From deterministic hazard modelling to risk and loss estimation

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ABSTRACT: Several steps need to be accomplished for a quantitative landslide risk assessment. First, an analysis of the hazardous process and intensity has to be performed. Afterwards, the physical consequences inflicted by the hazard need to be quantified, preferentially in monetary values. For that purpose, a hazard deterministic modelling has to be coupled with information about the value of the elements at risk and its vulnerability to the hazard intensity. Dynamic run-out models for debris flows are able to calculate physical outputs (extension, depths, velocities, impact pressures) and to determine the zones where the elements at risk could suffer an impact. These results can then be applied for vulnerability and risk calculations. The presented risk assessment has been conducted in the area of Tresenda in the Valtellina Valley (Lombardy Region, Northern Italy). Three quantitative hazard scenarios for different return periods were prepared using available rainfall and geotechnical data. The FLO-2D program was applied for the simulation of the debris flow propagation. FLO-2D uses an Eularian formulation with a finite difference numerical scheme that requires the specification of a discharge hydrograph as an input and the basal shear stresses are calculated using a quadratic model. The modelled hazard scenarios were consequently overlaid with the elements at risk. The prospective damage to the houses was estimated using proposed vulnerability functions (flow height and impact pressure). Direct economic losses to the buildings were estimated, reaching € 610,088 to 6,453,366, depending on the hazard scenario and vulnerability curve used.

1 INTRODUCTION

Critical situations are unique because of their intrinsic uncertain nature, and the human behaviour changes in relation to the critical state; therefore, standardization of activities in an emergency situation can be hardly definable in a rigorous way (Drabek & Hoetmer 1991). As a consequence, different spatial and temporal scenarios have to be outlined, analysed, and integrated in emergency plans. Starting from hazard scenarios that identify the temporal and physical characteristics of the expected hydrogeological events, risk scenarios should be defined by describing the possible effects on the social, economic and environmental systems.

The integration of both hazard and its consequences is becoming an accepted and expected practice in risk reduction management (Glade et al. 2005). For this reason, landslide risk investigation has been a major research focus for the international community in recent times (Leroi et al. 2005, Dai et al. 2002). Several approaches has been applied in the past to analyze landslide risk depending on the scope of the analysis; the scale of the study; the physical context; and social environment. These approaches can be classified regarding the way they estimate the risk based on the level of quantification in: (i) qualitative methods; (ii) semi-quantitative methods; and (iii) quantitative methods (van Westen et al. 2006).

Significant efforts have been performed in the past in terms of expressing the hazard frequency and the vulnerability of the elements at risk in numerical terms. Hence, obtaining a quantitative risk assessment (QRA) that can provide a systematic display of economic and non-economic consequences of each analyzed event or scenarios (Michael-Leiba et al. 2003, Bell & Glade 2004, Remondo et al. 2008, Zêzere et al. 2008, Jaiswal et al. 2010). This type of method is an effective and robust technique that allows a good understanding of each process involved in the final assessment. One of the main advantages of a QRA is that it can be compared with other types of risk that can affect a community and because of its quantitative nature it can be communicated more comprehensibly to the policy and decision makers to be used for risk management strategies.

In this site-specific study which is located in the Tresenda village, hazard scenarios are prepared and risk is quantified in economic terms as potential loss to buildings. For the hazards scenario preparation, available meteorological and geotechnical data are used as inputs for the dynamic run-out modelling of possible debris flows. Afterwards, risk is quantified in economic terms for three return periods.

2 STUDY SITE

2.1 Tresenda village

The village of Tresenda in the municipality of Teglio (Fig. 1) was selected as a suitable test-site because its geological and geomorphological settings are favourable for a debris flow occurrence. Spatial distribution of past damage derived from historical records, local chronicles, and interviews with local people; suggested this site to be highly susceptible to hazardous events and subject to significant potential losses (Blahut et al., in press). Soil slips-debris flows can be triggered on the steep slopes above Tresenda, as the soil thickness varies between 70 to 250 cm and material could involve both earth and stones. Past events has been documented where the flows crosses minor roads and impact buildings in the Tresenda village, while running along main drainage lines. If a major event occurs, casualties and serious damages can be expected as well as the obstruction of a main road (S.S. 38).

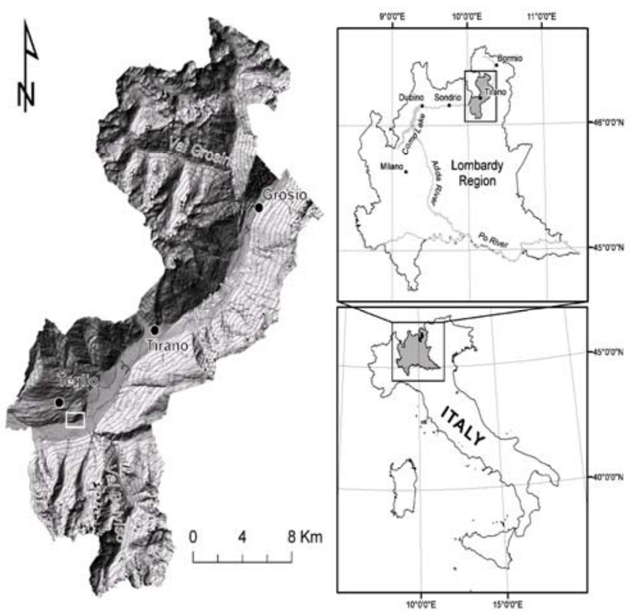

Figure 1. Location of the Tresenda case study area shown as white rectangle.

2.2 Past events on the region

In May 1983, severe precipitations triggered more than 200 shallow landslides and debris flows in Valtellina. Landslides occurred mainly on vine-terraced slopes between Tirano and Sondrio. Most of the landslides started on slopes between 30° and 40°. In Teglio, on 22nd and 23rd of May 1983, three soil-slips evolved into larger debris flows with lengths from 300 to 460 m and areas reaching 60,000 m^2. Two of them occurred on 23rd May on the slopes above the village of Tresenda (Fig. 2), causing 14 casualties and destruction of buildings and infrastructure. The national road S.S. 38 was blocked, and this made impossible to reach the upper part of the valley for few days. (Cancelli & Nova 1985).

A similar event happened on the same slope on 26th of November 2002 (Fig. 3), producing less damage than in year 1983 and, fortunately, no victims. The flow remained confined and caused a minor flooding of the area close to the village due to an obstruction in the drainage channel. In this case, the fast response of the groundwater table and the high intensity of the rainfall played an important role in the evolution of the event (Di Trapani 2009, pers. comm.).

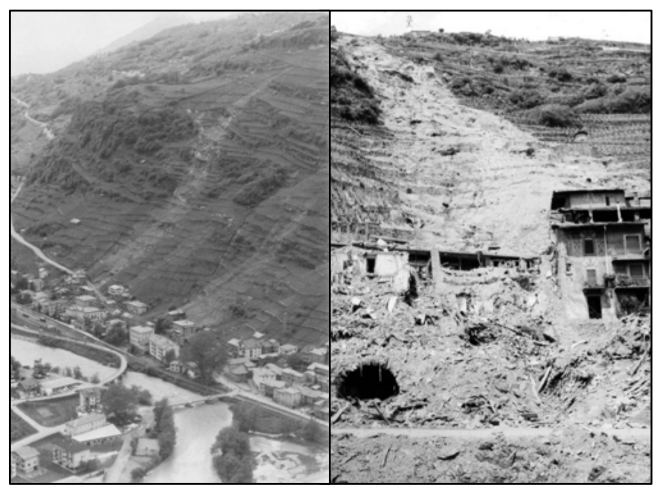

Figure 2. Photographs of two debris flow from 23rd May 1983 in Tresenda. Photo: Archive of CNR-IRPI, Torino.

3 HAZARD SCENARIOS

It was assumed that potential debris flows occurring in the study area will be triggered in areas of high slope and high flow accumulation. After the field surveys and DEM analysis, three potential debris flow sources were selected (Fig. 3). These potential sources were modelled in a dynamic numerical approach to assess the run-out intensity.

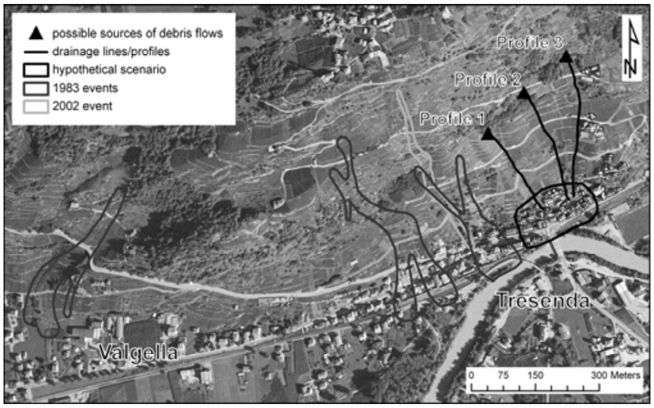

Figure 3. Delimitation of the 1983 and 2002 debris flow according to GeoIFFI database and CM Valtellina di Tirano. Possible sources and drainage lines/profiles of new debris flows are shown and area of a hypothetical risk scenario is delimited.

To delimit the hazard of these debris flows, several steps have to be implemented in order to be modelled: (i) detailed analysis and estimation of rainfall return periods for the study area and modelling the rainfall-runoff process based on the different return period scenarios; (ii) analysis of the terrain features; (iii) laboratory tests of soil samples and determination of the debris flow rheology; and (iv) modelling of the debris flows.

Firstly, available hourly-rainfall records were used to calculate rainfall return periods of 10, 50, and 100-years. A 48-hour rainfall, which may trigger a debris flow, was simulated in the study area and the time of exceedance of rainfall threshold was investigated for different return periods. The simulated rainfall was used to specify the time when rainfall threshold was exceeded and a debris flow triggered. The rainfall-runoff modelling allowed specifying nine input hydrographs for the three potential debris flow sources and three return periods.

Soil samples were collected during the fieldwork and analysed in geotechnical laboratory. Two representative samples were selected based on the criteria of the proximity location to the possible initiation and run-out zones. Geotechnical parameters and particle size distribution for each sample were obtained and used to infer the rheological parameters to be used in the dynamic run-out model. The debris flows scenarios were modelled with the 2-dimensional depth averaged FLO-2D software (FLO-2D 2009).

3.1 *Rainfall modeling and threshold exceedance*

Hourly rainfall data from Castelvetro rain gauge were analysed in order to calculate return periods of rainfalls. Castelvetro rain gauge lies in the vicinity of the study zone, about 3 km west from Tresenda. The hourly rainfall data available cover a 30-year period from 1980 to 2009. To calculate the rainfall return period of 10, 50, and 100-years a Gumbel Extreme Value Type I distribution was used (Gumbel 2004). The results for the three return periods are summarized in Table 1.

Table 1. Calculated precipitation for different return periods and rainfall duration.

Return Period	10 years	50 years	100 years
Duration (h)	Precipitation (mm)		
1	27	37	39
2	39	53	59
3	45	61	67
6	60	80	88
12	85	113	125
24	111	147	162
48	143	191	212

A 48-hour rainfall storm was modelled using the FLO-2D model based on historical information (Guzzetti et al. 1992, Crosta et al. 2003, Di Trapani, pers. comm.) of past debris flow events. The storm rainfall was discretized as a cumulative percentage of the total. This discretization of the storm distribution was established through local rainfall data that defines storm duration and intensity. The storm was modelled spatially over the grid system.

Several rainfall thresholds available for the study area have been calculated in the past. Debris flow initiation thresholds were calculated for the 48-hour rainfall (Table 2).

Table 2. Rainfall thresholds for debris flow initiation using a 48-hour rainfall in Castelvetro rain gauge.

	Threshold	
Author	Type	Value
Govi et al. (1984)	I-D	2.74 mm/h
Cancelli & Nova (1985)	I-D	2.18 mm/h
Ceriani et al. (1992)	I-D	2.38 mm/h
Agostoni et al. (1997)	IMAP-D	2.51 mm/h
Luino et al. (2008)	IMAP-D	1.74 mm/h

3.2 *Laboratory analysis*

Soil samples were collected between July 2009 and February 2010 along the slope uphill from Tresenda. The materials are mixed loose deposits mostly composed of gravel and sand with a consistent percentage of silt and almost absent clay. According to the Unified Soil Classification System (USCS), chosen by the American Society for Testing and Materials (ASTM) as standard, they are GM (silty gravel with sand) or SM (silty sand with gravel), with a uniformity coefficient (CU) between 20 and 157. The mean sample has the following composition: gravel 36%, sand 44%, silt 19% and clay 1%. All the samples are very superficial so they are particularly rich of organic matter (3.3-7.3%). The natural water content (W_0) is strictly dependent on the climatic condition during sampling, and its value range from 0.5% to 14.5%. The bulk unit weight (γ_0), measured in place by the sand-cone method, ranges between 13.8-16.1 kN/m^3 while the calculated γ_{dry} ranges between 12.8-15.7 kN/m^3. With an estimated specific gravity of the soil solids (G_s) equal to 27.2 kN/m^3, the calculate porosity (n) is 42-53% and the sediment volumetric concentration varies between 0.47 and 0.58 m^3/m^3. Atterberg limit results are not determinable because of the almost total lack of clay: this means that the studied material pass from the semi-solid to the liquid state in a while. Direct shear tests were performed to obtain the peak and residual values of the shear strength parameters: c_p = 3.4-18.5 kPa; φ_p = 28°-36°;c_r = 0-17 kPa; φ_r = 26°-35°. These values are in good agreement with past laboratory analysis made of the area (Cancelli & Nova 1985, Crosta et al. 2003).

3.3 Debris flow modeling

The time where the rain storm exceeded the threshold was registered and discharge hydrographs were produced from the previous rainfall-runoff modelling. Volumes were calculated from the peak discharge hydrographs (Table 3 & 4).

Table 3. Release volumes in cubic meters for the three profiles and return periods.

	10 years	50 years	100 years
		Volume (m^3)	
Profile 1	390	1162	1424
Profile 2	330	1142	1410
Profile 3	425	1251	1518

Table 4. Peak discharge in cubic meters per second for the three profiles and return periods.

	10 years	50 years	100 years
		Peak Discharge (m^3/s)	
Profile 1	4.8	11.4	13.4
Profile 2	4.2	11.2	13.3
Profile 3	5.1	12.1	14.1

The debris flows run-out was modelled with the FLO-2D software. The FLO-2D model uses a quadratic rheological model that incorporates a Bingham shear stress as a function of sediment concentration, and a combination of turbulent and dispersive stress components based on a modified Manning *n* value (Eq. 1):

$$S_f = \frac{\tau_y}{\gamma_m h} + \frac{K\eta V}{8\gamma_m h^2} + \frac{{n_{td}}^2 V^2}{h^{4/3}} \quad (1)$$

where, S_f is the friction slope (equal to the shear stress divided by $\gamma_m h$); V is the depth-averaged velocity; τ_y and η are the yield stress and viscosity of the fluid, respectively, which are both a function of the sediment concentration by volume; γ_m is the specific weight of the fluid matrix; K is a dimensionless resistance parameter that equals 24 for laminar flow in smooth, wide, rectangular channels; and n_{td} is an empirically modified Manning *n* value that takes into account the turbulent and dispersive components of flow resistance. The rheological properties of the flow were estimated based on the results of the laboratory analysis. The final parameters used in the modelling were τ_y = 1,500 Pa and η = 2,800 Pa. The Manning *n*-value that characterises the roughness of the terrain was selected as 0.04 sm$^{1/3}$. This value was confirmed in the FLO-2D user's manual (FLO-2D 2009).

4 QUANTIFICATION OF RISK AND PROSPECTIVE ECONOMIC DAMAGE

Quantification of damage to buildings in the case study area was done by examination of the results from the hazard modelling to the respective building. Heights of accumulation and highest impact pressures near the walls were extracted for each interested building. The results were used to calculate risk maps for the three return periods by using two different vulnerability curves.

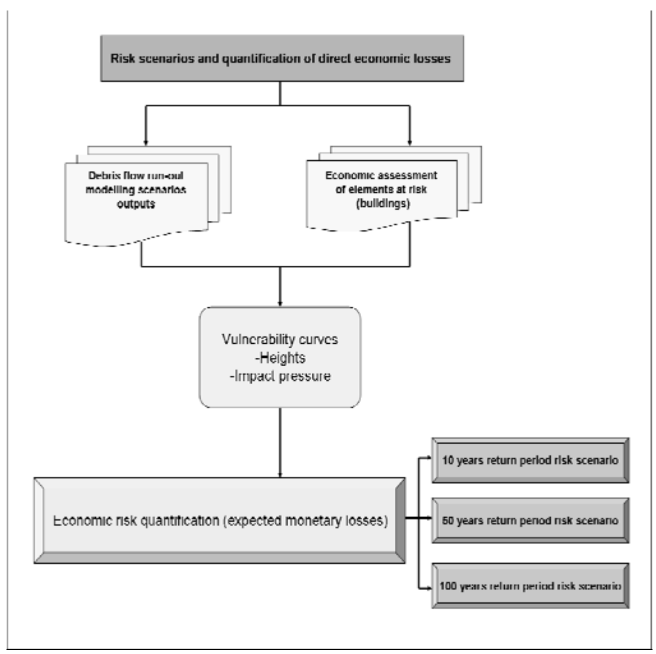

Figure 4. Flowchart of the methodological framework for the risk scenario quantification.

A vulnerability curve proposed by Fuchs et al. (2007) based on the height of the debris flow as an intensity parameter and the proposed vulnerability curve by Barbolini et al. (2004) for impact pressure of snow avalanches were used for the analysis. Direct losses to the buildings were calculated by multiplying the calculated vulnerability by the building value (Fig. 4).

4.1 *Elements at risk in the study area*

There are 111 buildings in the immediate vicinity of the Tresenda scenario, 57 of them within the delimited hypothetical scenario area. The majority of them are three story buildings constructed with brick masonry and concrete structures. Value of each building was estimated using the construction prices provided by Engineers and Architects of Milan (DEI 2006). According to them, a construction cost of 801 €/m^2 corresponds to single standing house with 2-3 storeys. The value of the buildings was calculated by multiplying their area from the DB2000 (2003) database by the number of floors and by the reconstruction value per m^2. Total value of the buildings within the scenario area is reaching € 14,895,500 with a range from € 34,360 to € 1,079,000 for a single building, and with an average reconstruction cost of € 261,324 per building.

Besides the buildings, a state road S.S.38 lies between the buildings and the Adda River and minor paved roads are present. A principal railway line is running along the state road, connecting province capital Sondrio with Tirano and Switzerland upstream the Adda River. According to the database of Registry Office, 173 people are living in the houses within the delimited scenario. In this approach, only economic risk to buildings is quantified, neglecting the damage to other infrastructure and to the people living in the area.

4.2 *Hazard scenarios and damage to buildings*

In total, six hazard scenarios were prepared for each return period and for accumulation heights and impact pressures, respectively. The results are presented in Figures 5-7 showing the difference in the magnitude of the hazard. Moreover, information about the possible damage to the houses is shown, resulting from the calculated vulnerability using the respective vulnerability function. Light damage means vulnerability between 0 and 0.1, medium damage represents vulnerability 0.1-0.5 and heavy damage relates to vulnerabilities between 0.5 and 1. Destruction means that vulnerability of 1 was reached.

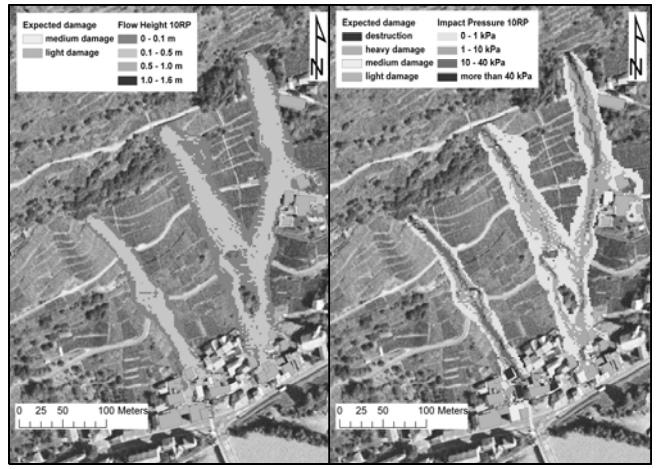

Figure 5. Results of the hazard modelling for the 10-year return period showing the calculated degree of damage to the buildings. On the left height of accumulation, on the right impact pressures.

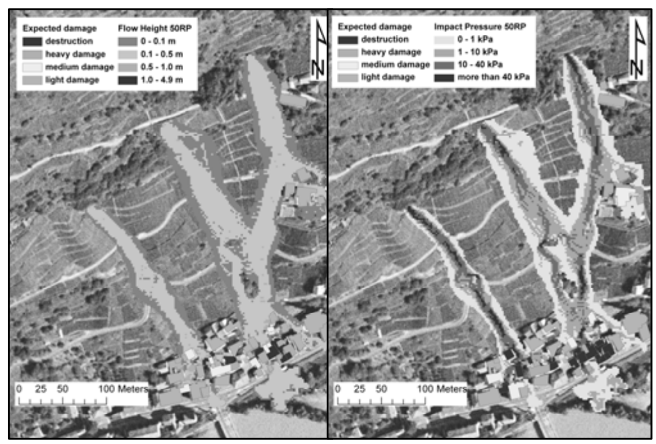

Figure 6. Results of the hazard modelling for the 50-year return period showing the calculated degree of damage to the buildings. On the left height of accumulation, on the right impact pressures.

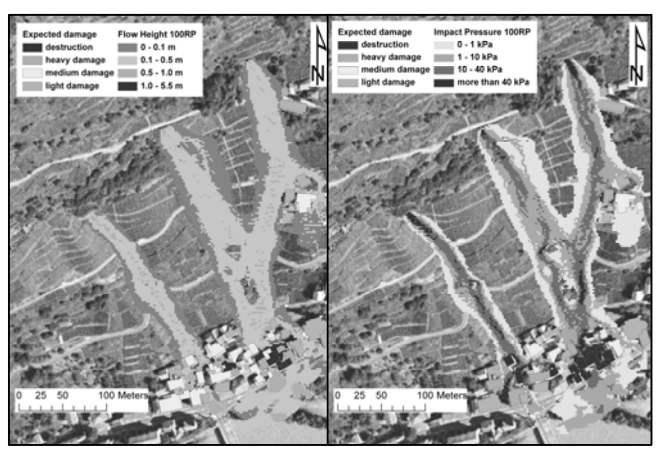

Figure 7. Results of the hazard modelling for the 100-year return period showing the calculated degree of damage to the

buildings. On the left height of accumulation, on the right impact pressures.

4.3 Risk scenarios and quantification of direct economic losses

4.3.1 10-year return period

In the hazard scenario considering the 10-year return period (0.1 probability) of the debris flows, 35 buildings are likely to be impacted. The total direct damage to houses is considerably affected by the use of different vulnerability functions. Considering the flow height vulnerability function, the direct damage reaches € 610,088. In the case of impact pressure vulnerability function, the total direct monetary loss to the buildings is estimated to € 2,059,321 (337.55% of the first damage estimate). Risk levels span from 0 (no risk) to 8,271 €/year for a single building in case of the height of accumulation vulnerability function and from 0 to 27,780 €/year for a single building in case of the use of impact pressure vulnerability function.

4.3.2 50-year return period

In the 50-year return period hazard scenario (0.02 probability), 49 buildings are likely to be impacted. After the application of the vulnerability function using as an intensity parameter the flow height, 32 buildings will suffer light damage, 9 buildings medium damage, and 5 buildings high damage. Three buildings will be completely destroyed. After application of the impact pressure vulnerability function, different results were obtained: 21 buildings will suffer light damage, 8 buildings will have medium damage and 6 buildings will have heavy damage. Fourteen buildings will be probably destroyed. Considering the flow height vulnerability function, the direct damage reaches € 2,311,219. In the case of impact pressure vulnerability function, it reaches € 5,059,011. Risk reaches 7,644 €/year for a single building in both cases of risk calculation (Fig. 11.18).

4.3.3 100-year return period

In the 100-year return period hazard scenario (0.01 probability), 49 buildings are likely to be impacted as in the case of the 50-year scenario. After the application of the vulnerability function using as an intensity parameter the flow height, 19 buildings will suffer light damage, 22 buildings medium damage, and 4 buildings high damage. Four buildings will be completely destroyed. After application of the impact pressure vulnerability function, higher damage pattern was obtained: 16 buildings will suffer light damage, 7 buildings will have medium damage and 8 buildings will have heavy damage. Eighteen buildings will be probably destroyed. These results show the same pattern as in the case of 10 and 50-year return periods. The number of affected houses is similar to the previous scenario. Expected damage is, however, much higher.

The total direct damage to houses is considerably affected by the used of the different vulnerability functions as in the case of the previous scenarios. Considering the height of accumulation vulnerability function, the direct damage reaches € 3,151,675. In the case of impact pressure vulnerability function application, the total direct monetary loss to the buildings is estimated to € 6,453,366. Risk reaches 3,822 €/year for a single building in case of the flow height vulnerability calculation and 6,127 €/year for a single building in case of the impact pressure use.

4.4 Limitation of the results

The modelling itself as well as the results allows expressing the economic risk to exposed buildings in a quantitative way. However, there are still some limitations, which need to be addressed. Firstly, it is assumed that the return period of a rainfall, potentially causing a debris flow, is the same as the return period of the resulting debris flow. Other assumptions arise from the modelling itself: DEM resolution, rheological properties acquired in the laboratory that are upscaled to the entire area, and volume estimates. Other implications arise from the application of vulnerability curves applied to the Tresenda scenario which might seriously affect the resulting damage and risk estimates. It turned out, that the use of impact pressure-based vulnerability curve is giving much higher damage estimates than the flow height-based vulnerability curve (Fig. 8).

Figure 8. Comparison of loss estimations for the three return periods using two vulnerability curves. RP – return period; h – height vulnerability function; P – impact pressure vulnerability function.

Estimated economic value of the building has also important effect on the results, as it is assumed similar unit value of buildings, neglecting its particular conditions and current state. Finally, estimates about the value of the furniture and expenses needed to remove and re-deposit the debris material, or damage to the roads and lifelines are not taken into account.

Besides the presented limitations, we believe that the approach applied in this analysis is generally applicable to other areas and may give important information to the local stakeholders.

5 CONCLUDING REMARKS

Presented approach allowed to assess debris flow hazard and risk in a quantitative way and to calculate prospective direct damage to buildings in the case study area. Direct economic losses to the buildings were estimated, reaching € 610,088 to 6,453,366, depending on the hazard scenario and vulnerability curve used.

The approach proposed in this study may assist local decision makers in determining the nature and magnitude of the expected losses due to a dangerous event. Besides, a preventive knowledge of the prospective physical effects and economic consequences may help to properly allocate financial resources for disaster prevention and for mitigation measures. Improved information may support decision makers on how to allocate and manage resources to deal with future hazards in the area.

It is obvious that the approach still has some weak points (e.g. delimitation of initiation areas, assessment of people's vulnerability, etc.). However, beside its limitations, it increases the knowledge about prospective outcomes of future hazards and thus contributes to the protection of the people and their assets.

6 REFERENCES

Agostoni, S., Laffi, R., Sciesa, E. 1997. Centri abitati instabili della provincia di Sondrio. CNR-GNDCI, Milano, 59 pp. + Annexes.

Barbolini, M., Cappabianca, F., and Sailer, R. 2004. Empirical estimate of vulnerability relations for use in snow avalanche risk assessment. In: Brebbia, C. (Ed.): Risk analysis IV, WIT Press, Southampton, pp. 533-542.

Bell, R., Glade, T. 2004. Quantitative risk analysis for landslides – Examples from Bíldudalur, NW-Iceland. Natural Hazards and Earth System Sciences, 4: 117-131.

Blahut, J., Poretti, I., Sterlacchini, S. De Amicis, M. 2010. Database of Geo-hydrological Disasters for Civil Protection Purposes. Natural Hazards (in press)

Cancelli, A., Nova, R. 1985. Landslides in soil debris cover triggered by rainstorms in Valtellina (Central Alps – Italy). In: Proceedings of 4th International Conference and Field Workshop on Landslides. The Japan Geological Society, Tokyo, pp. 267–272.

Ceriani, M., Lauzi, S., Padovan, N. 1992. Rainfall and landslides in the Alpine area of Lombardia Region, Central Alps, Italy. In: Proceedings of the Internationales Symposium Interpraevent. Bern, 2: 9-20.

Crosta, G.B., Dal Negro, P., Frattini, P. 2003. Soil slips and debris flows on terraced slopes. Natural Hazards and Earth System Sciences, 3: 31-42.

Dai, F.C., Lee, C.F. and Ngai, Y.Y. 2002. Landslide risk assessment and management: an overview. Engineering Geology, 64(1): 65-87.

DB2000 2003.Database of the CM Valtellina di Tirano mapped at 1:2,000 scale .CM Valtellina di Tirano. Available at: http://www.cmtirano.so.it/sistemainformativo.php

DEI 2006. Prezzi Tipologie Edilizie 2006. DEI Tipografia del Genio Civilie. CD-ROM.

Drabek, T.E., Hoetmer, G.J. 1991. Emergency Management: Principles and Practice for Local Government. International City Management Association, Washington, D.C., 416 p.

FLO-2D 2009. Reference manual 2009. FLO-2D Software Inc., 73 p. Available at: http://www.flo-2d.com/wp-content/uploads/FLO-2D-Reference-Manual-2009.pdf

Fuchs, S., Heiss, K., Hübl, J. 2007. Towards an empirical vulnerability function for use in debris flow risk assessment. Natural Hazards and Earth System Sciences, 7: 495-506.

Giacomelli, L. 1987. Speciale Valtellina 1987: Cronaca, storia, commenti. Notiziario della Banca Popolare di Sondrio, No. 45, Bergamo, 227 p.

Glade, T., Anderson, M., Crozier, M.J. (Eds). 2005. Landslide Hazard and Risk. John Wiley & Sons Ltd, Chichester, UK: xii.

Govi, M., Mortara, G., Sorzana, P. 1984. Eventi idrologici e frane. Geologia Applicata e Idrogeologia, XCVIII, 3 p.

Gumbel, E.J. 2004. Statistics of extremes. reprint of the 1958 edition, Dover Publications, Mineola, 375 p.

Guzzetti, F., Crosta, G., Marchetti, M., Reichenbach, P. 1992. Debris flows triggered by the July, 17–19, 1987 storm in the Valtellina area (Northern Italy). International Symposium Interpraevent 1992, Bern, Switzerland, pp. 193-203.

Jaiswal, P., Westen, C. J. van., and Jetten, V.: Quantitative assessment of direct and indirect landslide risk along transportation lines in southern India, Nat. Hazards Earth Syst. Sci., 10, 1253-1267, doi:10.5194/nhess-10-1253-2010, 2010.

Leroi, E., Bonnard, Ch., Fell, R., McInnes, R. 2005. A framework for landslide risk assessment and management. . In: Hungr, O., Fell, R., Couture, R., Eberhardt, E. (Eds.): Landslide Risk Management. Taylor & Francis, London, pp. 159-198.

Luino, F., Nigrelli, G., Biddoccu, M., Cirio, C.G., Di Palma, M., Missaglia, M., Fassi, P. 2008. Definizione delle soglie pluviometriche d´innesco di frane superficiali e colate torrentizie: accorpamento per aree omogenee. IRER, Milano, 125 p.

Michael-Leiba, M., Baynes, F., Scott, G. and Granger, K. 2003. Regional landslide risk to the Cairns community. Natural Hazards, 30(2): 233-249.

O'Brien J.S., Julien, P.Y. 1988. Laboratory analysis of mudflow properties. Journal of Hydraulic Engineering, 114(8): 877-887.

Remondo, J., Bonachea, J. and Cendrero, A. 2008. Quantitative landslide risk assessment and mapping on the basis of recent occurrences. Geomorphology, 94(3-4) pp. 496-507.

van Westen, C.J., van Asch, T.W.J., Soeters, R. 2006. Landslide hazard and risk zonation—why is it still so difficult? Bulletin of Engineering Geology and the Environment, 65: 167-184.

Zêzere, J.L., Garcia, R.A.C., Oliveira, S.C. and Reis, E. 2008. Probabilistic landslide risk analysis considering direct costs in the area north of Lisbon (Portugal). Geomorphology, 94(3-4), pp. 467-495.