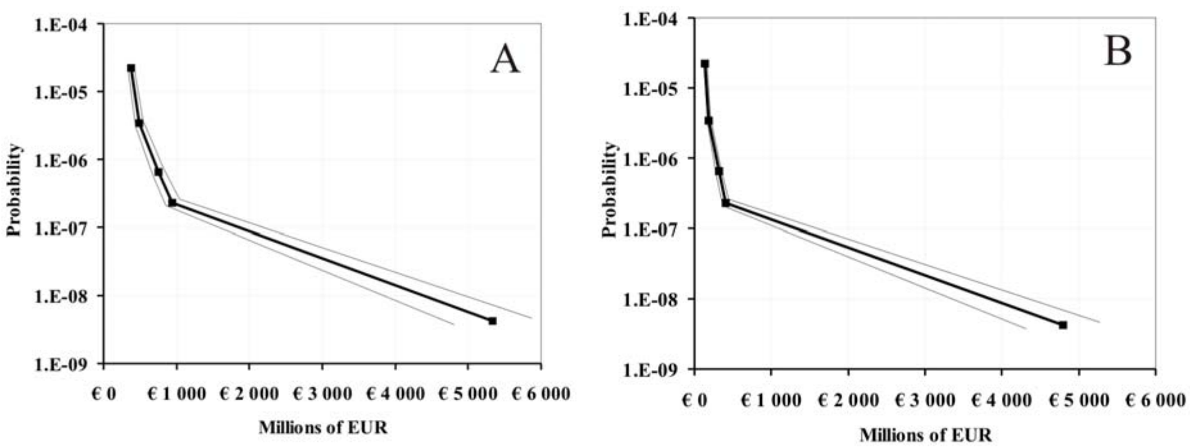

Figure 8 Risk curves calculated from direct economic risk maps. A – curve derived from risk map B; B – curve derived from risk map C. The range variation accounts for the uncertainty in the input parameters of the modelling considering 10% variation of the parameters.

For example, if the total cost of countermeasures in the high risk zones of map B exceeds the value of assets in these zones (about 374 millions €), these measures are not economically efficient given that the total cost of preventive measures is higher than the monetary value of the assets which should be protected. It has to be noted, however, that it is not sufficient to perform the cost-effectiveness analysis without considering tangible and intangible prospective consequences (in terms of number of lives lost and people injured, among the most important aspects, together with environmental damage, cultural disruption, societal disaggregation and political/institutional consequences). These consequences have to be evaluated in a qualitative way as assigning a monetary value to human lives opens ethical issues. There also exist tangible indirect costs such as business interruption, unemployment, etc. They do not open ethical issues but are very hard to express and should be also considered in a cost-effectiveness analysis.

4.3 Comparison of the risk maps

In order to evaluate the spatial agreement of predicted risk patterns in different risk maps, a comparison is made by applying the Rank Difference tool of the Spatial Data Modeller Toolbox of ArcGIS (Sawatzky et al. 2008) and considering each risk class of each risk map separately.

The results show (Table 5) that the semi-quantitative risk maps B and C do not differ consistently; the level of agreement is very high and equal to 99.78% and the differences are mainly caused by the restricted high risk zone and larger medium risk zone in case of map C. The difference between the semi-quantitative maps (B and C) and the institutionally-based, qualitative map A is much more striking, as they correspond to each other only in about 36.55% and 36.62%, respectively. We are aware that this comparison has to be taken carefully as we compare maps in which the elements at risk are classified in different way. Surprisingly, the difference in the highest class is not very noticeable showing a level of agreement equal to 93.75% between map A and map B.

The highest and clearest differences can be found in the two lowest risk classes. This situation is due to the presence of low, but quantifiable, areas of potential economic loss on the risk maps B and C which are considered as free risk areas in the risk map A. In the two highest risk classes, fewer differences appear comparing the risk maps B and C to the map A. This situation is caused by urban areas which have the highest values in the monetary as well as in the expert-based estimate.

Table 5 Level of correspondence (in %) among the three risk maps and their classes

36.55%		A			
		High	Medium	Low	Very low
B	High	93.75%	0.16%	0.00%	0.00%
	Medium	0.78%	54.02%	2.36%	0.08%
	Low	0.00%	0.00%	10.70%	58.94%
	Very Low	0.00%	0.00%	24.18	30.87%
36.62%		A			
		High	Medium	Low	Very low
C	High	68.65%	0.16%	0.00%	0.00%
	Medium	5.00%	59.80%	1.77%	0.01%
	Low	0.00%	0.01%	10.86%	58.92%
	Very Low	0.00%	0.00%	24.18%	30.87%
99.78%		B			
		High	Medium	Low	Very low
C	High	72.88%	0.00%	0.00%	0.00%
	Medium	4.17%	82.29%	0.00%	0.00%
	Low	0.00%	0.29%	99.71%	0.00%
	Very Low	0.00%	0.00%	0.00%	100.00%

Although fewer differences appear from a “graphical” point of view among risk maps, it is considerably different the amount of information carried by each map, especially comparing semi-quantitative risk maps B and C on the one hand and institutionally-based, qualitative risk map A on the other hand. Another very important aspect arising from the comparison between map A and maps B and C is that railways, quarries and junkyards are considered in the second highest class of the map A but they do not have a precise economic value assigned in the maps B and C. However, this situation is mostly caused by the unfeasibility to estimate or evaluate the direct monetary loss concerning these assets from official sources.

4.4 Limitations of risk mapping and possible sources of uncertainties

At a regional scale (1:25,000 - 1:50,000),

Table 6 Qualitative estimation of uncertainties in diverse steps of the risk analysis at a medium scale applied in this study. For more information about the data and analysis steps in the susceptibility and hazard analysis, please refer to the papers of Blahut et al. (2010a, 2010b). Table structure is adopted from Bell and Glade (2004).

Factor	Uncertainty	Reason	Significance	Improvement
Susceptibility analysis				
Inventories	Low-medium	Imprecision	High	Increase of data collection
DEM	Low	Resolution	Medium	Increase of resolution
Geo-factors	Low	Resolution	Low-medium	Up-to-date information
Susceptibility model	Low-medium	Model limitations	Medium-high	Non-linear models
Map classification	Medium	Subjectivity	Medium-high	-
Hazard analysis				
Temporal probability	Medium-high	Average values	High	Higher frequency of imagery
DEM	Medium	Imprecision	Very high	Increase of resolution
Model calibration	Medium-high	Average values	High	Analysis of past events
Map classification	Low-medium	Subjectivity	High	-
Risk analysis				
Value of elements at risk	Low	Data availability	Low-medium	Up-to-date information
Vulnerability approximation	High	Subjectivity	Very high	Analysis of past events
Elements at risk classification	Low	Subjectivity	Low-medium	Analysis of past damage
Map classification	High	Subjectivity	High	Risk perception studies

several limitations exist in risk analysis and many uncertainties may reduce the consistency of results (Table 6). As already stated by Bell and Glade (2004), due to the uncertainties inherent in each input factor of risk analysis, the resulting risk values also include a considerable level of uncertainty. To estimate this uncertainty as the variability of the results, a 10% variation of the input parameters is plotted into the risk curves (Figure 8). It can be seen that uncertainty increases with decreasing probability of the hazard and increasing the value of the possible direct monetary loss. However, many other limitations due to uncertainties exist in the analysis.

The main limitation, as in the case of susceptibility and hazard mapping at a regional scale, concerns the spatial resolution and reliability of the inputs. The approach proposed in this study used only inputs with similar resolution (1:10,000) which are consequently rasterized as 10×10 m cells to avoid errors and misunderstandings due to the working scale. However, there is no guarantee that all the information concerning past events (in space and in time) is being used in hazard and risk analysis due to database incompleteness.

Moreover, IUGS Working Group on Landslides - Committee on Risk Assessment (1997) and Heinimann (1999) recommended that final results should be treated as relative results and not as absolute ones. This is probably the only way of using the many valuable tools of hazard and risk analysis in natural disaster mitigation on the one hand but not to lose the trust in the results on the other hand (Bell and Glade 2004). Although the date of the analysis and the quality/completeness of information strongly control the results, the proposed approach allows the values of the elements at risk to be easily updated as well as the degree of loss. As a consequence, risk maps can be recalculated according to the availability of new information providing the final users with updated maps and table to be used in decision making process.

From a methodological point of view, many limitations still exist for a proper QRA at a regional scale. Specific risk maps (economic, social, environmental, etc.) should be the first step for the calculation of total quantitative risk maps. However, this still seems to be a step too far because of the amount and type of data needed for the analysis: high-resolution and “dynamic” data are as essential as difficult to be collected for large areas. Some future developments in remote (near) real-time data acquisition of inputs and automated (but supervised) processing of the outcomes might result in dynamic quantitative risk maps at regional scale, which represents the ultimate goal in QRA at this scale of the study. Moreover, an evident difficulty exists in combining different data types: i.e. tangible and intangible loss. In effect, the number of dimensions to be explored in vulnerability studies appears to be large and difficult to integrate in a single index (i.e.: physical/structural/functional, socio-economic, socio-cultural, ecological/environmental, or political/institutional).

5 Conclusions

In this study, a debris flow risk analysis is performed at a regional scale and three different debris flow risk maps are prepared. First, an institutionally-based, qualitative risk map (A), using an officially-provided risk matrix, is derived. Afterwards, two semi-quantitative risk maps (B and C), showing the potential direct monetary loss, are calculated for the study area. Risk curves are also computed to summarize the expected direct monetary loss against the respective hazard probability. These results can be directly used by the local decision makers for a preliminary cost-benefit analysis.

The results show areas of high economic as well as strategic importance which should be affected by debris flows in the future and where important consequences may arise. There is no simple solution on how to choose an appropriate risk map from the three possibilities. Semi-quantitative risk maps (B and C) have the advantage of more objective and quantified values; however, they do not respect some non-economic properties of the area and the elements at risk as the qualitative map (A). As a result, semi-quantitative risk maps should be used to help allocate future investments and focus on areas with high potential direct monetary loss. On the other hand, qualitative risk map should be used to inform better the inhabitants about potential debris flow risk and to delimit areas where potential intangible consequences may occur.

Aside from its limitations and inaccuracies (inherently included in the risk analysis and concerning process intensity estimation, temporal validity and spatial resolution), delimitation of high risk areas allows local decision makers to focus their attention on the "hot-spots", where local (large) scale study needs to be performed with more precise cost-benefit analysis.

The methodological approach here presented is flexible enough to allow decision makers to change/refine/modify the input parameters of the analysis at their own convenience to derive valuable information for designing different spatial planning alternatives. These can be later disseminated with the aim to help citizens protecting themselves more efficiently. Through specific public education programs, people who may be threatened by a disaster may learn in advance what to expect and how to react, increasing personal and community resilience (Sterlacchini and Frigerio under review). This, in ultimate analysis, can increase people's capacity to anticipate, cope with, resist against, and recover from the impact of natural hazards (Blaikie et al. 1994). Increasing people's ability to withstand shocks and stresses to livelihood (Adger 2000) also increases their adaptive capacity that includes their ability to plan, prepare for, facilitate, and implement adaptation options against hazards, as well as to implement social and technical measures before, during, and after a hazard event (proactive resilience). Some future developments in remote (near) real-time data acquisition of inputs and automated (but supervised) processing of the outcomes might result in dynamic quantitative risk maps at regional scale, which represents the ultimate goal in QRA at this scale of study.

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