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REGIONAL-SCALE DEBRIS-FLOW RISK ASSESSMENT FOR AN ALPINE VALLEY

S. LARI(*), G. B. CROSTA(*), P. FRATTINI(*), P. HORTON(**) & M. JABOYEDOFF(**)

(*)Università degli Studi di Milano Bicocca - Dep. Geologic Sciences and Geotechnologies - Italy
(**)Institut de géomatique et d'analyse du risque (IGAR), Unil, Lausanne - Switzerland

ABSTRACT

In this paper, we perform a societal and economic risk assessment for debris flows at the regional scale, for lower Valtellina, Northern Italy. We apply a simple empirical debris-flow model, FLOW-R, which couples a probabilistic flow routing algorithm with an energy line approach, providing the relative probability of transit, and the maximum kinetic energy, for each cell.

By assessing a vulnerability to people and to other exposed elements (buildings, public facilities, crops, woods, communication lines), and their economic value, we calculated the expected annual losses both in terms of lives (societal risk) and goods (direct economic risk). For societal risk assessment, we distinguish for the day and night scenarios. The distribution of people at different moments of the day was considered, accounting for the occupational and recreational activities, to provide a more realistic assessment of risk. Market studies were performed in order to assess a realistic economic value to goods, structures, and lifelines.

As terrain unit, a 20 m x 20 m cell was used, in accordance with data availability and the spatial resolution requested for a risk assessment at this scale. Societal risk the whole area amounts to 1.98 and 4.22 deaths/year for the day and the night scenarios, respectively, with a maximum of 0.013 deaths/year/cell. Economic risk for goods amounts to *1,760,291* €/year, with a maximum of 13,814 €/year/cell.

Key words: *economic risk, societal risk, regional scale risk assessment, debris flow modelling*

INTRODUCTION

Debris flow in Alpine areas are widespread phenomena threatening people and goods (Cancelli & Nova, 1985; Aleotti & Polloni, 1998c; Crosta *et alii*, 2003; Carrara *et alii*, 2008). The considerable hazard potential of debris flows is related to the abundance of susceptible areas, the high areal density and the high velocity of the movements (Crosta *et alii*,2003). In the last 30 years, lower Valtellina (1,050 km^2, Central Alps, Northern Italy, about 90,000 residents) was frequently affected by debris-flow triggering rainstorms (1983, 1987, 1997, 2000, 2002, 2004, 2008) causing extensive damages to private buildings and public facilities, and 31 casualties (Govi & Turitto, 1994; Tropeano *et alii*, 1999; Progetto IFFI, 2007; AVI, 2007). These data highlight the importance of a regional scale debris-flow risk assessment for land planning and management.

Triggering and propagation of debris flows are strongly controlled by local topography, mechanical and hydraulic soil properties (Costa, 1984). Due to the fact that they are difficult to fully understand, the occurrence of debris flows hardly can be precisely forecast (He *et alii*, 2003). At present, there are few methods allowing a strict assessment to determine an exact probability of debris-flow occurrence, based either on physically measured characteristics of a catchment or on a statistical analysis. Information available on past debris flow events is often the most reliable data (Rickenmann, 1999).

Physically-based models are widely used to assess debris-flow susceptibility (Montgomery & Dietrich, 1994; Wu & Sidle, 1995; Burton & Bathurst, 1998; Crosta & Frattini, 2003). Although these models may be suitable for modelling the predisposing hydrological conditions, they have several limitations if applied to predict the spatial distribution of debris flows, at the regional scale (Carrara *et alii*, 2008). With the exception of slope morphology, in fact, the physical variables that control the spatial distribution of debris flows (i.e., physical and mechanical parameters of the slope and the failed material) cannot be acquired over large areas at reasonable cost (Carrara *et alii*, 2008).

In order to perform a debris flow risk assessment and to provide sound basis for the design protective measures, it is necessary to estimate important parameters describing the phenomena, such as potential debris volume, mean flow velocity, peak discharge, and runout distance (Rickenmann, 1999): empirical studies demonstrated to be useful to achieve this tasks (Costa, 1984; Hungr *et alii*, 1984; Johnson,1984; Jan & Shen, 1997; PWRI, 1988; Rickenmann, 1999).

Due to the diffuse nature of the phenomena, a spatially distributed modelling tool which is capable to simulate the propagation over complex terrain is needed (Iverson, 1987). The complexity of physical processes governing debris-flow propagation and the uncertainty in modelling parameters (He & Xie), requires a simplified model, which is still more suitable for regional scale study (Iverson *et alii*, 1998).

In this paper, we perform a societal and economic risk assessment for debris flows at the regional scale, for lower Valtellina, Northern Italy. We apply a simple empirical debris-flow model, FLOW-R, which couples a probabilistic flow routing algorithm with an energy line approach, providing the relative probability of transit, and the maximum kinetic energy, for each cell.

STUDY AREA

The study area encompasses 40 municipalities of lower Valtellina, including Sondrio and Morbegno (Fig. 1), which are the two most populated municipalities (almost 22,000 and 12,000 inhabitants, respectively). In total, 90,278 people live in the study area (ISTAT, 2007), with a mean density of population of 76 people/km^2. This is a low value if compared with the

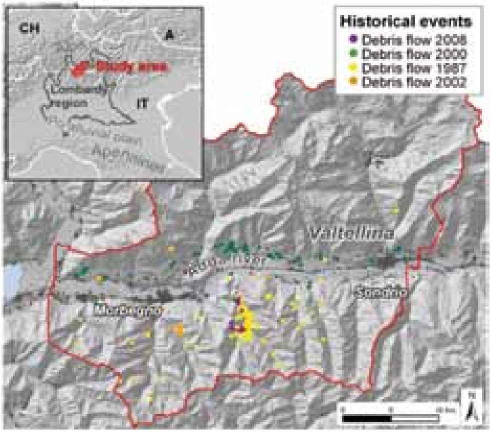

Fig. 1 - Study area and main recent historical events

Italian national mean (197,6 p/km^2) and regional mean (404,1 p/km^2), since it includes a wide mountainous territory with a very low density. Considering only the valley bottom, the density grows up to 790 p/km^2.

The road network, due to territory morphology, is not very developed, but the whole area is crossed by the Stelvio state street SS 38, which is very busy, being the main road along the valley.

The orientation of the valley strongly controls the sun exposure, so that slopes facing South and North have different vegetation and land use. The first ones have been used extensively since centuries to develop an agricultural activity (vineyards) up to 600-700 m a.s.l., the second has a prevalent forestal vocation.

Agricultural activities are widely diffused, also in the valley bottom, with permanent grasses and corn cultures.

RISK ASSESSMENT METHODOLOGY

The adopted methodology leads to the quantification of risk in terms of:

- societal risk (annual casualties): $R_s = f * e * v * n$
- economic risk (direct economic annual losses): $R_e = f * e * v * w$

where:

f = expected annual frequency of occurrence of the event;
e = probability of an exposed element present in the area to be effectively impacted, not accounting for implemented mitigation works (i.e., exposure factor);
v = degree of damage;
n = exposed people effectively present in the impacted area.
w = economic value of goods in the impacted area.

FREQUENCY OF OCCURRENCE

The expected frequency of occurrence, f, of the debris flows was considered as composed of a triggering frequency, f_d, and a transit frequency, f_t.

Triggering frequency, f_d, was assumed to be constant in the study area, and calculated from the frequency of past events, divided by the number of source areas. Source areas were detected by means of a simplified simulation of slope instability due to shallow landslides using a model, which couples steady state hydrology and a limit equilibrium infinite slope stability model (SHALSTAB, Montgomery & Dietrich, 1994). The majority of debris flow occurring in the areas, in fact, are triggered as shallow landslides, and the number of debris flows triggered in different circumstances (debris erosion in riverbed, fire-hose effect) is assumed to be balanced by the number of shallow landslides not evolving into debris flow. Triggering frequency in lower Valtellina results to be 9.4 10^{-4} events/year/cell.

To calculate the transit frequency, we used the semi-empirical model FLOW-R proposed by Horton *et alii* (2008), which couples a probabilistic flow routing algorithm with an energy line approach.

The routing algorithm spreads flow downstream by calculating the probability that flow passes through a cell based on slope gradient and inertia. The slope gradient has a strong effect on the debris flow direction. Many different algorithms have been proposed in the literature. In the simple single-flow D8 approach, the flow is entirely transferred from each cell to the neighbouring cell along the steepest direction. The multiple flow direction method (Quinn *et alii* 1991) considers the spreading over every downward cell in a continuous, and not random way:

$$f_{si} = \frac{\tan\beta_i}{\sum_{j=1}^{8}\tan\beta_j} \quad \text{for } \tan\beta > 0 \qquad (1)$$

where:

i, j = flow direction;

f_{si} = flow proportion in direction i;

$\tan\beta_i$ = slope gradient between the central cell and cell in one down slope direction

Holmgren (1994) introduced an exponent, x, in the algorithm, to allow a control on the spreading of the flow. The higher the exponent x, the more convergent the flow:

$$f_{si} = \frac{(\tan\beta_i)^x}{\sum_{j=1}^{8}(\tan\beta_i)^x} \qquad (2)$$

In particular,

if $x = 1$, f_{si} = multiple flow direction method

if $x \to \infty$, single flow direction (D8)

To take into account the inertia, in terms of direction, which is the tendency of the flow to maintain its direction, a further weighting of the flow direction is included in the code. Based on Gamma (2000), the persistence weight for each cell is a function of the change α in angle from the last flow direction.

$f_{pi} = w_0$ if $\alpha=0°$

$f_{pi} = w_{45}$ if $\alpha=45°$

$f_{pi} = w_{90}$ if $\alpha=90°$

$f_{pi} = w_{135}$ if $\alpha=135°$

$f_{pi} = 0$ if $\alpha=180°$

where i = flow directions, f_{pi} = persistence term of flow proportion in direction i, α_i=angle between the previous flow direction and the new flow direction from the central cell i, w = weights for the corresponding change in direction.

The slope-related algorithm and the persistence are combined to obtain the resulting probabilities (Fig. 2).

The energy line approach calculates the run-out distance based on a reach angle and an upper limit for flow velocity. Runout distance algorithms are energy-based calculations that define, for each cell, if the debris flow can potentially reach another cell. Thus, they control the distance reached by the debris flow. Moreover, they influence the flow direction: in fact, some of the cells that could receive a flow from the direction algorithm, are not reached by the flow because of energy, and their debris flow probability is set to zero. The source mass, is unknown, thus, runout distance calculation is based on unit energy balance, a constant loss function and a maximum velocity threshold. This approach does not aim to exactly represent the physical processes, but to provide a realistic figure of the phenomena.

Potential energy is in part transformed in kinetic energy, and in part lost as friction. Energy loss is mod-

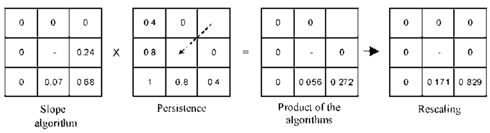

Fig. 2 - Example of flow apportion with persistence effect. Provenience of flow is indicated by the arrow, and it is divided into the lower cells. The probability deriving from the product of slope algorithm and persistence is rescaled to 0-1

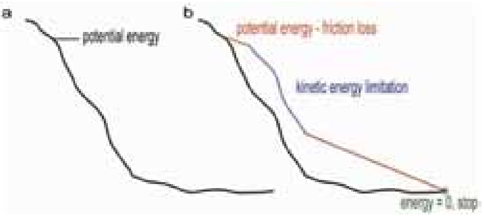

Fig. 3 - Illustration of the runout distance calculation principles, from HORTON *et alii, 2008*

elled with a pre-determined friction angle. Kinetic energy is limited by a upper velocity threshold to avoid excessive or unrealistic energies.

At the beginning, a debris flow source has a certain unit potential energy (without considering the volume) (Fig. 3) (a).

During propagation, part of the energy is lost in friction (b). The kinetic energy increases and may reach the maximum threshold value, leading to an energy line having the same profile as the terrain. In fact, while the threshold is reached, energy loss is equal to the difference in potential energy. The debris flow stops when the energy becomes null (HORTON *et alii*, 2008).

Outputs of each simulation provide the maximum kinetic energy of the debris flow in each cell, and the propagation probability for each cell. The model requires a DTM for terrain description, and a few calibrated parameters that controls the routing (i.e., flow direction algorithm, inertial scheme, reach angle, upper limit velocity). We used a 20 x 20 m DTM.

Outputs of the model are the relative probability of transit, and the maximum kinetic energy, for each cell. Probability of transit in the model is to be considered mainly in a qualitative way rather than as real probabilities values (HORTON *et alii,* 2008). These outputs were used to calculate risk for people and for private and public goods for the study area (Fig. 4).

To calibrate the model, it was necessary to make a number of simulations modifying each time the control parameters. After several attempts, we identified the two different parameterizations, for open-slope and channelled debris flows, best fitting the distribution and the extension of the historical events in the area. For open-slope debris flows we used more dispersive flow direction algorithms to account for small-scale topographic variability which is not fully represented in the DTM, and a reach angle of 15°. For channelled-debris flows, we decreased the reach angle to 5° to account for higher mobility basically

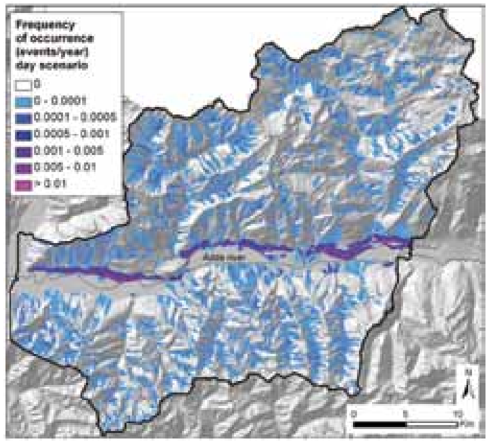

Fig. 4 - Expected frequency of occurrence, f, for the day scenario, obtained combining triggering frequency f_d, and transit frequency, f_t

	MODEL 1	MODEL 2
Direction Algorithm	*Holmgren. exp10*	*Holmgren exp9*
Reach angle	*15°*	*5°*
Limiting Kinetic Energy	*<30m/s*	*<30 m/s*

Tab. 1 - Parameters for debris flow model calibration

related to larger water content (Tab. 1). Holmgren algorithm (HOLMGREN, 1994) with exponent 10 and 9 results the best in order to simulate the flow direction for open slope and channelled debris flows, respectively. In both cases, a limiting kinetic energy of 30 m/s results to be reasonable (Tab. 1).

DEGREE OF DAMAGE, v

The degree of damage, v, related to debris flows depends on both the intensity, in terms of depth and velocity of the flow, and the vulnerability of exposed elements. The model provides velocity, but not the depth of the flow. For this reason, a constant flow depth of 2 m was assumed, which is a conservative value based on observations of historical events. Vulnerability of buildings and infrastructures was calculated starting from the simulated kinetic energy using empirical vulnerability curves available in the literature for debris flows (BOVOLIN & TAGLIATATELA, 2002). In general, the flow proceeds with high velocities and has a great destructive power. For this reason, people impacted by debris flow are supposed to have a high probability of death. By means of expert evaluations, a value of v = 0.75 was assumed.

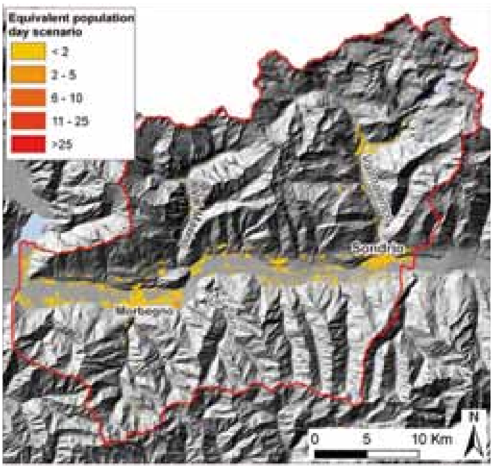

Fig. 5 - Equivalent population for day scenario, Valtellina

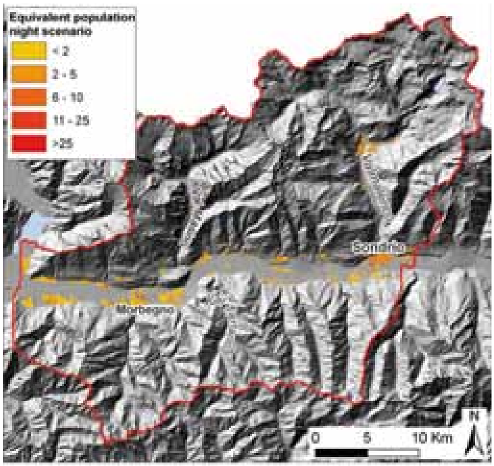

Fig. 6 - Equivalent population for night scenario, Valtellina

EXPOSURE FACTOR, e

Once a debris flow reaches a certain grid cell, where an element at risk is located, the probability of this element to be effectively impacted by a debris flow, e, is quite high, being debris flows sudden, fast and in general unpredictable phenomena. The value of e depends on 1) the time of permanence of the elements in the grid cell (1 for buildings and infrastructures, <1 for people); 2) debris flow extent with respect to cell size; 3) the proportion of people and goods located either at the first floor or in the basement of buildings. The exposure factor e was then calculated as 0.125 for people and 0.25 for the other exposed elements.

For each activity (such as staying at home, working, moving, frequenting schools or other public facilities), a different spatial and temporal exposure was considered for day (from 8 a.m. to 6 p.m.) and night scenarios (from 6 p.m. to 8 a.m.) (Fig.5 and 6).

VALUE

The value of the damaged elements at risks, w, was calculated for each cell using different data sources. For societal risk, the value corresponds to the number of injured people, considering both residents, workers and people in transit.

For economic risk, the value was calculated considering different categories of elements at risk, mapped from aerial photographs and economically evaluated using local market prices (Tab.2).

Exposed element	Value	Data source
Technologic plants	*3,000,000 €/m^2* *50,000 €/m^2*	*4*
Commercial centres	*1400 €/m^2*	*1*
Hospitals	*1500 €/m^2* *1800 €/m^2*	*3*
Schools	*1300 €/m^2*	*1*
Field	*0.24 €/m^2*	*4*
Railway station	*1400 €/m^2*	*1*
Airport	*1500 €/m^2*	*1*
Cinema	*1400 €/m^2*	*1*
Fair	*1400 €/m^2*	*1*
Agricultural productive	*800 €/m^2*	*1*
Commercial /productive activity	*1000 €/m^2*	*1*
Electric power line	*80 €/m*	*2*
Railway	*2500 €/m*	*5*
Wood	*11 €/m^2*	*6*
Rural house	*1500 €/m^2*	*1*
Camping	*50 €/m^2*	*1*
Orchard	*5,2 €/m^2*	*4*
Vineyard	*7 €/m^2*	*4*
Olive grove	*6.3 €/m^2*	*4*
Residential	*1500 €/m^2*	*1*
Sport facility	*1300 €/m^2*	*1*
Double lane road	*2500 €/m*	*2*
Single lane road	*1900 €/m*	*2*

Tab. 2 - Economic value of exposed elements. For sources: 1 market researches; 2 provincial administration; 3 regional administration; 4 Centre for Environment and Sustainable Development of Lombardy (CRASL), personal communication; 5 Italian Railways; 6 ERSAF (2007)

RISK ASSESSMENT

A map of economic risk, in terms of €/year, and a map of societal risk, in terms of casualties/year, for the day and the night scenario, was produced (Fig. 7).

DISCUSSION AND CONCLUDING REMARKS

As resulting from the modelling, debris flow on the slopes cover a wide surface, especially in the south fac-

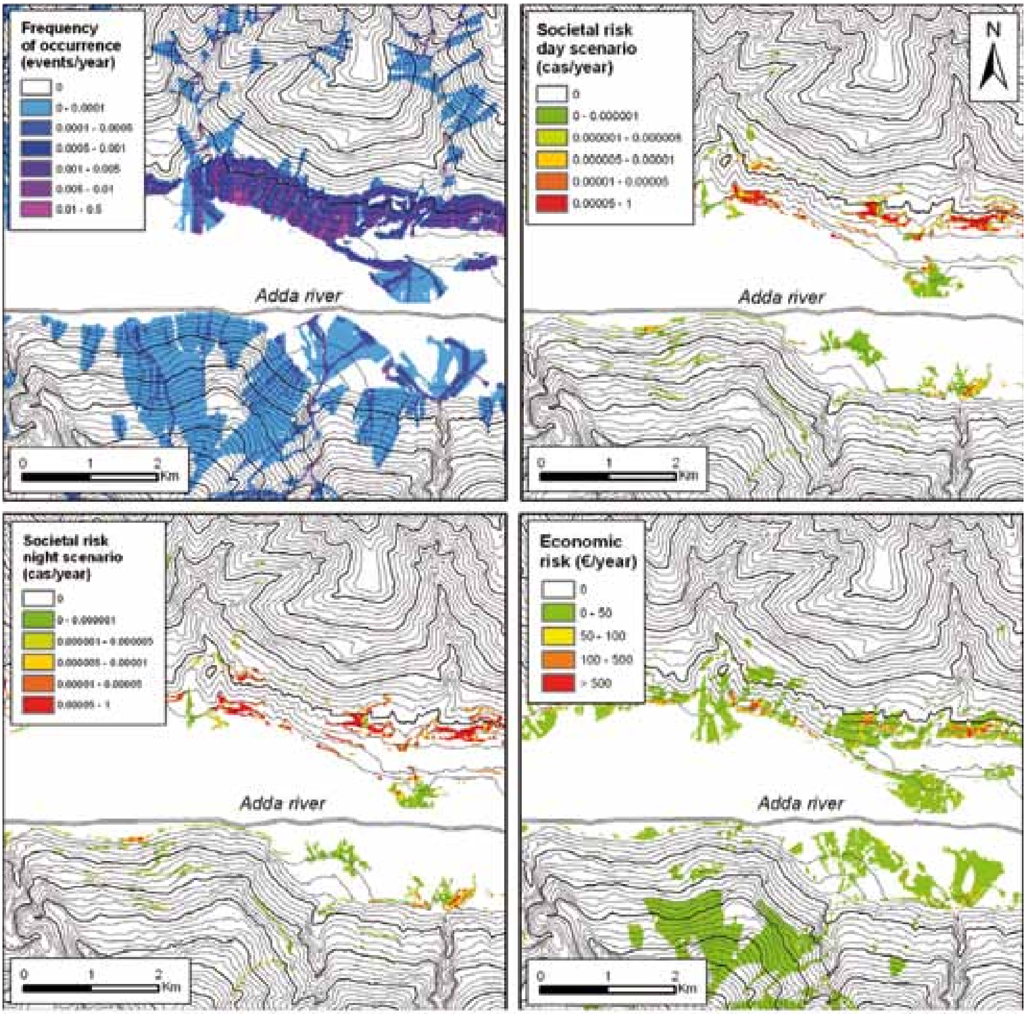

Fig. 7 - Debris flow frequency of occurrence, societal and economic risk values

ing slope: here the presence of old agricultural terraces with scarce maintenance increases the triggering of the events (Crosta *et alii*, 2003). Impacted areas on the alluvial fans are quite limited in space, but they show considerable values of societal and economic risk. Clearly, the villages located at the outlet of the secondary valleys, built on the fans, are the most impacted by debris flows.

Societal risk connected with debris flow is concentrated at the foot of the slopes, where settlements and communication lines are located. The impacted areas are quite narrow both for the day and the night scenario, but showing high level of risk.

The number of expected casualties for the night scenario on the whole study area (4.22) is about the double of the one expected for the day scenario (1.98) (Tab.3). In part, this is due to the different duration of the two temporal intervals, but in some measure it shows that houses and roads, which are busy during the evening ad the night, are in general more threatened than working plants or recreational facilities.

In the last 30 years, debris flows in the study area caused 31 deaths. Societal risk calculated in this study is consistent with this data, since we consider the number of expected casualties as comprehensive of injuries, adequately weighted by means of the vulnerability, v.

Economic losses are distributed on large surfaces on the open slopes, but risk values do not reach high levels per cell (max 13,814 €/year) (Tab. 4). Most of the cells do not reach 50 €/year of damage. Impacted elements, in fact, are nearly always woods, pastures,

	Day scenario	Night scenario
Range (cas/year/cell)	0-0.007	0-0.013
Total (cas/year)	1.98	4.22

Tab. 3 - Societal risk values for day and night scenario

	Risk
Range (€/year/cell)	0-13,814
Total (€/year)	1,760,291

Tab. 4 - Economic risk values for day and night scenario

and cultivations, which have a limited economic value if compared with equivalent surfaces of built areas. Some settled areas are involved, mainly at the toe of the northern slope and on alluvial fans.

The annual expenditure of the province of Sondrio for the mitigation of hydrogeological risk, amounts for the period 2007-2010 to 65 M€. Considering that a large number of other hydrogeological processes threaten the area of the province (rockfalls, floods), the result of risk assessment can be considered largely in accordance with this data.

Some approximations were necessarily introduced in the analysis while assessing value and exposure of the exposed elements. For the economic risk, values/m^2 were assumed to be homogeneous on the study area, while some differences can be found between cities and villages, between town centres and agricultural areas.

The time of permanence of people in structures was estimated without the use of models, just according to the type of activity, and to the opening hours.

Probabilistic studies of debris flow risk at the regional scale are generally difficult, due to the impossibility of calculating a correct return time for the events. FLOW-R allows a good modelling of both open slope and channelled debris flows. The availability of photo-interpreted data was extremely important to calibrate the models, and to guarantee realistic previsions. The adopted methodology, then, rescaled the results of the modelling with the historical events registered on the area, allowing a more realistic representation of the process.

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